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A multifunctional divergent scaffold to access the formal syntheses of various sesquiterpenoids†

Vera P. Demertzidou, Maria Kourgiantaki and Alexandros L. Zografos *

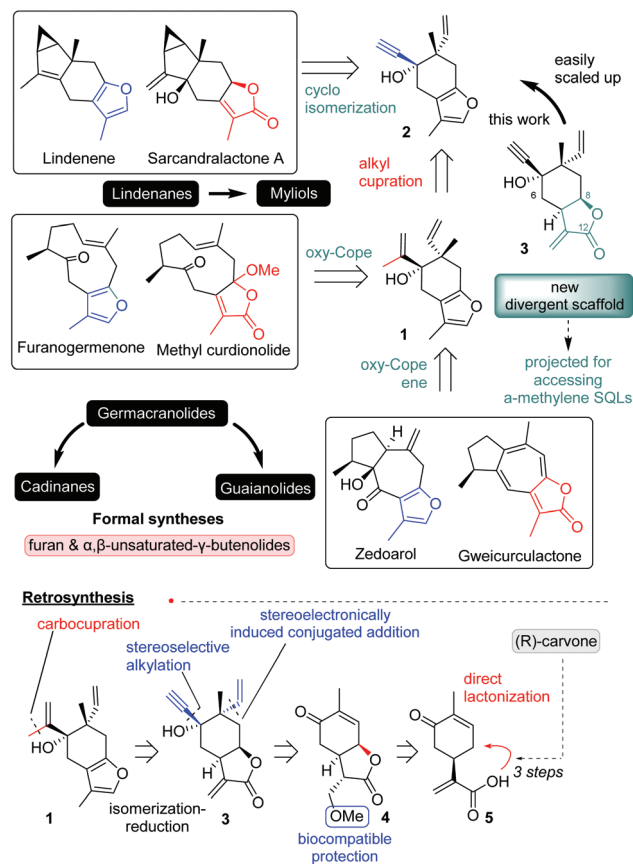
The development of a divergent scaffold able to access an array of diverse natural sesquiterpenoids is described. The route unifies the scope of previously reported plans of our group to allow the scalable synthesis of 8,12-furo and lactone sesquiterpenoid carbocyclic cores of elemanes, germacrane, guaiane, cadinane, lindenane and myliols. The formal syntheses of furogermenone, methyl-curdionolide, zedoarol, qweicurculactone, lindenene and sarcandralactone A are reported.

Introduction

The power of divergent synthesis is undeniably highlighted in its limits by Nature, where divergent scaffolds are built as essential intermediates of the primary metabolism of an organism and utilized to produce a largely diverse pool of secondary metabolism.¹ The most impressive paradigm of this process is well emphasized by the essential unlimited diversity of terpenoids. Although divergent synthesis is probably the best machinery of evolution, its implementation in laboratory scale synthesis is still problematic due to the usual inability of organic chemists to recognize and efficiently synthesize divergent scaffolds.²

Spotting this challenge, our group is focusing on developing divergent scaffolds of maximum potential.³ During the past years, we have reported a series of total syntheses for 8,12-sesquiterpenoids relying on two common furo-eleman scaffolds bearing either 2-propenyl substitution (1; Scheme 1) for accessing germacrene, guaiane and cadinene complexity^{3b,c} or propargylic moiety (2; Scheme 1) for lindenane and myliol carbocyclic cores.^{3d} Despite their undeniable success, furo-eleman common scaffolds suffer from their poor scalability

and their inability to be oxidized to biological important α -methylene- γ -butenolide sesquiterpenoids (SQLs) (α -methylene- γ -butenolide moiety is depicted in green colour; Scheme 1).⁴ To overcome these drawbacks divergent scaffold 3 was designed bearing a protected α -methylene- γ -butenolide ring at 8,12-positions instead of the furan ring. The proposed



Scheme 1 The development of a new divergent scaffold (3) to access the formal syntheses of several furan and α,β -unsaturated sesquiterpenoids.

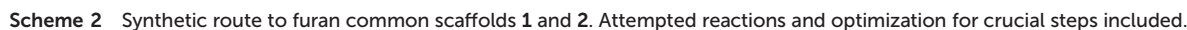
Aristotle University of Thessaloniki, Department of Chemistry, Laboratory of Organic Chemistry, University Campus, Chemistry Old Building, Thessaloniki 54124, Greece.
E-mail: alzograf@chem.auth.gr

† Electronic supplementary information (ESI) available: Full experimental details for all prepared compounds. Copies of NMR ^1H and NMR ^{13}C . See DOI: 10.1039/d1ob01716k



The synthesis began by preparing carvonic acid (**5**) following reported procedures.⁶ Attempts to introduce the *cis*-8,12-lactone functionality was found extremely challenging using various methods (see inset of Scheme 2). Utilization of NCS, NIS and iodine under ionic and radical conditions provided complex mixture of products deriving from the polyhalogenation and halolactonization of alkenes (ex. compound **11**), while interestingly the addition of Br₂ produced *cis*-6,12-lactone **12**. The same was also evidenced when CH-lactonization was attempted following White's protocol⁷ or when LHMDS was used in the presence of CuCl₂ or FeCl₃,⁸ albeit in lower yields. Although product **12** was not the desired, these results show the ability of carvonic acid to selectively access 6,12-lactone, something that is beneficial in cases where 6,12-sesquiterpenoids are targeted. On the other hand, careful addition of NBS under radical conditions with AIBN as initiator allowed the synthesis of *cis*-8,12-lactone **6**, in rather low yield (35%) besides the extensive optimization, due to its facile oxidation to aromatic component **13**. With lactone **6** in hands, we next set the stage for the introduction of the tertiary vinyl group. As expected, the notorious lability of α -methylene- γ -butenolide in **6** towards nucleophiles prohibited its direct alkylation. Inspired by the concept of pharmacophore-directed

To address the poor scalability of our prior plans, a completely new synthetic strategy was designed for the synthesis of **3**. Retrosynthetically, compound **3** (Scheme 1) was projected to derive from protected lactone **4**, to allow the consequent successive stereoselective alkylations for the introduction of the two tertiary stereocenters. The necessity for protection of α -methylene- γ -butenolide functionality was expected to be counterbalanced by the selection of a biocompatible cell-cleaved protection.⁵ Lastly, a *syn*-direct lactonization was envisioned from the known natural product carvonic acid (**5**). Early introduction of the lactone moiety would supposedly induce firstly the stereoselective introduction of the vinyl group



capacity for current to deliver gram scale quantities for all synthetic intermediates.

In conclusion, we report a new synthetic route for the synthesis of 8,12-sesquiterpenoids. The synthetic plan employs a highly stereoselective access to both furo-elemanes **2** and **1** for the first time allowing the unified divergent synthesis of germacranes, guaianes and lindenanes among other carbocycles by taking advantage of the stereoelectronic effects of an early introduced protected α -methylene- γ -butenolide core for the stereoselective introduction of two tertiary centers. The newly developed divergent scaffold is expected to serve as cornerstone for the synthesis of biologically intriguing α -methylene- γ -butenolide lactone sesquiterpenoids. This work is currently underway and will be reported in due course.

V. P. D. and A. L. Z. were responsible for the conceptualization of the work in every step of the project. M. K. was responsible for scaling-up some experimental procedures.

The authors have no conflicts to declare.

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- 1 A. L. Zografos, in *From Biosynthesis to Total Synthesis: Strategies and Tactics for Natural Products*, Wiley & Sons, Hoboken, 2016.
- 2 Seminar report on divergent synthesis by:
(a) C. E. Brotherthorn and D. L. Boger, Total synthesis of

Alkylation of ketone **9** by lithium TMS-acetylene prepared by TMS-acetylene and *n*-BuLi was found productive but it resulted in poor diastereoselectivities for the desired β -isomer (2:1 ratio over its epimer) (Scheme 2; Table 2). To this end several conditions were tried to find that ethynylmagnesium bromide can allow the synthesis of desired diastereoisomer in a 3.5:1 ratio over its epimer. Subsequent DBU deprotection of methoxy group provided compound **3** in 64% yield over the two steps (Scheme 2). The isomerization of α -methylene- γ -butenolide **3** to α,β -unsaturated- γ -butenolide **10** was found difficult to achieve and was only accomplished by catalytic hydrogen atom transfer to the alkene, a protocol that was developed by Shenvi's group.¹¹ Finally, the direct reduction of **10** to furan moiety by DIBAL furnishes the known furoelemene **2**, allowing the formal synthesis of *epi*-lindenene and sarcandra lactone **A**.^{3d}

Access to the formal syntheses of germacranes: furanoger-
menone and methylcurdionolide and to guaianes: zedoarol
and gweicurculactone (Scheme 1) and other differentiated
scaffolds can be obtained by selective alkylation of acetylene
functionality of **2** to unify for the first time all synthetic plans.
After extensive experimentation was found that methyl cupra-
tion of alkyne can be accomplished with copper iodide fol-
lowed by slow addition of methylmagnesium bromide¹² allow-
ing the synthesis of 2-propenyl-intermediate **1** as the parent
compound for the known oxy-Cope reaction that can build the
10-member macrocycle or the oxy-Cope/ene reaction that
serves for obtaining guaiane carbocyclic core. All formal syn-
theses were accomplished in the same number of steps as in the
previously reported plan (11 steps for common scaffold **2** from
R-carvone) in slightly better yields, nonetheless with the

12 K. A. Parker and Q. Xie, *Org. Lett.*, 2008, **10**, 1349–1352.