Use of Sequential Intramolecular Heck Cyclizations for Preparing Bicyclo[3.2.1]octane Fragments of Tetracyclic Stemodane and Stemarane Diterpenes

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We dedicate this publication to Professor Ryoji Noyori in recognition of his seminal contributions to the field of organic synthesis and the insightful leadership he has provided to the worldwide organic chemistry community.

Abstract: Use of an intramolecular bis-Heck cyclization to furnish the BCD ring systems of tetracyclic diterpenes of the stemodane and stemarane families is disclosed.

Key words: Heck reaction, terpenoids

Stemodinone (1) and stemarin (2) are members of a group of tetracyclic diterpenes that have been isolated from the leaves of the West Indies plant Stemodia maritima L. (Scrophulariaceae) (Figure 1).2 These stemodia extracts are structurally similar to the fungal metabolite aphidicolin (3), another tetracyclic diterpene that exhibits a variety of pharmacological activities including antiviral and antitumor properties.3

Figure 1 Structures of Representative Tetracyclic Diterpenes.

As a result of their challenging structures and significant biological activities, the stemodia family of natural products has attracted considerable attention from synthetic chemists, with imaginative total syntheses being described from several laboratories.4-5 We recently reported the first total syntheses of (-)-4 and (+)-scopadulcic acid A, a member of the structurally related tetracyclic scopadulan diterpene family.6 The defining reaction of our approach to 4 was a cascade intramolecular bis-Heck cyclization of trienyl iodide 5A, a transformation that assembles the B, C and D rings as well as the C9 and C12 quaternary stereocenters of the scopadulan ring system (Figure 2).7 Herein we describe our evaluation of the use of a related strategy for assembling the bridged tricyclic BCD rings of the stemodia natural products.

An intriguing finding during our earlier synthesis of scopadulcic acid A (4) was the profound effect that stereochirality of the allylic C6 siloxy group played in the pivotal bis-Heck cyclization: the 6S,8R epimer 5A cleanly cyclized, as depicted in Figure 2, to scopadulan precursor 6 [R = (OCH2CH2O)CH2CH2CH2], whereas the corresponding 6R,8R epimer 5B furnished a complex mixture of products under identical conditions.6a-d Although structures of these latter materials were not firmly established, there were indications that the major products arose by a process in which initial Heck insertion of the exo methylene group occurred from the β-face (the opposite sense to that observed with epimer 5A). If this conjecture was correct and the efficiency of the process could be optimized, bis-Heck cyclizations of stereoisomer 5B could provide a route to tricyclic products having the stemodane or stemarane skeleton. To further evaluate this possibility, we
chose to explore related cyclizations of a simpler substrate having \( R = H \) with the anticipation that elucidation of the structure of products would be more straightforward in this series.

Using a strategy identical to the one employed in our synthesis of \( 4 \), racemic \( 6R^*,8R^* \) trienyl iodide \( 13 \) was assembled as summarized in Scheme 1. Coupling the organolithium derivative of \( 7 \) with racemic cyclopentyl carboxamide \( 8 \) provided a mixture of epimeric ketones \( 9 \) in 70% yield (Scheme 1). Silylation of \( 9 \) under thermodynamic conditions yielded the corresponding enoxysilanes,\(^a\) which underwent Cope rearrangement at 100 °C in toluene to give cycloheptenones \( 10 \) as a 1:1 mixture of epimers. Installation of the exocyclic methylene group and subsequent deprotection of the TIPS ether delivered a separable mixture of \( 11 \) and \( 6R^*,8R^* \) epimer \( 12 \); the undesired \( 6S^*,8R^* \) epimer \( 11 \) could be converted to \( 12 \) by Mitsunobu inversion. This two stage sequence provided \( 12 \) in 69% overall yield from \( 10 \).\(^b\) Reduction of \( 12 \) with sodium bis-(2-methoxyethoxy)aluminum hydride (Red-Al\(^d\)), followed by quenching the vinylalane intermediate with NIS furnished an iodo alcohol that was protected to give \( 13 \). The choice of the MOM protecting group was made after initial survey experiments indicated that silicon protecting groups were labile under some Heck reaction conditions.

With sufficient quantities of the \( 6R^*,8R^* \) stereoisomer \( 13 \) available, a variety of Heck cyclization conditions were screened (Scheme 2). Attempted cyclization of \( 13 \) using the catalyst system employed in our scopadulcic acid A synthesis \([Pd(OAc)\(_2\), Ag\(_2\)CO\(_3\), THF]\) gave a complex mixture of products, as did reactions employing \((Ph_3P)_2Pd\). Use of \( Pd\)-bis(tert-o-tolylphosphine) with a variety of acid scavengers \([Ag_2CO_3, Et_3N, i-Pr_2EtN \text{ or KOAc}]\) surprisingly led to the elimination of HI to regenerate the propargylic alcohol unit. Fortunately, we found that \( 13 \) cyclized reasonably cleanly under cationic Heck conditions.\(^c\) For example, cyclization of \( 13 \) at 75 °C in \( N,N\)-dimethylacetamide (DMA) using 10 mol% of \( Pd(dppb) \) and excess \( Ag_2CO_3 \) and KOAc provided two readily separable tricyclic products \( 14 \) and \( 15 \) in 40% and 25% yields, respectively.\(^d\) Structures for \( 14 \) and \( 15 \) followed unambiguously from extensive 2D NMR and nOe experiments. The diagnostic \( ^1H=^1H \) nOe enhancements depicted in Scheme 2 firmly established that the larger bridge is \( cis \) to the angular hydrogen in both products.\(^e\)

\[\text{Scheme 1} \quad \text{Reagents and conditions: a) 7, Et}_3O, -78 °C, t-BuLi; b) TMSOTI, Et_3N, toluene, 100 °C, c) KHMDMS, Me_2CO, PBr, 0 °C, d) TBAF (1.0 M THF solution), 25 °C, e) HPLC, 1,25 EtOAc-hexanes, 60 Å SiO_2, f) DEAD, Ph_2P, PhCO_2H, K_2CO_3, MeOH, g) Red-Al, 25 °C, NIS, -78 °C, h) CH_2OCH_2Cl, i-Pr_2EtN, CH_2Cl_2.\]

A possible rationale for the outcome of the Heck cyclization of \( 6R^*,8R^* \) trienyl iodide \( 13 \) is provided in Figure 3. As we have discussed earlier, insertion of the vinylpalladium intermediate initially generated from \( 13 \) could take place by two conformations \((16 \text{ and } 16')\) that have a favored (nearly coplanar) arrangement of the Pd-\( \pi \) bond. As suggested in Figure 3, a destabilizing interaction between the palladium fragment and the allylic alkoxy group in conformer \( 16' \) should result in the initial insertion taking place by way of \( 16 \) to form \( trans \)-bicyclo[5.4.0]undecadienyl palladium alkyl intermediate \( 17 \). A surprising outcome of the present investigation is...
that subsequent insertion of the trisubstituted cycloheptenyl double bond of this intermediate occurs to generate both 14, having the stemodane BCD skeleton, and 15, having the BCD stemarane ring system. Since the insertion pathways leading to both of these tricyclic products involve 5-exo ring formation, we would have expected the 17B → 20 → 15 pathway to be favored, because it avoids formation of intermediate 19 having a relatively unstable tertiary Pd–Cσ bond. Obviously others factors, at this time only poorly understood, come into play and override the relative instability of intermediate 19.15,16

In summary, this investigation shows that bis-Heck cyclizations of the 6R*,8R* epimer of trienyl iodide intermediates employed in our earlier total synthesis of scopadulcic acid A (4)6a can generate the synthetically challenging BCD tricyclic moieties of tetracyclic diterpenes of the stemodane and stemarane families. If the factors that are necessary to control regioselection of the second Heck insertion step can be defined, a potentially powerful new approach for total synthesis of stemodia natural products should emerge.

Figure 3  Bis-Heck Cyclizations of the 6R*•8R* Epimer.

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References and Notes
(1) Current address: Bayer Corporation, 400 Morgan Lane, West Haven, CT 06516-4175.
(4) For reviews of the synthesis of tetracyclic diterpenes, see:


(6) Prepared from 3-[(tert-butyldimethylsiloxy)propanal 9 by the following standard sequence: (a) EtMgBr, THF, 0 °C; (b) TIPS-Cl, imidazole, DMF, rt; (c) n-BuLi, MeI, –78 °C to rt; (d) 3:1 AcOH–THF–H2O, rt; (e) I2, Ph3P, imidazole, MeCN, rt.

(7) For recent reviews of the use of intramolecular Heck reactions see: (a) Fox, M. E.; Li, C.; Marino, J. P., Jr.; Overman, L. E. Metal-Catalyzed Cross Coupling Reactions; Stang, P. J. and Diederich, F., Eds.; Wiley: New York, 1992; Vol. 8, Chapter 1.

(8) Data for 1H NMR (500 MHz, CDCl3) δ 5.70 (d, J = 5.5 Hz, 1H), 5.14 (br s, 1H), 4.68 (d, J = 6.6 Hz, 1H), 4.64 (d, J = 6.6 Hz, 1H), 3.96–3.94 (m, 1H), 3.36 (s, 3H), 2.62–2.57 (br d, J = 15.0 Hz, 1H), 2.18–2.08 (m, 3H), 1.99–1.93 (m, 1H), 1.75–1.70 (m, 1H), 1.75 (d, J = 1.5 Hz, 3H), 1.67 (d, J = 2.0 Hz, 3H), 1.64–1.55 (m, 1H) 1.44 (dd, J = 8.0 Hz, 3.0 Hz, 1H), 1.36–1.32 (m, 1H), 1.26–1.20 (m, 1H); 13C NMR (125 MHz, CDCl3) δ 146.0, 141.7, 122.3, 117.4, 94.7, 68.8, 55.2, 45.5, 43.4, 41.2, 40.1, 37.5, 37.2, 35.5, 22.3, 20.0; IR (film) 2924, 1445, 1378, 1147, 1096, 1042, 917 cm–1; HRMS (EI) m/z 248.1786, (248.1776 calcd for C16H24O2, M). Data for 151H NMR (500 MHz, CDCl3) J= 15.0 Hz, 1H), 5.70 (br dd, J = 6.8, 1.5 Hz, 1H), 5.44 (dd, J = 9.4 Hz, 4.0 Hz, 1H), 4.77–4.70 (m, 2H), 4.02–4.00 (br s, 1H), 3.33 (s, 3H), 2.35 (dt, J = 13.3, 4.2 Hz, 1H), 2.20–2.14 (m, 1H), 1.88–1.73 (m, 2H), 1.82 (d, J = 1.5 Hz, 3H), 1.59–1.41 (m, 4H), 1.29 (br d, J = 10 Hz, 1H), 1.17 (s, 3H); 13C NMR (125 MHz, CDCl3) δ 145.4, 138.9, 129.2, 123.0, 95.1, 69.2, 55.6, 47.9, 43.6, 43.1, 42.7, 42.4, 35.2, 33.1, 24.3, 18.8; IR (film) 3012, 2934, 2865, 1653, 1540, 1377, 1149, 1099, 1039, 988, 918 cm–1; HRMS (EI) m/z 248.1786, (248.1776 calcd for C16H24O2, M).

(9) A Monte Carlo conformational search was conducted on an analog of 17 in which the palladium unit was replaced by H using the MacroModel V6.5X implementation of the MM2* force field. The five lowest energy conformers found had a universally shorter separation between C13 and C14 than between C12 and C14. An identical search made with this congener of the C6 epimer of cis-bicyclo[5.4.0]undecadienyl palladium allyl intermediate 18 that would arise from cyclization of the 6S,8R* epimer of 16 found the separation between C12 and C14 was shortest, which could contribute to the clean generation of the scopadulan ring system from Heck cyclizations of this stereoisomer series.


(11) Epimers 11 (δ 2.68–2.73, m) and 12 (δ 2.60–2.63, m) showed particularly diagnostic 1H NMR signals for their C8 methane hydrogens. Comparison of these resonances with those of the related more complex epimer pair studied earlier, whose structures were rigorously secured by single-crystal X-ray analysis of a derivative, allowed for unambiguous definition of the stereostuctures of 11 and 12.

(12) The catalyst was generated by reaction of Pd(dba)2•CHCl3 and 1,4-diphenylphosphinobutane (dpbb) at rt in DMA for 15 min (solution changes color from dark red to green-orange). An aliquot of this catalyst solution (10 mol% Pd) was added to a suspension of Ag2CO3 (2 equiv), K2OAc (2 equiv), and iodide 13. The resulting suspension was degassed and refilled with Ar, heated at 75 °C for 16 h, allowed to cool rt, and concentrated.

(13) 1H NMR spin systems were established using 1H COSY and 1H decoupling techniques. The 1H–1H noe experiments were conducted at 500 MHz using the DPPFGSE (double pulsed field gradient spin echo) method; Stott, K.; Keeler, J.; Van, Q. N.; Shaka, A. J. J. Magn. Res. 1997, 125, 302.

(14) A detailed listing of synthetic work in this area prior to 1994 is provided in this publication. (g) Toyota, M.; Ihara, M. Tetrahedron 1990, 43, 1453.