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EDGE ARTICLE

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A de novo approach for the rapid construction of orthogonally protected L- and D-deoxysugars and analogues is described. A novel and robust silicon-acetal undergoes Prins cyclisations with a series of homoallylic alcohols in high yield and excellent stereocontrol. Modified Tamao–Fleming oxidation of the resulting silyltetrahydropyrans gives direct access to deoxyglycoside analogues and the approach was showcased in the synthesis of protected L-oliose, a component of the anticancer agent aclacinomycin A.

Introduction

Deoxyglycosides are important components of a wide variety of natural products isolated from plants, fungi and bacteria including compounds exhibiting anticaner and antibiotic activities. Some have proved effective for use in the clinic (e.g. the antibiotic vancomycin and the anthracine antibiotic altromycin B) or as lead compounds to pharmaceuticals.1 In addition, deoxyglycans are also prevalent in bacterial membrane glycoproteins, thus being a viable target for drug discovery and vaccine development.2

The ability to fully understand and exploit the glyobiology of rare deoxysugars and analogues is hindered by the challenges of isolating pure materials in reasonable quantities from natural sources.3 In addition, synthetic approaches from naturally-abundant carbohydrates often require lengthy synthetic routes which make rare sugars very expensive.4 An alternative and potentially more versatile approach is the de novo asymmetric synthesis of deoxy sugars.5,6 An ideal synthetic strategy would be efficient, robust and readily adapted for the construction of a series of deoxysugars and derivatives. To this end, we have developed a new approach for the enantioselective synthesis of differentially-protected L- and D-deoxyglycosides and analogues via Prins cyclisations and its utility exemplified by the synthesis of 2,4- and 2,6-dideoxyglycosides including protected L-oliose.

Prins cyclisations involve acid-mediated reactions of homoallylic alcohols 1 (or derivatives thereof) to form an oxy-carbenium ion I which cyclises via carbocation II and is subsequently trapped by a nucleophile, giving tetrahydropyrans 2 with excellent stereocontrol (Scheme 1).6 Reddy, Yadav and co-workers have used sugar derivatives as substrates in Prins cyclisations.7 Success of our proposed approach to deoxyglycosides relied upon use of a suitable electrophile bearing a hydroxyl surrogate (X in Scheme 1) which would need to be both stable to the acidic conditions required for the cyclisation and would readily be converted to a suitable functional group (e.g. acetate 3) for use in glycosylation reactions. An orthoformate was considered as the electrophile to directly introduce a 1-O-alkyl side-chain, but these have rarely been used in Prins cyclisations and are limited to substrates in which the reaction proceeds via a tertiary carbocation.8,9

Results and discussion

A trialkylsilane was considered a suitable hydroxyl surrogate as, following cyclisation, a Tamao–Fleming oxidation would lead to the required acetol. Whilst dimethylphenylsilanes have been widely used,10 Hosomi and co-workers reported the benzylidimethylsilyl group (BDMS) as an attractive alternative that is readily oxidised to alcohols.11 An important criterion for our synthetic strategy was that the electrophile should be stable and readily prepared on a synthetically valuable scale. Thus, novel silyl acetal 5 was prepared in two steps and 76% overall yield via treatment of 2-lithio-1,3-dithiane12 with benzylidimethylsilyle chloride (BDMSCl) to give dithiane 4 followed by mercuric-
mediated deprotection in ethanol (Scheme 2). The reaction was conducted on a multigram scale and the acetal is stable with no apparent decomposition after 6 months on the bench.

Initially, the key Prins cyclisation was optimised using the known (R)-homoallylic alcohol 6 prepared from dihydrocinnamaldehyde via a Nakomi crotyl transfer reaction. Several methods have been reported for the introduction of oxygen nucleophiles, and in this case treatment of alcohol 6 and acetal 5 with trifluoroacetic acid (TFA) at 0 °C, then hydrolysis of the resultant ester gave alcohol 7 in 97% yield (Scheme 3). A single diastereomer was isolated in which all four substituents were equatorial.

Our ultimate targets, 2,6- and 2,4-dideoxysugar analogues, lack a substituent at C-2 and their synthesis requires a substrate partner which on reaction with an aldehyde would enable the cyclisation, the enantiopurity (97.5:2.5 e.r.) of 9 was confirmed by chiral SFC.

An alternative synthetic approach to the silyltetrahydropyrans was to incorporate the silyl moiety into the alkene coupling partner which on reaction with an aldehyde would enable the facile introduction of a range of side-chains at C-5 of the target deoxysugars (Scheme 4). Several methods were investigated for the synthesis of z-silyl-homoallylic alcohol 10 via acid-mediated allylation of acetal 5 (e.g. in the presence of InCl₃, AgNO₃, SnCl₄) but none of the required product was isolated. In contrast, when silyl acetal 5 was treated with allyltetramethylethylsilane and LiBF₄ in wet acetonitrile, alcohol 10 was isolated in 61% yield. The TFA mediated reaction of 10 with either acetaldehyde or 3-benzyloxypropanal followed by hydrolysis of the resultant ester gave silyltetrahydropyrans 11 and 12 in 89% and 82% yields, respectively, from acetal 5. By varying the reaction conditions the analogous acetates 13 and 14 were readily prepared. Further studies are ongoing to investigate the enantioselective allylation of acetal 5.

The second stage of our synthetic strategy required oxidation of the benzyldimethylsilyl group; Trost and Donohoe have reported the use of tetrabutylammonium fluoride (TBAF) followed by hydrogen peroxide for similar transformations. Following detailed investigations we established suitable conditions for the successful oxidation of silane 7 (Scheme 5). It was evident that two steps are involved. First addition of TBAF converted silane 7 to silanol 15 which could be isolated and characterised.

However, it was not necessary to isolate 15 as it was converted in situ to hemiacetal 16 via a urea hydrogen peroxide oxidation and then directly acetylated to give 17 in 73% yield from silane 7. It proved vital to keep the temperature of the fluoride activation step in the range 0–5 °C, as at higher temperatures disiloxanes were formed from the condensation of two silanols, which were only slowly oxidised under the reaction conditions.

To confirm that the oxidation/acetylation protocol was compatible with different protecting groups commonly used in carbohydrate chemistry, the secondary alcohols in 7 and 9 were converted to acetates (18 and 19) and benzyl ethers (20 and 21) in high yields using standard reaction conditions (Scheme 6). Oxidation of each silane gave the corresponding anomeric acetates (17, 22–24) in 64–80% isolated yield.

Next the optimised cyclisation/oxidation/acetylation strategy was applied to the preparation of protected 2,4-dideoxyglycosides (Scheme 7). Homoallylic alcohol 26 was prepared in 88% overall yield from (S)-glycidol via protection of the alcohol as silyl ether 25 and ring opening of the oxirane with
vinyl magnesium bromide and CuCN. Treatment of 26 with silyl acetal 5 and TESOTf in acetic acid gave silyl tetrahydropyran 27 in 65% yield which was readily converted to triacetate 28 as a 1:2 mixture of anomers using the oxidation/acetylation protocol. Interestingly, treatment of the mixture of homoallylic alcohol 26 and acetel 5 with TFA, our standard cyclisation conditions, gave none of the expected product, instead the analogous ethyl ether 29 was isolated. Some deoxysugars indeed have ethers at C-3, for example, D-olivose is a component of the highly potent and selective anticancer agent durhamycin A and l-cymarose, found in the DNA-helicase inhibitor, heliquinomycin and so this unexpected result has potential significant synthetic value.

To access orthogonally protected 2,4-dideoxyglycosides, benzyl-protected tetrahydropyran 30 was prepared via a similar protection/vinyl addition/cyclisation strategy from (S)-glycidol benzyl ether in 71% overall yield (Scheme 8). Oxidation of 30 gave diacetate 31 which subsequently was used to glycosylate cyclohexanol in the presence of BF$_3$·Et$_2$O giving 32 as exclusively the α-anomer in 72% yield. The synthetic approach was extended to 2,4-dideoxyglycosides with an axial C-3 oxygenated substituent via hydrolysis of acetate 30 and Mitsubou inversion to give 33 which was oxidised to protected glycoside 34 in 75% yield.

Next we turned out attention to the synthesis of protected 2,6-dideoxy sugars as all diastereoisomers of d- and l-2,6-dideoxyhexoses have been found in biologically active natural products e.g. d-olivose is a component of angucycline antibiotic landomycin A whereas d-digitoxose is present in the steroidal glycoside digitoxin (Fig. 1).

Initial studies revealed that whilst homoallylic alcohol 35 was readily prepared via Brown allylation of allyl ethyl ether, reaction of 35 with silyl acetal 5 under our standard TFA conditions gave the 5-membered ring aldehyde 36 in 46% yield (Scheme 9). Aldehyde 36 is likely to be formed via a Prins-pinacol reaction involving oxonia-Cope rearrangement of o xo carbonium ion III to enol ether IV followed by cyclisation to tetrahydropyran V and finally α-alkyl cleavage to generate the carbonyl group. Hence to favour formation of a tetrahydropyran over a tetrahydrofuran we reasoned that an electron withdrawing group rather than an ether was required and a carbamate protecting group was selected.

Thus an asymmetric synthesis of homoallylic alcohol 40 was required which could be readily adapted for both the d- or l-protected 2,6-dideoxysugars since, for example, l-olivose is a component of aclarcubicin, clinically used for the treatment of acute leukaemias, whilst d-olivose is present in the antitumour drugs mithramycin and chromocyclomycin, as well as the HIV-inhibitor durhamycin A.

Singh and Guiry reported that Sharpless asymmetric epoxidation (SAE) of divinylcarbinol, followed by Mitsubou inversion of the resulting alcohol gives epoxide 37 (Scheme 10). Importantly, choice of (−)-DIPT or (+)-DIPT in the SAE step allows access to the d- and l-series, respectively. Protection of alcohol 37 with N$_3$N-disopropylcarbamoyl chloride gave a mixture of chlorohydrins 38 and the required epoxide 39. Chlorohydrin 38 was readily converted to 39 by treatment with NaOH in THF at room temperature within a matter of minutes. Reductive ring opening of the oxirane with DIBALH gave monoprotected syn allylic diol 40 which cyclised with acetal 5 to give the required tetrahydropyran 41 with an equatorial C-3 alcohol.

![Scheme 7 Preparation of 2,4-dideoxyglycosides](image1)

![Scheme 8 Synthesis of protected 2,4-dideoxyglycosides 31 and 34.](image2)

![Scheme 9 Cyclisation to tetrahydrofuran 36 and nOe correlations.](image3)

![Scheme 10 Enantioselective synthesis of protected l-olivose 42.](image4)
and the axial C-4 protected hydroxyl. Finally oxidation of silane 41 gave protected l-olivose 42 in 77% yield as a 1 : 1 mixture of anomers. The methodology could be extended to the synthesis of l-olivose via protected alcohol 44 which was prepared from epoxide 43 using the same conditions as for assembly of the diastereomer 40 (Scheme 11). Interestingly, reaction of 44 with acetal 5 under the standard conditions gave a mixture of products due to migration of the carbamoyl group but on reduction of the mixture with LiAlH4, diol 45 was isolated in 57% yield. It is possible that neighbouring group participation by the carbamoyl group traps the intermediate carbocation I in the Prins cyclisation giving II and resulting in migration of the carbamoyl group but this has not been proven.

Conclusions

In conclusion, a de novo approach for the rapid construction of a series of orthogonally protected l- and d-dideoxysugars and analogues is described from simple starting materials. A stable acetal 5 was prepared in two high yielding steps and used in a series of acid-mediated Prins cyclisations with different homoallylic alcohols to give the corresponding tetrahydropyrans in good yield and excellent diastereoselectivity. These reactions are readily performed on gram scales. A modified Tamao–Fleming oxidation/acetylation protocol gave the target 2,4-dideoxy sugars with an acetyl group at the anomeric position. Extending the utility of the new methodology to the synthesis of 2,6-dideoxysugars revealed the importance of the choice of protecting group to avoid formation of tetrahydropyrans. The enantioselective synthesis of protected l-olivose is described using N,N-diisopropylcarbamoyl as a protecting group. Silane 41 has potential value for the synthesis of other 2,6-dideoxyhexoses for example methylation of the free hydroxyl group will lead to protected l-diginose while Mitsunobu inversion will give l-bovinose derivatives and subsequent methylation to l-sarmentose and these investigations are ongoing in our laboratories.

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Notes and references

1 For reviews see: (a) A. C. Weymouth-Wilson, Nat. Prod. Rep., 1997, 14, 99–110; (b) V. Kren and T. Rejzanka, FEMS Microbiol. Rev., 2008, 32, 858; (c) A. Kirschning, A. F. W. Bechthold and J. Rohr, Bioorganic Chemistry Dideoxy sugars, Polyketides and Related Classes: Synthesis, Biosynthesis, Enzymes, in Topics in Current Chemistry, Springer Berlin/Heidelberg, 1997, vol. 188, pp. 1–84.

2 For recent reviews on the importance of oligosaccharides see: (a) P. Stalforth, B. Lepenies, A. Adibekian and F. H. Seeberger, J. Med. Chem., 2009, 52, 5561–5577; (b) M. C. Galan, D. Benito-Alfonso and G. M. Watt, Org. Biomol. Chem., 2011, 9, 3598–3610; (c) M. C. Galan, P. Dumy and O. Renaudet, Chem. Soc. Rev., 2013, 42, 4599–4612.

3 Recently some elegant strategies have been reported for the synthesis of d-deoxyglucosides starting from readily available carbohydrates, e.g. M. Emmadi and S. S. Kulkarni, Org. Biomol. Chem., 2013, 11, 3098–3102.

4 For selected reviews see: (a) A. Kirschning, M. Jesberger and K. U. Schoning, Synthesis, 2001, 507–540; (b) R. M. De Ledegraeme and C. Marino, in Advances in Carbohydrate Chemistry and Biochemistry, vol. 188, ed. D. Horton, 2008, vol. 61, pp. 143–216; (c) A. Z. Alajdali, P. Shi, Y. Zhong and G. A. O’Doherty, in Advances in Carbohydrate Chemistry and Biochemistry, ed. D. Horton, 2013, vol. 69, pp. 55–123.

5 For selected examples see: (a) H. Guo and G. A. O’Doherty, Angew. Chem., Int. Ed., 2007, 46, 5206–5208; (b) R. S. Babu, Q. Chen, S.-W. Kang, M. Zhou and G. A. O’Doherty, J. Am. Chem. Soc., 2012, 134, 11952–11955; (c) D. Leonori and P. H. Seeberger, Beilstein J. Org. Chem., 2013, 9, 332–341; (d) R. Pragani, P. Stalforth and P. H. Seeberger, Org. Lett., 2010, 12, 1624–1627.

6 For reviews see: (a) I. M. Pastor and M. Yus, Curr. Org. Chem., 2007, 11, 925–957; (b) C. Olier, M. Kaffarani, S. Gastaldi and M. P. Bertrand, Tetrahedron, 2010, 66, 413–445.

7 (a) B. V. S. Reddy, A. V. Ganesh, A. S. Krisha, G. G. K. S. N. Kumar and J. S. Yadav, Tetrahedron Lett., 2011, 52, 3342–3344; (b) J. S. Yadav, B. V. S. Reddy, A. P. Singh, D. N. Chaya and D. Chatterjee, Tetrahedron Lett., 2010, 51, 1475–1478.

8 (a) F. Perron-Sierra, M. A. Promo, V. A. Martin and K. F. Albizati, J. Org. Chem., 1991, 56, 6188–6199; (b) G. E. Keck, J. A. Covel, T. Schiff and T. Yu, Org. Lett., 2002, 4, 1189–1192.

9 Prins cyclisations have been used to assemble tetrahydropyrans with a hydroxymethyl side-chain which then can be oxidatively cleaved to give lactones, see for example, J. S. Yadav, M. S. Reddy and A. R. Prasad, Tetrahedron Lett., 2005, 46, 2133–2136.

10 K. Tamao, Proc. Jpn. Acad., Ser. B, Phys. Biol. Sci., 2008, 84, 123–133.

11 K. Miura, T. Hondo, T. Takahashi and A. Hosomi, Tetrahedron Lett., 2000, 41, 2129–2132.

12 (a) E. J. Corey, D. Seeback and R. Freedman, J. Am. Chem. Soc., 1967, 89, 434–436; (b) A. G. Brook, J. M. Duff, P. F. Jones and N. R. Davis, J. Am. Chem. Soc., 1967, 89, 431–434.

13 A. Degl’Innocenti, P. Scafato, A. Capperucci, L. Bartoletti, C. Spezzacatena and R. Ruzziconi, Synlett, 1997, 361, 362.
14 (a) J. Nokami, M. Ohga, H. Nakamoto, T. Matsubara, I. Hussain and K. Kataoka, J. Am. Chem. Soc., 2001, 123, 9168–9169; (b) C. S. Barry, N. Bushby, J. R. Harding and C. L. Willis, Org. Lett., 2005, 7, 2683–2686.

15 (a) J. J. Jaber, K. Mitsui and S. D. Rychnovsky, J. Org. Chem., 2001, 66, 4679–4686; (b) E. H. Al-Mutairi, S. R. Crosby, J. Darzi, J. R. Harding, R. A. Hughes, C. D. King, T. J. Simpson, R. W. Smith and C. L. Willis, Chem. Commun., 2001, 835–836; (c) K. Tadpetch and S. D. Rychnovsky, Org. Lett., 2008, 10, 4839–4842; (d) J. S. Yadav, B. V. Subba Reddy, G. G. K. S. Narayana Kumar and S. Aravind, Synthesis, 2008, 395–400; (e) J. S. Yadav, B. V. S. Reddy, A. V. Ganesh and G. G. K. S. Narayana Kumar, Tetrahedron Lett., 2010, 51, 2963–2966.

16 (a) C. S. J. Barry, S. R. Crosby, J. R. Harding, R. A. Hughes, C. D. King, G. D. Parker and C. L. Willis, Org. Lett., 2003, 5, 2429–2432; (b) C. S. Barry, J. D. Elsworth, P. T. Seden, N. Bushby, J. R. Harding, R. W. Alder and C. L. Willis, Org. Lett., 2006, 8, 3319–3322; (c) P. T. Seden, J. P. H. Charmant and C. L. Willis, Org. Lett., 2008, 10, 1637–1640.

17 H. C. Brown and P. K. Jadhav, J. Am. Chem. Soc., 1983, 105, 2092–2093.

18 (a) S. Marumoto, J. J. Jaber, J. P. Vitale and S. D. Rychnovsky, Org. Lett., 2002, 4, 3919–3922; (b) R. Jasti and S. D. Rychnovsky, J. Am. Chem. Soc., 2006, 128, 13640–13648; (c) C. S. Barry, N. Bushby, J. R. Harding, R. A. Hughes, G. D. Gregory, R. Roe and C. L. Willis, Chem. Commun., 2005, 3727–3729.

19 B. H. Lipshutz and D. F. Harvey, Synth. Commun., 1982, 12, 267.

20 (a) B. M. Trost and Z. T. Ball, J. Am. Chem. Soc., 2005, 127, 17644–17655; (b) B. M. Trost, M. R. Machacek and Z. T. Ball, Org. Lett., 2003, 5, 1895–1898; (c) T. J. Donohoe, P. C. M. Winship, B. S. Pilgrim, D. S. Walter and C. K. A. Callens, Chem. Commun., 2010, 46, 7310–7312.

21 (a) S. E. Denmark, R. F. Sweis and D. Wehrli, J. Am. Chem. Soc., 2004, 126, 4865–4875; (b) S. E. Denmark, D. Wehrli and J. Y. Choi, Org. Lett., 2000, 2, 2491–2494.

22 E. J. Rayment, N. Summerhill and E. A. Anderson, J. Org. Chem., 2012, 77, 7052–7060.

23 S. K. Woo, M. S. Kwon and E. Lee, Angew. Chem., Int. Ed., 2008, 47, 3242–3244.

24 For selected examples where the source of nucleophilic trapping originates from the electrophile, see: (a) K. Zheng, X. Liu, S. Qin, M. Xie, L. Lin, C. Hu and X. Feng, J. Am. Chem. Soc., 2012, 134, 17564–17573; (b) J. S. Yadav, B. V. Subba Reddy, G. Mahesh Kumar and C. V. S. R. Murthy, Tetrahedron Lett., 2001, 42, 89–91.

25 Y. Hayakawa, J. W. Kim, H. Adachi, K. Shin-ya, K.-I. Fujita and H. Seto, J. Am. Chem. Soc., 1998, 120, 3524–3525.

26 M. Brasholz, S. Sörgel, C. Azap and H.-U. Reißig, Eur. J. Org. Chem., 2007, 3801–3814.

27 R. T. Crow, B. Rosenbaum, R. Smith III, Y. Guo, K. S. Ramos and G. A. Sulikowski, Bioorg. Med. Chem. Lett., 1999, 9, 1663–1666.

28 H. C. Brown, P. K. Jadhav and K. S. Bhat, J. Am. Chem. Soc., 1988, 110, 1535–1538.

29 Prins-pinacol reactions have been used in the synthesis of tetrahydrofurans, (a) N. Hanaki, J. T. Link, D. W. C. MacMillan, L. E. Overman, W. G. Tranke and J. A. Wurster, Org. Lett., 2000, 2, 223–226; (b) L. E. Overman and L. D. Pennington, J. Org. Chem., 2003, 68, 7143–7157.

30 (a) L. D. M. Lolkema, H. Hiemstra, C. Semeyn and W. N. Speckamp, Tetrahedron, 1994, 50, 7115–7128; (b) L. D. M. Lolkema, C. Semeyn, L. Ashek, H. Hiemstra and W. N. Speckamp, Tetrahedron, 1994, 50, 7129–7140.

31 Carbamates have been used to good effect in intramolecular Samurai cyclisations, B. Leroy and I. E. Markó, Tetrahedron Lett., 2001, 42, 8685–8688.

32 W. Kersten, H. Kersten, W. Szybalski and M. Fiandt, Biochemistry, 1966, 5, 236–244.

33 H. Jayasuriya, R. B. Lingham, P. Graham, D. Quamina, L. Herranz, O. Geniloud, M. Gagliardi, R. Danzeisen, J. E. Tomassini, D. L. Zink, Z. Q. Guan and S. B. Singh, J. Nat. Prod., 2002, 65, 1091–1095.

34 W. Lu, C. Leimkuhler, M. Oberthür, D. Kahne and C. T. Walsh, Biochemistry, 2004, 43, 4548–4558.

35 S. Singh and P. J. Guiry, J. Org. Chem., 2009, 74, 5758–5761.