A convergent total synthesis of ouabagenin†

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A convergent total synthesis of ouabagenin, an aglycon of cardenolide glycoside ouabain, was achieved by assembly of the AB-ring, D-ring and butenolide moieties. The multiply oxygenated cis-decalin structure of the AB-ring was constructed from (R)-perillaldehyde through the Diels–Alder reaction and sequential oxidations. The intermolecular acetal formation of the AB-ring and D-ring fragments, and combination of the intramolecular radical and aldol reactions, assembled the requisite steroidal skeleton in a stereoselective fashion. Finally, stereoselective installation of the C17-butenolide via the Stille coupling and hydrogenation led to ouabagenin.

Ouabain (Scheme 1), which belongs to a unique class of steroids known as cardenolides, has been used for the treatment of congestive heart failure for more than two centuries.1,2 Ouabain was isolated from the bark and roots of the ouabaio tree, and was more recently identified as an adrenal hormone that naturally occurs in mammals.3 The cardiac activity of ouabain is attributed to a high affinity inhibitory interaction with the membrane-bound sodium pump, Na+/K+-ATPase. As functional modulation of Na+/K+-ATPase activates multiple downstream signal transduction pathways, ouabain is implicated in the regulation of diverse physiological and pathological states. Importantly, cardenolides have received considerable attention for their preventive actions of proliferative diseases such as cancer.4

The steroidal skeleton of ouabagenin (1, Scheme 1), an aglycon of ouabain, possesses six hydroxy groups and the β-oriented butenolide. This highly oxygenated structure of 1 has posed a formidable synthetic challenge.5,6 Despite numerous synthetic studies on cardenolides, only two successful total syntheses of 1 have been reported to date. Deslongchamps constructed 1 through a polyanionic cyclization methodology and converted 1 to ouabain,7 while Baran designed the redox relay strategy and efficiently transformed adrenosterone to 1.8 Motivated by the architectural complexity coupled with the valuable bioactivities, we have launched synthetic studies of cardenolides based on a distinctive convergent strategy.9 Here we report the total synthesis of ouabagenin (1) by assembling the AB-ring fragment with the simple achiral D-ring and butenolide moieties.

The three-dimensional structure of 1 is disparate from the classical steroidal skeleton in that all the functional groups at the ring junctions (C5, 10, 13, 14) are β-configured (Scheme 1). This atypical ring fusion gives the nucleus a characteristic ‘U’ shape. The ring framework of 1 is further decorated by one primary (C19) and three secondary (C1, 3 and 11) hydroxy groups and an unsaturated lactone ring (C17). The congested disposition of these functionalities creates synthetic problems. To simplify the overall scheme, we retrosynthetically disassembled 1 into AB-ring 5, D-ring meso-B and butenolide A. According to this plan, achiral Aα and meso-Bβ were easily prepared, while introduction of only four out of ten stereocenters of 1 would be necessary for the synthesis of 5. The
remaining six centers were planned to be installed en route to 1. Most importantly, the stereochemistry of the four angular positions (C8, 9, 13, 14) was to be controlled by two intra-molecular reactions. After tethering 5 and meso-B through the acetal linkage, 6-eno radical cyclization of 4 would establish the C9-stereochemistry. Aldol reaction of 3 would then be employed for simultaneous introductions of the C8-, 13- and 14-centers of 2. The two peripheral functional groups at C11 and 17 were planned to be constructed from 2 at the last stage of the total synthesis.

It would be challenging to control the three stereocenters in the reaction from 3 to 2: eight diastereomers would be potentially generated through desymmetrization of the meso-substructure (Scheme 2A). We envisioned that the linker structure (X-Y) would affect the stereochemical outcome of the aldol reaction, and accordingly designed the two possible intermediates, acetal 3a and vinyl ether 3b, which would be integrated in the planned scheme. To assess suitability of 3a or 3b as the precursor, the relative energies of the eight isomers of the reaction from 3b were thermodynamically more stable than the six other adducts. However, selectivity between desired 2aa/2ba and undesired 2ab/2bb was not clarified by the simulation due to their small energy difference (<0.5 kcal mol⁻¹).

To experimentally examine the role of the linker (X-Y), the synthetically more accessible models 3c and 3d were prepared and subjected to the aldol reactions (Scheme 2B). Despite their abbreviated structures, the trans-decalin rings of 3c and 3d were assumed to mimic the rigid orthoester-protected AB-ring of 3a and 3b, respectively. Treatment of acetal 3c with catalytic KN(TMS)₂ in refluxing THF led to formation of desired 2ca as the sole isolable isomer, whereas application of the same conditions to vinyl ether 3d selectively afforded undesired 2db. These results demonstrated the crucial function of the linker in influencing the stereoselectivity, and permitted us to target acetal 3a as the key intermediate for the total synthesis.

Prior to the synthesis of 3a, AB-ring 5 was prepared from (R)-perillaldehyde 6 in 15 steps (Scheme 3). The Diels–Alder reaction between 6 and Rawal’s diene C₃ proceeded in regio- and diastereoselective manner to afford the cis-decalin, which was treated with aqueous acid to provide 7 as a single product. The two carbonyl groups of 7 were simultaneously reduced with LiAlH₄ to produce diol 8, the allylic alcohol of which was chemo-selectively oxidized with MnO₂ to provide ketone 9. Treatment of 9 with TBSOTf and Et₃N then introduced the two TBS groups at the C3-enol and C19-hydroxy groups, resulting in 10. Pd(OAc)₂-mediated oxidation of 10 in turn provided diene 11. For introduction of the β-configured C1- and 5-oxygen functional groups, the C3-β-alcohol was utilized as the directing group. Namely, ketone 11 was stereoselectively reduced by the action of the chiral reductant D¹⁰ to produce 12 (dr = 3 : 1). Thus obtained 12 was treated with m-CPBA to induce the requisite bis-β-epoxidation in addition to the epoxidation at C7', leading to tris-epoxide 13. After Dess–Martin oxidation of alcohol 13 to ketone 14, reductive opening of the two epoxides of 14 proximal to the C3-ketone was realized using Al/Hg and a dibromide. The C19-hydroxy group of AB-ring 5 selectively displaced the O-activated C11'-bromo group of E in the presence of an acid scavenger PhNMe₂, leading to acetal 4 as a diastereomixture. The remaining C11-bromo group of 4 was in turn utilized as a radical donor by treatment with Et₃B/O₂ and...
The acetal tether of 4 effectively constrained the generated radical to add from the β-face of the C9-olefin to provide 21 (C11,11'-diasteromixture). Saponification of the two acetates of 21 and subsequent Dess–Martin oxidation of 22 furnished the diastereomerically pure triketone 3a after chromatographic purification (26% yield from 5). As expected from the computational simulation and the model experiments in Scheme 2, the acetal-tethered 3a was selectively converted into the desired isomer 2aa. Specifically, treatment of 3a with KN(TMS)_2 (30 mol%) in refluxing THF delivered desired 2aa (65%) along with its minor diastereomer 2ab (8%). Of note, this mild five-step sequence realized introduction of four new stereocenters (C8, 9, 13 and 14) without affecting the pre-existing oxygen functionalities.

Having constructed the properly substituted steroid, ouabagenin (1) was synthesized from 2aa through adjustments of the C7,11-functional groups, attachment of the C17-butenolide and global deprotection. First, the C7-oxygen functionality was removed. Chemoselective NaBH₄ reduction at C7 of diketone 2aa afforded alcohol 23, which was derivatized into thio-carbamate 24 by means of thiosiocyanate and NaH. Reductive cleavage of the C7-thiocarbamate of 24 was realized by mixing with AIBN and (TMS)₂SiH in refluxing benzene, providing 25. Next, the α-oriented C11-hydroxy group was constructed from the C11-branched carbon linker, which served as the stereocontrolling element. Before doing so, the acetal of 25 was converted to the vinyl ether of 26 by acid-promoted elimination of MeOH. Oxidative scission of the resultant C11-olefin of 26 with ozone, reductive workup and the basic deformylation at C19-OH gave hemiacetal 27. TBSOTf and Et₃N then introduced TBS groups at both C19- and C17-oxygen atoms of 27, liberating the C11-ketone of 28. Subjection of 28 to Birch reduction conditions resulted in formation of 29 with the thermodynamically favorable equatorial C11-OH group.

The β-oriented C17-butenolide was incorporated through the Stille coupling reaction and stereoselective hydrogenation (Scheme 4). Treatment of bis-TBS ether 29 with TBAF at −78 °C resulted in formation of C17-ketone 30, which was in turn transformed to vinyl iodide 31 via the hydrazide intermediate. The Stille coupling between 31 and A proceeded in the presence of Pd[PPh₃]₄ and CuCl in DMSO, leading to 32 bearing the entire carbon structure of 1. To achieve hydrogenation from the concave α-face of the ‘U’-shape skeleton, the C14-hydroxy group of 32 was capped with the bulky TMS-ether to generate 33. Presumably because the C14-OTMS blocked the approach of reagents from the β-face, Pd/C-catalyzed hydrogenation of 33 occurred selectively from the α-face to yield 34 as the major product. Finally, global deprotection of 34 with 3 M HCl in MeOH removed the two TMS and one methine groups, giving rise to ouabagenin (1). The analytical data of synthetic 1 including the optical rotation, IR, ¹H-, ¹³C-NMR and HRMS were identical with those of authentic 1.

In conclusion, we achieved the convergent total synthesis of ouabagenin (1) using highly functionalized AB-ring 5 together with the simple achiral D-ring meso-B and butenolide A (33 steps from (R)-perillaldehyde 6). After preinstalling the four stereocenters of 5, introduction of the six remaining stereocenters and construction of the entire pentacyclic structure of 1 required only 18 steps, demonstrating the efficiency of the strategy. The key transformations that enabled the convergent synthesis include: (i) the mild acetal formation between AB-ring 5 and dibromide E; (ii) the tether-guided 6-exo radical cyclization of 4; (iii) the stereoselective aldol reaction of triketone 3a that was judiciously designed based on *in silico* and model

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**Scheme 3** Stereoselective synthesis of AB-ring 5. Reagents and conditions: (a) toluene, 110 °C, 1.2 M aqueous HCl, THF, 67%; (b) LiAlH₄, Et₂O, −78 °C, 80%; (c) MnO₂, CH₂Cl₂, 89%; (d) TBSOTf, Et₂N, CH₂Cl₂, 0 °C; (e) Pd(OAc)₂, CH₂CN, 0 °C, 81% (2 steps); (f) D, t-BuOMe, Et₂O, −100 to −40 °C, 68% for 12 (dr = 3 : 1); (g) m-chloroperoxybenzoic acid (m-CPBA), NaHCO₃, CH₂Cl₂, 0 °C, 82%; (h) Dess–Martin reagent, NaHCO₃, CH₂Cl₂, 0 °C, 100%; (i) Al/Hg, NaHCO₃, THF, EtOH, H₂O, 0 °C; (j) diisobutylaluminum hydride (DIBAL-H), CH₂Cl₂, −40 °C; (k) p-tolSO₂H-pyridine, HCl(OMe)₂, DMF, 0 °C; (l) POCl₃, pyridine, 0 °C; (m) O₂, CH₂Cl₂, −78 °C; Me₂S, 22% (5 steps); (n) Pd(OOCOCF₃)₂, NaOAc, DMSO, 50 °C, 91%; (o) tetrabutylammonium fluoride (TBAF), AcOH, THF, 50 °C, 91%.

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**Scheme 4** The convergent total synthesis of ouabagenin (1).

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**X-ray structure of 19 (CCDC: 1027185)**

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experiments; (iv) installation of the C17-butenolide by the Stille coupling using $A$; (v) the stereoselective hydrogenation of C17-double bond; and (vi) the single-step global deprotection. Because of its flexibility and robustness, the present route would be applicable for the synthesis of a variety of bioactive cardenolides, and synthetic and SAR studies of such molecules will be our next focus.

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Notes and references


9 We recently reported the total synthesis of 19-hydroxysarmentogenin, one of the cardenolides, K. Mukai, H. Renata, Q. Zhou and P. S. Baran, Angew. Chem., Int. Ed., 2013, 52, 5300.


13 See ESL†


20 Reduction of 11 with achiral reagents (e.g. NaN₃ and CeCl₃, LiAlH₄, AlH₃, and DIBAL-H) generated the α-oriented alcohol or 1,4-reduced product as the major product.


26 For a review on radical-mediated deoxygenation, see: S. W. McComb, W. B. Motherwell and M. J. Tozer, Org. React., 2012, 77, 161.


