

RESEARCH ARTICLE

View Article Online
View Journal | View IssueCite this: *Org. Chem. Front.*, 2023,
10, 1435Received 28th October 2022,
Accepted 24th December 2022

DOI: 10.1039/d2qo01718k

rsc.li/frontiers-organic

Stereoselective semisynthesis of uzarigenin and *allo*-uzarigenin†Sarah Al Muthafer,^a Christoph Schissler,^a Vanessa Koch,^a Hannes Kühner,^a Martin Nieger^b and Stefan Bräse^{a,c}

Herein, we report the concise semisynthesis of the natural cardenolide uzarigenin and its diastereoisomer *allo*-uzarigenin in nine and seven steps, respectively, starting from the broadly available *epi*-androsterone. For this purpose, the synthetic strategy for the stereoselective introduction of the β -hydroxy group at C-14 *via* Mukaiyama oxidation is discussed. Additionally, the installation of the butenolide ring at C-17 is performed using a Stille-cross-coupling reaction with subsequent stereoselective hydrogenation of the C-16/C-17 double bond to exclusively give *allo*-uzarigenin. By directing the hydrogenation *via* a protecting group strategy, the C-17 β isomer can also be obtained stereoselectively.

Introduction

Uzarin (1) and its aglycone uzarigenin (2) belong to the natural product class of cardiac glycosides, and have been known for their medicinal use since centuries (Fig. 1).¹ They can be obtained from the Uzara plant (*Xysmalobium undulatum*), which belongs to the milkweed family (*Asclepiadoideae*). In African folk medicine, the extracts isolated from the Uzara root were used for a long time to treat wounds, diarrhea, spasms, menstrual cramps, and headaches. Unlike other cardiac glycosides such as digitoxin (3), Uzara glycosides have a low cardio-tonic effect, making intoxication less likely to occur.^{2–4} Uzarin (1) and its aglycone uzarigenin (2) exhibit several structural characteristics of the steroid class of cardiac glycosides, such as the β -orientated unsaturated lactone ring at C-17 and the β -hydroxy group at C-14, resulting in a *cis*-fusion of the C/D rings. Like many other cardiac glycosides derived from the plant family of *Asclepiadoideae*, they feature a typical *trans* A/B ring junction, whereas most other cardiac glycosides, such as the well-investigated digitoxin (3), have *cis*-fused A/B rings.⁵ Uzarigenin (2), therefore, can be assigned to the 5 α -configured

family of cardenolides, to which the better-known calotropin (4) also belongs.

The correspondence of concurrent reactions in the two configurationally and energetically different series (5 α and 5 β) is not self-evident. For example, a reaction sequence leading to digitoxigenin in the 5 β -series is not generally transferable to the 5 α -series.⁶ Nevertheless, Kurt Radscheit and co-workers succeeded in converting 15 α -hydroxy-cortexon into 3-oxo-5 α -carda-14,20(22)-dienolide and claimed to have successfully synthesized uzarigenin (2) *via* two different synthetic routes. However, the stereochemistry at C-14 was not further discussed.⁷ The same applies to Khristulas' uzarigenin (2) semi-synthesis, which started from 3 β -acetoxy-5 α -pregn-16-en-20-one and did not provide any direct proof of the configuration of the synthesized compounds.⁸ Emil Angliker managed to

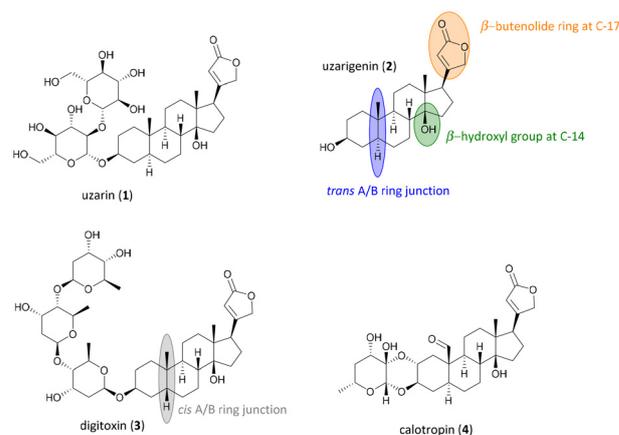


Fig. 1 Molecular structures of the cardiac glycosides uzarin (1), its aglycone uzarigenin (2), digitoxin (3) and calotropin (4).

^aInstitute of Organic Chemistry, Karlsruhe Institute of Technology (KIT), Fritz-Haber-Weg 6, 76131 Karlsruhe, Germany. E-mail: braese@kit.edu;

Fax: (+49)-721-608-48581; Tel: (+49)-721-608-42903

^bDepartment of Chemistry, University of Helsinki, P. O. Box 55, 00014 University of Helsinki, Finland

^cInstitute of Biological and Chemical Systems – Functional Molecular Systems (IBCS-FMS), Karlsruhe Institute of Technology (KIT), Hermann-von-Helmholtz-Platz 1, 76344 Eggenstein-Leopoldshafen, Germany

†Electronic supplementary information (ESI) available. CCDC 2207135 (11), 2207136 (13), 2207137 (16), 2207138 (17), and 2207139 (SI-06). For ESI and crystallographic data in CIF or other electronic format see DOI: <https://doi.org/10.1039/d2qo01718k>



introduce a 14 β -hydroxy group but struggled with the configuration at C-17 and, therefore, could only report the synthesis of *allo*-uzarigenin.⁹ Wicha *et al.* investigated the D ring chemistry in more detail and achieved the stereoselective synthesis of 3-OMe uzarigenin; however, the introduction of the butenolide ring at C-17 in the β -position involved 13 steps and the ether moiety at C-3 was not removed at the end of the sequence.^{10,11}

So far, uzarigenin (**2**) with unambiguously correct stereochemistry can only be obtained with the support of nature: for example, Bauer and Gonzalez were able to extract uzarigenin (**2**) from *Asclepias syriaca* L. or leaves of *Scrophulariaceae*.^{12,13} Sauer *et al.* instead used *Strophanthus kombé*, a member of the *Apocynaceae* family, to convert 5 α -pregnanolone into uzarigenin (**2**) via a foliar application method.^{14,15} Okada and Anjyo successfully converted the more widely occurring digitoxigenin to uzarigenin (**2**) via epimerization at the C-5 position.¹⁶

Besides these nature-supported methods, none of the pioneering syntheses described earlier give access to the natural version of uzarigenin (**2**) and the syntheses suffer furthermore from quite lavish procedures and a lack of stereocontrol. Therefore, we aimed to develop a straight and high-yielding synthesis route, which puts emphasis on well-characterized compounds by using 2D NMR spectra and X-ray analysis for the efficient semisynthesis of uzarigenin (**2**) and its C-17 epimer *allo*-uzarigenin (**21**).

Results and discussion

Inexpensive and readily available *epi*-androsterone (**5**) was chosen as the starting material for the semisynthesis of uzarigenin (**2**), requiring the introduction of the butenolide ring at C-17 and the inversion of the stereogenic center at C-14. To substitute the hydrogen atom attached in the α -position at C-14 with the aimed β -hydroxyl group, a three-step sequence was envisioned, with the first step comprising the synthesis of the Michael system **8**. As presented in Scheme 1, *epi*-androsterone (**5**) was lithiated at -78 °C and subsequently the TMS enol ether **7** was formed by adding trimethylsilyl chloride.

Without further purification, the enol ether **7** was subjected to the Saegusa–Ito oxidation, which is a well-known method for steroid compounds.^{17–23} However, most of the procedures use stoichiometric amounts of palladium, although many reoxidants have been described in the literature, including copper(II) salts such as copper(II) acetate or copper(II) chloride, 1,4-benzoquinone, oxygen, and Oxone®.^{24–28} With the aim of using palladium in catalytic amounts, different reaction con-

ditions were screened, focusing on inexpensive oxygen and copper(II) acetate as reoxidants (see Table 1 and Table SI-1 in the ESI†).

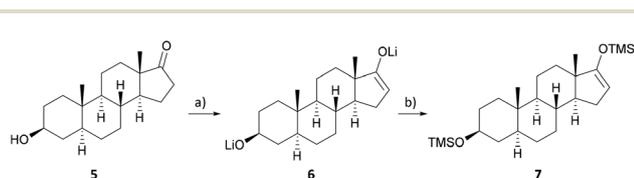
Using catalytic amounts of palladium and oxygen or copper(II) acetate as the reoxidant, comparable yields to that obtained when using stoichiometric amounts of palladium could be obtained (entries 1–3). Varying the solvent apparently influenced the yield, with a mixture of CH₂Cl₂/DMSO achieving the highest yields (entries 5 and 6). A further decrease in the catalyst amount resulted in only a minor drop in yield (compare entries 5 and 8). Furthermore, no reaction took place without palladium(II) acetate (entry 7), proving the latter to be the active metal in the reaction. The use of copper(II) chloride, Oxone® or 1,4-benzoquinone as the reoxidant did not give any further improvement in yields (see ESI Table SI-1†).

The rearrangement of the conjugated Δ^{15} to the isolated Δ^{14} double bond has already been effectively applied in many natural product syntheses^{17–21,29} and should once more serve as a starting point for the introduction of the C-14 hydroxy group in this work. Analogously to Johns *et al.*,^{17,30–32} isomerization was carried out with *p*-toluene sulfonic acid in refluxing toluene to give the desired product **9** in 61% yield after a reaction time of 15–20 minutes (Scheme 2).

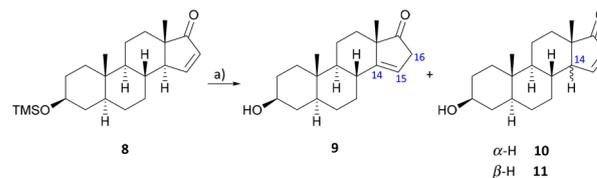
Table 1 Investigation of the optimal reaction conditions for the synthesis of the Michael system **8** using palladium(II) acetate as a catalyst

| Entry | Reagents ^a | Reaction conditions | Isolated yield [%] |
|-------|--|--|--------------------|
| 1 | Pd(OAc) ₂ ^b | CH ₂ Cl ₂ /MeCN (3 : 1), r.t., 16 h | 48 |
| 2 | Pd(OAc) ₂ , Cu(OAc) ₂ | CH ₂ Cl ₂ /MeCN (2 : 3), r.t., 24 h | 43 |
| 3 | Pd(OAc) ₂ , O ₂ | CH ₂ Cl ₂ /MeCN (2 : 3), r.t., 24 h | 39 |
| 4 | Pd(OAc) ₂ , Cu(OAc) ₂ | MeCN, 60 °C, 24 h | 45 |
| 5 | Pd(OAc)₂, Cu(OAc)₂ | CH₂Cl₂/DMSO (2 : 3), r.t., 24 h | 66 |
| 6 | Pd(OAc)₂, O₂ | CH₂Cl₂/DMSO (2 : 3), r.t., 24 h | 62 |
| 7 | Cu(OAc) ₂ , O ₂ | CH ₂ Cl ₂ /DMSO (2 : 3), r.t., 24 h | 0 |
| 8 | Pd(OAc) ₂ , Cu(OAc) ₂ ^c | CH ₂ Cl ₂ /DMSO (2 : 3), r.t., 24 h | 55 |

^a 20 mol% Pd(OAc)₂ and 40 mol% Cu(OAc)₂ were used if not stated otherwise. ^b 1.00 equiv. of Pd(OAc)₂ were used. ^c 10 mol% Pd(OAc)₂ and 15 mol% Cu(OAc)₂ were used.



Scheme 1 Synthesis of the precursor for the Saegusa–Ito oxidation. (a) LDA, THF, -78 °C, 1 h; (b) TMSCl, NEt₃, -78 °C to r.t., 1.5 h.



Scheme 2 Rearrangement reaction at the steroidal D ring double bond. (a) *p*-TsOH, toluene, 130 °C, 15–20 min, 61% (**9**).



In the course of this, deprotected starting material **10** and its 14 β -epimer **11** could also be isolated by column chromatography on silica gel and reused for the rearrangement reaction. The molecular structure of **11** could be determined by X-ray crystallographic analysis (see the ESI†).

Starting from the isolated Δ^{14} double bond, the following step aimed to diastereoselectively attach the hydroxy group at C-14 in the β -position. Epoxidation with subsequent ring opening indicated the formation of many different products, and thus the Mukaiyama oxidation should accomplish the installation of the tertiary hydroxy group.^{33–36} To investigate whether diastereoselectivity can be observed for this reaction, a wide range of reaction conditions were tested by varying the catalyst, solvent, additives, reaction time and the addition rate and amount of the reductant (see Table 2 and Table SI-2 in the ESI†).

For the Mukaiyama oxidation of **9**, no product formation could be observed in non-anhydrous 1,4-dioxane, making the use of an absolute solvent crucial (entries 1 and 2). Increasing the amount of reductant and adding molecular sieves to the reaction mixture resulted in a slight improvement in the yield from 44% to 53% (entry 3). To prevent the oxidation of the secondary hydroxyl group at C-3 as a possible side reaction, a TBDMS protecting group was introduced at C-3 prior to the oxidation, which led to a significant increase in the yield from 53% to 64% (entry 4). Unfortunately, an inseparable mixture of both hydroxy epimers was obtained in all experiments described above. The ratio of epimer A to epimer B was determined to be 2:1 by integration of the resonances of the angular methyl protons in the ¹H NMR spectra. Considering the improved yield, a benzyl-protecting group was introduced at C-3, which enabled the separation of the two epimers

(entry 5), whose absolute configuration was determined by X-ray crystallographic analysis (see Fig. 2), and the desired 14 β -epimer **16** was identified as the main product. Having the two epimers separated and assigned, the reaction was further optimized in terms of yield and particularly the diastereomeric ratio. Varying the catalyst or adding PPh₃³⁷ as an additive did neither improve the yield nor the diastereomeric ratio significantly (entries 6–8). Moreover, contrary to the literature,³⁸ no reaction took place at all with Co(III) or Mn(III) species (Table SI-2 in the ESI†). Ultimately, varying the solvent not only improved the yield (entries 9 and 12), but the use of a polar protic solvent also shifted the diastereomeric ratio sig-

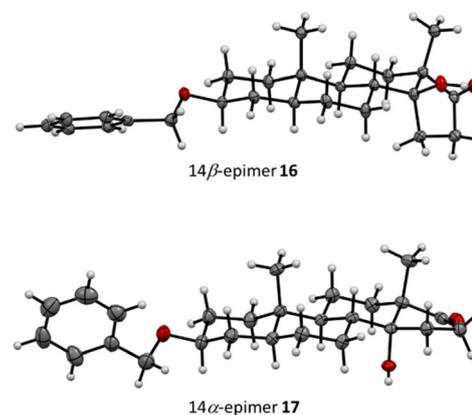


Fig. 2 Crystal structures of **16** and **17** (displacement parameters are drawn at the 50% probability level). The impact of the β -position of the C-14 substituent can be observed clearly: the 14 α -epimer is mostly flat due to its all-*trans* ring linkages, while the 14 β -epimer exhibits a more bowed shape due to the *cis*-linkage of the C-/D-rings.

Table 2 Optimization of the reaction conditions for the Mukaiyama oxidation of **9**, **12** and **13**

| Entry | R | PhSiH ₃ (equiv., a.r.) | Catalyst | Solvent | Additive | Reaction time | Yield [%], dr (β -OH : α -OH) |
|-------|-------|-----------------------------------|------------------------------------|--------------------------|---------------------------------------|---------------|---|
| 1 | H | 3.0, 1 h | Co(acac) ₂ | 1,4-Dioxane ^a | — | 3 h | 0 |
| 2 | H | 3.0, 1 h | Co(acac) ₂ | 1,4-Dioxane ^b | — | 3 h | 44 |
| 3 | H | 4.5, 2 h | Co(acac) ₂ | 1,4-Dioxane ^b | 4 Å MS | 20 h | 53 |
| 4 | TBDMS | 4.5, 2 h | Co(acac) ₂ | 1,4-Dioxane ^b | 4 Å MS | 20 h | 64 |
| 5 | Bn | 4.5, 2 h | Co(acac) ₂ | 1,4-Dioxane ^b | 4 Å MS | 20 h | 62 (2.0 : 1) |
| 6 | Bn | 4.5, 2 h | Co(dpm) ₂ | 1,4-Dioxane ^b | 4 Å MS | 20 h | 49 (2.0 : 1) |
| 7 | Bn | 4.5, 2 h | Mn(acac) ₂ | 1,4-Dioxane ^b | 4 Å MS, PPh ₃ ^c | 20 h | 33 (2.3 : 1) |
| 8 | Bn | 4.5, 2 h | Co(acac) ₂ | 1,4-Dioxane ^b | 4 Å MS, PPh ₃ ^c | 20 h | 60 (2.1 : 1) |
| 9 | Bn | 4.5, 2 h | Co(acac) ₂ | MeCN ^b | 4 Å MS | 20 h | 71 (2.4 : 1) |
| 10 | Bn | 4.5, 2 h | Co(acac) ₂ ^d | MeCN ^b | 4 Å MS | 20 h | 59 (2.5 : 1) |
| 11 | Bn | 4.5, 2 h | Co(acac) ₂ | MeOH ^b | 3 Å MS | 20 h | 45 ^e (4.7 : 1) |
| 12 | Bn | 4.5, 2 h | Co(acac) ₂ | EtOH ^b | 4 Å MS | 20 h | 73 (9.4 : 1) |

Reaction conditions: catalyst (30 mol%); yields refer to the isolated mixture; the diastereomeric ratio was determined by integration of the resonance of the angular methyl group C-18 in the ¹³C NMR spectra of the isomer mixture after prolonged relaxation delay (*d*₁ = 10 s). ^a HPLC quality. ^b Absolute solvent. ^c 2.00 equiv. of PPh₃ were used. ^d 10 mol% Co(acac)₂ was used. ^e No full conversion. a.r. rate of addition.

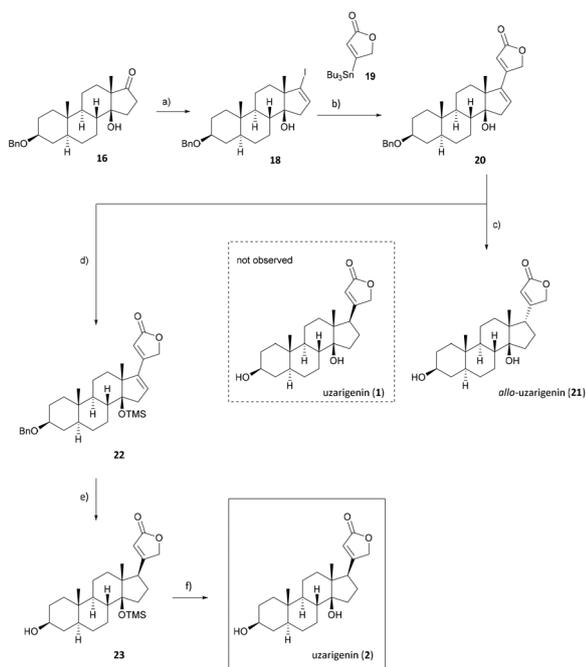


Research Article

nificantly from 2.0 : 1 to 4.7 : 1 for MeOH (entry 11) and eventually gave a dr of 9.4 : 1 in favour of the desired epimer **16** when ethanol was used as the solvent (entry 12).

After the successful diastereoselective introduction of the hydroxy group at C-14, the lactone ring has to be diastereoselectively attached to C-17. Thus ketone **16** was converted to the respective vinyl iodide **18** by following Barton's procedure.³⁹ For this purpose, the carbonyl functionality was treated successively with hydrazine and iodine to yield vinyl iodide **18** in 51% yield (Scheme 3). The sp²-hybridized C-17 could now undergo a cross-coupling reaction following the procedure developed by Stille *et al.*,⁴⁰ which has also been successfully applied by us previously,⁴¹ yielding cardadienolide **20** in 67% yield.

Cardadienolide **20** should then undergo a chemo- and diastereoselective reduction of the Δ^{16} double bond with simultaneous removal of the benzyl protecting group at C-3 using palladium on carbon as a catalyst. The reaction indeed proceeded diastereoselectively, as the formation of only one isomer was observed. Unfortunately, the reduction yielded the undesired isomer (*allo*-uzarigenin (**21**)) in 76% yield, which is consistent with the literature.^{42,43} In comparison, the exclusive formation of the desired C-17 β isomer was observed upon hydrogenation of 3 β -hydroxy-5 α ,14 α -carda-(16,20)-dienolide (**SI-06**, see the ESI[†]), suggesting a directing effect of the hydroxy group in the present substrate **20**. The stereochemistry at C-17 of **21** was determined by NOE correlation between the angular 18-CH₃ and 17-CH as shown in Fig. 3. Precise tuning



Scheme 3 Synthesis of uzarigenin (**1**) and *allo*-uzarigenin (**21**). (a) N₂H₄, NEt₃, EtOH, 50 °C, 16 h; (b) I₂, NEt₃, THF, 0 °C to r.t., 3 d, 51%; (c) Pd(PPh₃)₄, LiCl, CuCl, DMF, 60 °C, 24 h, 67%; (d) H₂, Pd/C (10 wt%), EtOAc, r.t., 30 min, 76%; (e) TMSCl, imidazole, DMF, r.t., 16 h, 94%; (f) H₂, Pd/C (10 wt%), EtOAc, r.t., 30 min, 62%; (g) 3 M HCl, MeOH, r.t., 4 h, 79%.

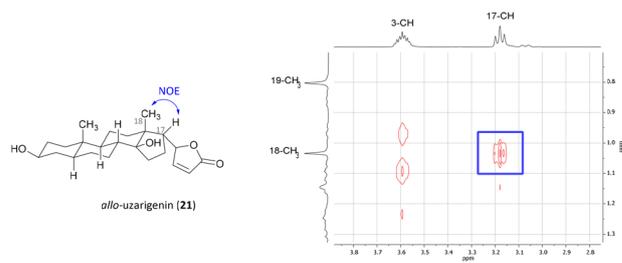


Fig. 3 Excerpt from the NOESY spectrum of *allo*-uzarigenin (**21**). A strong NOE correlation between 18-CH₃ and 17-CH indicates spatial proximity and thus hydrogenation from the β -face.

of the reaction time is mandatory for a chemoselective reaction since longer reaction times also result in a reduction of the double bond within the lactone ring, evident from the loss of the olefinic proton at $\delta = 5.77$ – 5.83 ppm as shown for the C-14 α -H system **SI-07** in the ESI[†].

Since the hydrogenation of Δ^{16} -olefin **20** occurred from the convex β -face, affording exclusively the C-17 α product (*allo*-uzarigenin (**21**)), TMS protection of the C-14 hydroxy group was conducted to circumvent a possible directing effect of the hydroxy group while introducing an even greater steric hindrance to the β -face at the same time (Scheme 3).^{42,44,45} A subsequent reduction of **22** gave exclusively the desired C-17 β product, which yielded the natural product uzarigenin (**2**) after acidic deprotection with 3 M HCl. The stereochemistry at C-17 was determined by 2D NOESY spectroscopy as shown in Fig. 4. NOE correlation between 22-CH and 18-CH₃ indicates spatial

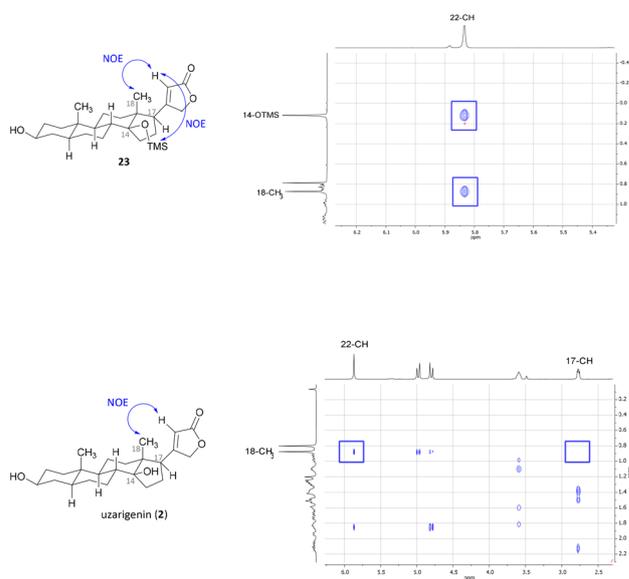


Fig. 4 Excerpt of the NOESY spectra of TMS protected uzarigenin **23** (top) and uzarigenin (**2**) (bottom). In both cases, a clear NOE correlation between 22-CH and 18-CH₃ indicates spatial proximity of the lactone ring and the 18-methyl group. Furthermore, a NOE cross peak between 22-CH and 14-OTMS can be seen, which further supports the successful hydrogenation from the α -face.



proximity of the lactone ring and the 18-methyl group and thus the successful hydrogenation from the α -face. Furthermore, no NOE correlation between 17-CH und 18-CH₃ can be seen, as exemplarily shown for the NOESY spectrum of uzarigenin (2). Moreover, the analytical data of *allo*-uzarigenin (21) and uzarigenin (2) synthesized in this work were compared with those from the literature and are in agreement (Tables SI-3–SI-5 in the ESI†).

Experimental section

The synthetic procedures for all synthesized compounds are available in the ESI.†

Conclusions

In summary, we have reported the first stereoselective semi-synthesis of uzarigenin (2) and *allo*-uzarigenin (21) starting from the widely available *epi*-androsterone (5) in nine and seven steps, respectively. This synthesis route offers efficient access to uzarigenin (2) by using moderate to high-yielding stereoselective reactions. Correct stereochemistry was confirmed by 2D NMR experiments and X-ray analysis.

Conflicts of interest

There are no conflicts to declare.

Acknowledgements

S. A. M. and C. S. gratefully acknowledge the Fonds der Chemischen Industrie and the graduate program of the federal state of Baden-Württemberg (LGF) for financial support. V. K. gratefully acknowledges the Studienstiftung des Deutschen Volkes for not exclusively financial support. H. K. acknowledges support from Deutsche Forschungsgemeinschaft (DFG, German Research Foundation) under Germany's Excellence Strategy—2082/1—390761711 and the Collaborative Research Center TRR 88 “3MET”.

References

- J. W. Estes and P. D. White, William Withering and the Purple Foxglove, *Sci. Am.*, 1965, **212**, 110–119.
- I. Vermaak, G. M. Enslin, T. O. Idowu and A. M. Viljoen, Xysmalobium undulatum (uzara)—review of an antidiarrhoeal traditional medicine, *J. Ethnopharmacol.*, 2014, **156**, 135–146.
- B.-E. Van Wyk, The potential of South African plants in the development of new medicinal products, *S. Afr. J. Bot.*, 2011, **77**, 812–829.
- M. Ghorbani, M. Kaloga, H. H. Frey, G. Mayer and E. Eich, Phytochemical reinvestigation of Xysmalobium undulatum roots (Uzara), *Planta Med.*, 1997, **63**, 343–346.
- H. R. El-Seedi, S. A. M. Khalifa, E. A. Taher, M. A. Farag, A. Saeed, M. Gamal, M.-E. F. Hegazy, D. Youssef, S. G. Musharraf, M. M. Alajlani, J. Xiao and T. Efferth, Cardenolides: Insights from chemical structure and pharmacological utility, *Pharmacol. Res.*, 2019, **141**, 123–175.
- F. Sondheimer, Syntheses in cardiac-active steroid field, *Chem. Br.*, 1965, **1**, 454–464.
- U. Stache, W. Fritsch, W. Haede, K. Radscheit and K. Fachinger, Herstellung von ungesättigten Lactonen der Steroid-Reihe, (IV1) Synthese von Uzarigenin, *Liebigs Ann. Chem.*, 1969, **726**, 136–144.
- F. S. Khristulas, M. B. Gorovits and N. K. Abubakirov, Synthesis of uzarigenin, *Chem. Nat. Compd.*, 1970, **6**, 563–568.
- E. Angliker, *Synthese von allo-Uzarigenin; Beitrag zur Konstitution der allo-Aglykone*, Doctoral Thesis, ETH Zürich, 1948.
- G. Groszek, A. Kurek-Tyrlik and J. Wicha, Synthesis of a cardenolide, 3-O-methyl uzarigenin, with 14 β -hydroxyandrost-16-ene as the key intermediate, *Tetrahedron*, 1989, **45**, 2223–2236.
- V. Koch, M. Nieger and S. Bräse, Towards the synthesis of calotropin and related cardenolides from 3-epiandrosterone: A-ring related modifications, *Org. Chem. Front.*, 2020, **7**, 2670–2681.
- Š. Bauer, L. Masler, O. Bauerová and D. Šikl, Uzarigenin and desglucouzarin from *Asclepias syriaca* L, *Experientia*, 1961, **17**, 15–15.
- A. González, J. Bretón, E. Navarro, J. Trujillo, J. Boada and R. Rodríguez, Phytochemical Study of *Isoplexis chalcantha*, *Planta Med.*, 1985, **51**, 9–11.
- H. H. Sauer, R. D. Bennett and E. Heftmann, Conversion of 5 α -pregnanolone to uzarigenin by *Strophanthus kombé*, *Phytochemistry*, 1969, **8**, 839–842.
- H. H. Sauer, R. D. Bennett and E. Heftmann, Conversion of pregnenolone to digifoligenin by *Digitalis lanata*, *Naturwissenschaften*, 1967, **54**, 226–226.
- M. Okada and T. Anjyo, Conversion of Digitoxigenin to Uzarigenin, *Chem. Pharm. Bull.*, 1974, **22**, 464–467.
- V. Koch, *Entwicklung neuer Synthesemethoden zur Darstellung von Calotropin und verwandten Cardenoliden als Leitstrukturen für potentielle Anti-Tumor-Wirkstoffe*, Logos Verlag, 2018.
- H. Renata, Q. Zhou, G. Dünstl, J. Felding, R. R. Merchant, C.-H. Yeh and P. S. Baran, Development of a Concise Synthesis of Ouabagenin and Hydroxylated Corticosteroid Analogues, *J. Am. Chem. Soc.*, 2015, **137**, 1330–1340.
- H. Renata, Q. Zhou and P. S. Baran, Strategic Redox Relay Enables A Scalable Synthesis of Ouabagenin, A Bioactive Cardenolide, *Science*, 2013, **339**, 59–63.
- U. Egner, K.-H. Fritzemeier, W. Halbrodt, N. Heinrich, J. Kuhnke, A. Müller-Fahrnow, G. Neef, K. Schöllkopf and



- W. Schwede, $7\alpha,15\alpha$ -Ethano bridged steroids. Synthesis and progesterone receptor interaction, *Tetrahedron*, 1999, **55**, 11267–11274.
- 21 P. J. Hilton, W. McKinnon, E. C. Gravett, J.-M. R. Peron, C. M. Frampton, M. G. Nicholls and G. Lord, Selective inhibition of the cellular sodium pump by emicymarin and 14β anhydroxy bufadienolides, *Steroids*, 2010, **75**, 1137–1145.
- 22 N. Isaka, M. Tamiya, A. Hasegawa and M. Ishiguro, A Concise Total Synthesis of the Non-peptide Bradykinin B1 Receptor Antagonist Velutinol A, *Eur. J. Org. Chem.*, 2012, 665–668.
- 23 M. E. Krafft, O. A. Dasse and Z. Fu, Synthesis of the C/D/E and A/B Rings of Xestobergsterol-(A), *J. Org. Chem.*, 1999, **64**, 2475–2485.
- 24 Y. Ito, T. Hirao and T. Saegusa, Synthesis of α , β -unsaturated carbonyl compounds by palladium(II)-catalyzed dehydrosilylation of silyl enol ethers, *J. Org. Chem.*, 1978, **43**, 1011–1013.
- 25 T. Z. Wang and L. A. Paquette, Photochemical route to a representative 1, 8-annulated 7-methylene-1, 3, 5-cyclooctatriene, *J. Org. Chem.*, 1986, **51**, 5232–5234.
- 26 S. F. Martin and D. E. Guinn, Stereoselective synthesis of (+)-Prelog-Djerassi lactone from furanoid intermediates, *J. Org. Chem.*, 1987, **52**, 5588–5593.
- 27 R. C. Larock, T. R. Hightower, G. A. Kraus, P. Hahn and D. Zheng, A simple, effective, new, palladium-catalyzed conversion of enol silanes to enones and enals, *Tetrahedron Lett.*, 1995, **36**, 2423–2426.
- 28 Y. Lu, P. L. Nguyen, N. Levaray and H. Lebel, Palladium-catalyzed Saegusa–Ito oxidation: synthesis of α , β -unsaturated carbonyl compounds from trimethylsilyl enol ethers, *J. Org. Chem.*, 2013, **78**, 776–779.
- 29 A. Cleve, G. Neef, E. Ottow, S. Scholz and W. Schwede, Synthesis of 14β -H antiprogestins, *Tetrahedron*, 1995, **51**, 5563–5572.
- 30 W. S. Johnson and W. F. Johns, 14-Isoestrone Methyl Ether and its Identity with Totally Synthetic Material, *J. Am. Chem. Soc.*, 1957, **79**, 2005–2009.
- 31 M. Sakakibara and A. Ogawa Uchida, Syntheses of ($14\beta,17\alpha$)-14-Hydroxy- and ($14\beta,17\alpha$)-2,14-Dihydroxyestradiols and Their Activities, *Biosci. Biotechnol. Biochem.*, 1996, **60**, 411–414.
- 32 M. Sakakibara and A. Ogawa Uchida, Syntheses of ($14\beta,15\beta,16\beta,17\alpha$)- and ($14\beta,15\alpha,16\alpha,17\alpha$)-1,3,5(10)-Estratriene-2,3,14,15, 16,17-hexaols, Possible Candidates for the Inagami–Tamura Endogenous Digitalis-like Factor, and Their Activity, *Biosci. Biotechnol. Biochem.*, 1996, **60**, 405–410.
- 33 M. Teruaki, I. Shigeru, I. Satoshi, K. Koji, Y. Tohru and T. Toshihiro, Oxidation-Reduction Hydration of Olefins with Molecular Oxygen and 2-Propanol Catalyzed by Bis(acetylacetonato)cobalt(II), *Chem. Lett.*, 1989, **18**, 449–452.
- 34 K. Koji, Y. Tohru, T. Toshihiro, I. Satoshi and I. Shigeru, Catalytic Oxidation-Reduction Hydration of Olefin with Molecular Oxygen in the Presence of Bis(1,3-diketonato)cobalt(II) Complexes, *Bull. Chem. Soc. Jpn.*, 1990, **63**, 179–186.
- 35 I. Satoshi, K. Koji, T. Toshihiro, I. Shigeru, Y. Tohru and M. Teruaki, Bis(trifluoroacetylacetonato)cobalt(II) Catalyzed Oxidation-Reduction Hydration of Olefins: Selective Formation of Alcohols from Olefins, *Chem. Lett.*, 1989, **18**, 515–518.
- 36 I. Shigeru and M. Teruaki, A New Method for Preparation of Alcohols from Olefins with Molecular Oxygen and Phenylsilane by the Use of Bis(acetylacetonato)cobalt(II), *Chem. Lett.*, 1989, **18**, 1071–1074.
- 37 Y. Y. See, A. T. Herrmann, Y. Aihara and P. S. Baran, Scalable C–H Oxidation with Copper: Synthesis of Polyoxypregnanes, *J. Am. Chem. Soc.*, 2015, **137**, 13776–13779.
- 38 S. W. M. Crossley, C. Obradors, R. M. Martinez and R. A. Shenvi, Mn-, Fe-, and Co-Catalyzed Radical Hydrofunctionalizations of Olefins, *Chem. Rev.*, 2016, **116**, 8912–9000.
- 39 D. H. R. Barton, R. E. O'Brien and S. Sternhell, A new reaction of hydrazones, *J. Chem. Soc.*, 1962, 470–476.
- 40 J. K. Stille, The Palladium-Catalyzed Cross-Coupling Reactions of Organotin Reagents with Organic Electrophiles, *Angew. Chem., Int. Ed. Engl.*, 1986, **25**, 508–524.
- 41 V. Koch, M. Nieger and S. Bräse, Stille and Suzuki Cross-Coupling Reactions as Versatile Tools for Modifications at C-17 of Steroidal Skeletons - A Comprehensive Study, *Adv. Synth. Catal.*, 2017, **359**, 832–840.
- 42 K. Mukai, D. Urabe, S. Kasuya, N. Aoki and M. Inoue, A Convergent Total Synthesis of 19-Hydroxysarmentogenin, *Angew. Chem., Int. Ed.*, 2013, **52**, 5300–5304.
- 43 H. Renata, Q. Zhou, G. Dünstl, J. Felding, R. R. Merchant, C.-H. Yeh and P. S. Baran, Development of a Concise Synthesis of Ouabagenin and Hydroxylated Corticosteroid Analogues, *J. Am. Chem. Soc.*, 2015, **137**, 1330–1340.
- 44 S. Watanabe, T. Nishikawa and A. Nakazaki, Total Synthesis of the Cardiotonic Steroid (+)-Cannogenol, *J. Org. Chem.*, 2021, **86**, 3605–3614.
- 45 B. Bhattarai and P. Nagorny, Enantioselective Total Synthesis of Cannogenol-3-O- α -l-rhamnoside via Sequential Cu(II)-Catalyzed Michael Addition/Intramolecular Aldol Cyclization Reactions, *Org. Lett.*, 2018, **20**, 154–157.

