Catalytic Z-Selective Cross-Metathesis in Complex Molecule Synthesis: A Convergent Stereoselective Route to Disorazole C1

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Supporting Information

ABSTRACT: A convergent diastereo- and enantioselective total synthesis of anticancer and antifungal macrocyclic natural product disorazole C1 is reported. The central feature of the successful route is the application of catalytic Z-selective cross-metathesis (CM). Specifically, we illustrate that catalyst-controlled stereoselective CM can be performed to afford structurally complex Z-alkenyl–B(pin) as well as Z-alkenyl iodide compounds reliably, efficiently, and with high selectivity (pin = pinacolato). The resulting intermediates are then joined in a single-step operation through catalytic inter- and intramolecular cross-coupling to furnish the desired 30-membered ring macrocycle containing the critical (Z,Z,E)-triene moieties.

We recently introduced a direct method for preparation of alkyl- and aryl-substituted Z-(pinacolato)alkenylboron [alkenyl–B(pin)] compounds through catalytic stereoselective cross-metathesis (CM; e.g., i → ii, Scheme 1); these transformations proceed in the presence of terminal alkenes, relatively robust and commercially available vinyl–B(pin), and an in situ-generated Mo- or W-based monoaeroloxide pyrrolylde (MAP) complex. A benefit of the CM protocol is that it may be combined with catalytic cross-coupling (CC) to furnish reliable access to a range of otherwise difficult-to-obtain Z alkenes. Another critical advantage of the stereoselective CM is that the resulting Z alkenylboron products can be efficiently and stereoselectively converted to the corresponding alkenyl iodides (e.g., i’ → iii). In this way, both substrates in a catalytic CC reaction to generate a (Z,Z)-1,3-diene (cf. iv) may originate from terminal alkenes (e.g., i and i’). The proposed strategy has significant implications vis-à-vis the design of convergent routes for synthesis of biologically active complex molecules that contain one or more (Z,Z,E)-1,3,5-triene fragments. Herein, we disclose the application of the above plan to the diastereo- and enantioselective preparation of anticancer and antifungal natural product disorazole C1.

The only extant total synthesis of disorazole C1, which also established its relative and absolute stereochemistry, is due to the seminal work of Wipf and Graham (Scheme 2). The route involved two Sonogashira-type CC reactions (C8′–C9′), one performed prior to generation of one of the ester linkages and the other carried out subsequently (C8′–C9′). A Yamaguchi-type lactone formation furnished the macrocyclic ring; this was followed by the unveiling of the C9′–C10 and C9′–C10′ Z alkenes through partial hydrogenation of the alkene units. The 2004 study illustrated that any approach toward disorazole C1 and related compounds must be mindful of the sensitivity of the polyene segments. By masking the latter moieties as ene-yne-ene units until the last event of the total synthesis, complications were largely sidestepped that would have otherwise negatively impacted the final stages of the 20-step sequence.

We envisioned two approaches for the assembly of disorazole C1 (Scheme 3). We hoped to identify convergent pathways by utilizing the aforementioned CM and CC processes and by exploiting the symmetric structure of the natural product. In one route (Approach 1), a Z-alkenyl iodide (v) and a Z-alkenyl–B(pin) (vi) would be subjected to catalytic CC conditions and

*pin = pinacolato.

Scheme 2. Previous Synthesis of Disorazole C1

Scheme 3. Proposed Strategy and the Targeted Natural Product

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the resulting (Z,Z,E)-triene (vii) would be converted to disorazole C1 through a double ester bond formation. In addition to the Wipf precedence,6 synthesis of related macrocycles with diene-yno or ene-yno moieties by sequential formation of ester bonds has been reported by Meyers7 and Hoffmann,8 respectively. In the earlier instance,7 partial hydrogenation of the alkyne units was unsuccessful and removal of silyl protecting groups could not be performed in high yield; in the other case, data regarding reduction of alkynes or unmasking of [2-(trimethylsilyl)ethoxy]methyl (SEM) groups were not provided.8 Additionally, single-step double esterification has been shown to be reasonably effective in accessing a derivative of disorazole Z (26% yield), although this member of the natural product family contains two Z,E,E triene groups within a 26-membered macrocycle (vs Z,Z,E units in a 30-membered ring in disorazole C1).9 In this latter initiative, a pair of t-Bu(Me)2Si (TBS) ethers within the macrocyclic product could be unmasked but only in 22% yield. We hoped that with a short and convergent route for accessing the requisite substrates, an effective double ester bond synthesis and an appropriately mild deprotection would be identified. The other strategy to be probed involved double CC of a precursor such as viii (Approach 2, Scheme 3).

We began by developing a concise route for synthesis of alkenyl iodide 7 (Scheme 4). Although a related derivative of this fragment (TES vs TMS) has previously been prepared, we opted to identify a more efficient pathway.11 The first key operation required stereoselective addition of an allyl unit to enantiomerically enriched aldehyde 1.9 After screening a variety of conditions involving assorted catalysts and reagents, we found that use of allylsilane 2 in the presence of 5.0 mol % Sc(OTf)3, as outlined by Leighton,12 delivered the most desirable outcome (>98% yield, 10:1 diastereomeric ratio (dr)). Use of the original and closely related reagent derived from norephedrine13 generated a nearly equal mixture of diastereomers.14 Protection of the secondary alcohol as a TMS ether (92% yield) was followed by a Z-selective CM with vinyl−B(pin) (performed on g-scale; 72% yield); this sequence, with complex 4a serving as the MAP complex, furnished 5 with complete Z selectivity. As long as vinyl−B(pin) was available, none of the competitive RCM, leading to the formation of cyclohexene 6, could be detected; this was despite the conformational rigidity provided by the gem-dimethyl unit and suggests that B(pin)-substituted Mo alkylidene, generated preferentially,15 serves as the propagating species (vs that derived from the terminal alkene of TMS-protected 3). Z-Alkenyl iodide 7 was then prepared in 79% yield (>98% Z).16

Next, we set out to identify an efficient sequence that would furnish (Z,E)-dienyl−B(pin) fragment 13 (Scheme 5). This task emerged as significantly more challenging, largely because introducing the sensitive dienyl moiety of 12 through a catalytic enantioselective or auxiliary-based diastereoselective aldol addition with pentadienyl aldehyde proved to be particularly difficult (extensive product decomposition and/or inferior stereoselectivity).17 A relatively efficient and diastereoselective
variant involving an N-acetylthiazolidinethione suffered substantial intramolecular acylation during attempts to obtain the derived methyl ether.\textsuperscript{17} We consequently designed an alternative scheme that would expose the dienyl moiety through an appropriately mild procedure at a later stage. Conversion of enantiomerically enriched allylic alcohol 8\textsuperscript{18} to serine-derived amide 9 was accomplished in 3 steps and 61% overall yield (Scheme 5). Cyclization with DAST, followed by oxidation initiated by BrCCl\textsubscript{3} and DBU\textsuperscript{19} generated oxazole 10. Installation of the 1,3-diene moiety was accomplished by the following sequence: CM between 10 and commercially available 4-bromo-1-butene in the presence of 5.0 mol % Ru carbene 11\textsuperscript{20} and subsequent treatment with DBU to facilitate elimination.\textsuperscript{21} E-Diene 12 was accordingly obtained in 74% overall yield and 93% E selectivity. Catalytic CM involving 12 and vinyl-B(pin), performed with 10 mol % in situ-generated 4a, afforded (Z,E)-1,3-diene 13 in 76% yield and 92% Z selectivity.

Z-Alkenyl iodide 14 was obtained as a single diastereomer after removal of the TMS group in 7 (85% yield).\textsuperscript{13} Coupling of 14 with (Z,E)-1,3-dienyl-B(pin) 13 by the use of 10 mol % Pd[(PPh\textsubscript{3})\textsubscript{4}] and 1.1 equiv of Ag\textsubscript{2}O\textsubscript{22} generated the desired (Z,Z,E)-triene, which was then converted to carboxylic acid 15 (Scheme 6). The latter transformation was complete in 1.5 h, but carboxylic acid derived from 13. We therefore chose to generate the carboxylic ester bond first without the possibility of interference by the organoboron group and then perform a Z-selective CM with vinyl-B(pin). Ester bond formation with the carboxylic acid derived from 1,3-diene 12 and the sizable alcohol 14 was indeed significantly more efficient, delivering ester 18 in 83% overall yield [vs 30% with acid of alkenyl-B(pin) 13]. The stage was thus set for catalytic CM with the highly functionalized polyene 18 (Scheme 7b), a transformation that proceeded readily with 10 mol % Mo MAP complex 4b (cf. Scheme 4; performed on ~0.2 g of 18) and ~7 equiv of vinyl-B(pin) to afford 17 with 95:5 Z/E selectivity. Silica gel chromatography furnished (Z,E)-diene=vinyl-B(pin) 17 in 91% yield as a single stereoisomer.

We searched for conditions that would allow the single-step inter- and intramolecular catalytic CC to provide the 30-membered ring structure of disorazole C\textsubscript{1}. Major side products included oligomeric compounds as well as 15-membered lactone 19 (Scheme 8), derived from intramolecular CC of 17. As might be expected, choice of Pd complex (especially to preserve to the stereochemical integrity of the Z,Z,E trienes),\textsuperscript{26} base, and solvent proved to be critical.\textsuperscript{17} Our investigations eventually led us to establish that, in the presence of 5.0 mol % Pd [{(o-tol),P}]\textsubscript{2} and 1.0 equiv of Cs\textsubscript{2}CO\textsubscript{3} in MeOH at ambient temperature for 12 h, the catalytic double CC is most efficient, affording 16 in 60% yield (>98% conv). Importantly, with MeOH as solvent, although some oligomeric products were formed, <2% of 19 was detected.\textsuperscript{15} The present system is more challenging than a previous study involving the “stitching” of di(alkenyl iodide) and a distannyl alkene, where neither reactant can undergo unimolecular cyclization (cf. 19).\textsuperscript{27} Moreover, in a formerly disclosed double-CC approach to a 16-membered ring triene, intramolecular ring closure would mean the formation of an energetically prohibitive E,E-cyclooctadienone.\textsuperscript{10b}

Considering the documented difficulties vis-à-vis deprotecting procedures with related compounds,\textsuperscript{10d} we were mindful of the remaining transformation. Significant screening was required.

\textbf{Scheme 6. Examination of Catalytic CC/Double Ester Formation Strategy}

\textbf{Scheme 7. Examination of Ester Bond Formation/Double CC Strategy}
here as well, leading us to determine that subjection of 16 to aqueous H$_2$SiF$_6$ and MeOH$^{28}$ for 72 h at 4 °C could deliver disorazole C$_1$ in 68% yield. The present approach, which relies on the combination of catalytic CM/CC is significantly more efficient than previous approaches utilized to access Z,E,E-triene-containing complex molecules and that entail the use of Wittig-type processes.$^{29}$

This study illustrates that CM reactions with high oxidation-state MAP complexes can involve highly functionalized substrates and be performed at relatively late stages of a multistep sequence. We show that, in combination with catalytic CC, CM reactions furnish efficient and stereoselective access to delicate conjugated trienes that contain two Z alkenes and reside in acyclic or macrocyclic natural products.$^{4}$ The total synthesis is convergent, contains a longest linear sequence of 12 steps (8 → 12 → disorazole C$_1$; 8.0% overall yield), and lends itself to analogue preparation.

## ASSOCIATED CONTENT

### Supporting Information
Experimental procedures and spectral and analytical data for all products. 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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