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Synthesis of a Propellane-Type 5/5/6-Tricyclic System by Tandem-Metathesis: A New Approach to a Quadranoid Skeleton

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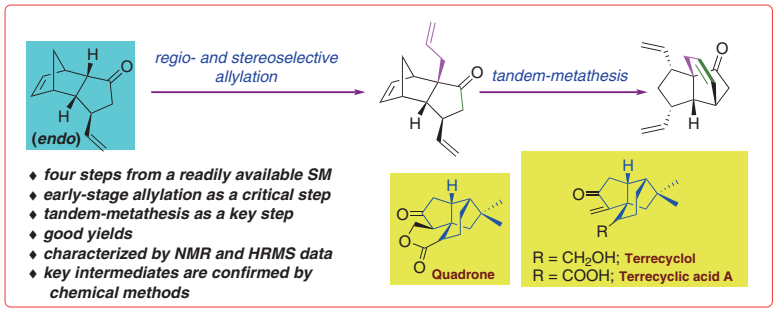

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Abstract We disclose a useful synthetic method for preparing the propellane-type 5/5/6-tricyclic system that is present in diquinane-based natural products such as quadrone, terrecyclic acid A, or terrecyclol. The method involves an LDA-mediated regio- and stereoselective allylation and a tandem metathesis as key steps. The target molecules were assembled in just two steps starting from a readily available building block, a 3β-vinyl tricyclic ketone prepared from *endo*-dicyclopentadiene-1-one. All the compounds prepared were characterized by NMR analyses and/or chemical methods. The synthetic methods demonstrated here are useful in syntheses of quadranoid-type natural products.

Keywords allylation, olefin metathesis, diquinanes, tricyclic compounds, dicyclopentadienone, natural products

Diquinane (octahydropentalene) is the simplest bicyclic system among the various cyclopentanoids, and is present in numerous polycyclic natural products as a critical structural unit.[1] Compounds in which a carbocyclic ring (a three-, four-, five-, or six-membered ring, etc.) is fused to the ring junction of a diquinane moiety are called propellanes. Propellanes are highly strained systems and have useful applications in various fields of chemistry.[2]

Among various propellane systems, six-membered-ring-fused diquinanes have attracted a great deal of attention from the synthetic community, due to the challenges involved in their synthesis, and because they are found as core units in many natural products.[3] Also, natural products containing a fused 5/5/6-tricyclic system are known to exhibit a wide range of biological properties.[4]

Depending on the mode of fusion of the six-membered ring to the diquinane moiety, 5/5/6-tricyclics are classified into various types **1**–**6** (Figure 1).[5] The six-membered ring can be fused to the diquinane in a 1,2- or a 1,3-fashion (Figure 1a). The 1,2-fused 5/5/6-tricyclics are of three types: linear (**1**), angular (**2**), or propellane (**3**). Along similar lines, 1,3-fused 5/5/6-tricyclics are categorized into 1,3-fused (**4**), 1,3-bridged (**5**), or 1,3-propellane (**6**) types. Furthermore, the 1,2- and 1,3-fusions can exist in either *cis* and/or *trans* forms. Linear and angularly fused 5/5/6-tricyclic systems (**1** and **2**) exist in both *cis* forms (Figures 1b and 1c; **1a** and **2a**) and *trans*-forms (**1b** and **2b**), whereas propellanes (**3**) exist only in a *cis* form (**3a**; *exo* or *endo*) because of the stereochemistry of the *cis* ring junction (Figure 1d). Along similar lines, the 1,3-fused type **4** exists in both *cis* (**4a**) and *trans* forms (**4b**) (Figure 1e), whereas the 1,3-bridged (**5**) and 1,3-propellane (**6**) types exist in a *cis* form (**5a** and **6a**; *exo* or *endo*) only (Figure 1f).

All these skeletal types **1**–**6** (Figure 1) are found in many natural products, such as alkaloids or terpenoids, and show useful biological properties.[6] Among these, the syntheses of skeletal types **1**–**5** have been well explored by several groups,[7] including our group. We have recently reported syntheses of skeletal types **1**, **2**, and **4** through metathesis approaches.[5,8] However, synthetic efforts toward 1,3-propellane-type skeletons **6** have been limited. The 1,3-propellane-type skeleton **6** is present in the sesquiterpenoid quadrone and its analogues (Figure 2).[9] These are isolated from the fungus *Aspergillus terreus* and contain a complex structural unit with a propellane-type 5/5/6-tricyclic core **6** and they exhibit useful biological properties that include antitumor activity.[10] Also, they are prone to undergo skeletal rearrangements due to the presence of ring strain.[11] Hence, they have become attractive targets for the synthetic community to develop new synthetic strategies.

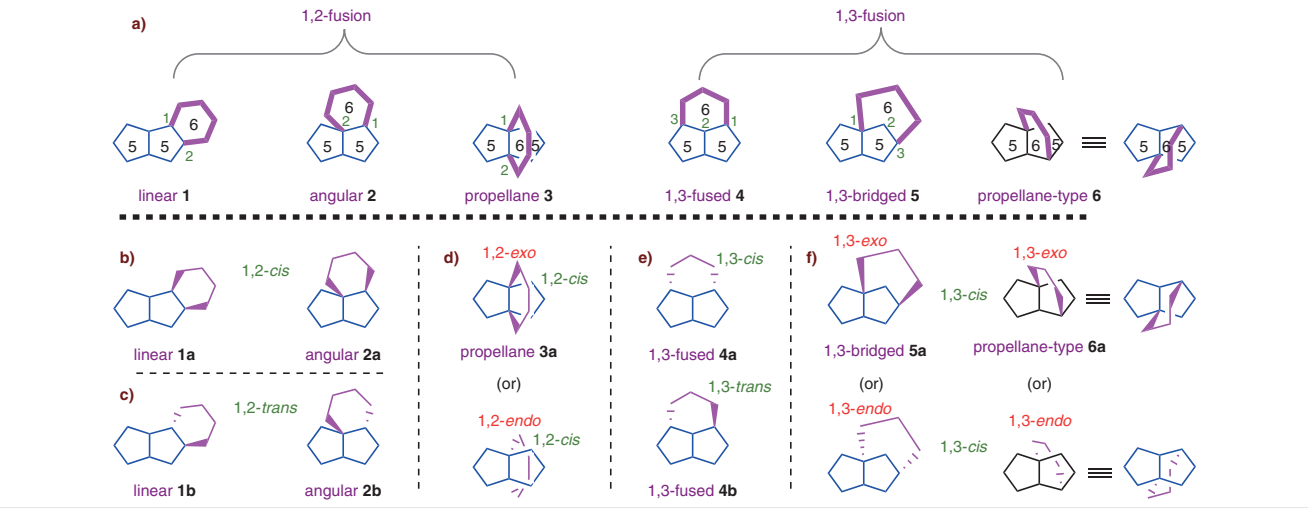


Figure 1 Types of fused 5/5/6-tricyclic skeletons

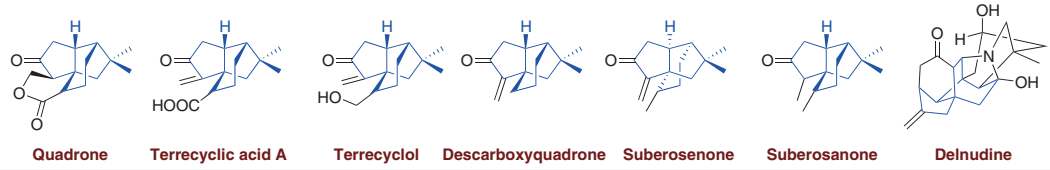


Figure 2 Representative examples of natural products containing 1,3-fused 5/5/6-tricyclic framework

There are a limited number of reports on the synthesis of these carbocycles, including their total synthesis.[9d,e,10e,12] Some selected methods are based on key reactions that include cyclization,[13] Claisen rearrangement,[14] acid-catalyzed rearrangements,[15] cationic rearrangement,[16] and skeletal synthesis.[9f,17] Moreover, the reported methods involve linear syntheses and large numbers of steps starting from commercially available materials or readily available building blocks. Additionally, we have not found any reports on the use of olefin metathesis for their synthesis. Therefore, we wish to report a rapid synthetic route to a propellane-type 5/5/6-carbocyclic framework **6** from readily available starting materials.

In view of our long-term interest in the use of C–C bond-formation reactions (e.g., olefin metathesis) to develop new synthetic strategies,[18] we envisioned a rapid synthetic approach to the propellane-type 5/5/6-carbocyclic framework **6** from a readily available building block, a 3β-vinyl tricyclic ketone that can be prepared from *endo*-dicyclopentadiene-1-one,[18f] by employing tandem metathesis as a key step. Also, we aimed to investigate the feasibility of metathesis between the olefin moieties present on the carbocyclic frameworks. Earlier reports on the feasibility of the metathesis approach are shown in Figure 3.[19] The *trans*-disposition of olefinic moieties at 1,3- or 1,2-positions seems to disfavor the ring-closing metathesis (RCM) sequence.

We aimed to study both an early-stage methylation sequence and an early-stage allylation sequence to construct the propellane-type 5/5/6-carbocyclic framework **6**, which serves as a key intermediate for the synthesis of a core skeleton of quadranoids. An overview of the present work is shown in Figure 4.

Our retrosynthetic approach to target compound **8** is depicted in Figure 5. Tricyclic compound **8** could be prepared by following a five-step synthetic sequence starting from the vinyl derivative **7**. The target compound **8** could be synthesized through hydrogenation of the tricyclic ketone **9**. The tricyclic ketone **9** could be assembled through a tandem metathesis of allyl derivative **10**. The ring-junction allyl derivative **10** might be prepared from compound **7** through methylation followed by a bridgehead allylation sequence. The vinyl derivative **7**, in turn, could be obtained from *endo*-dicyclopentadiene-1-one through a conjugate addition with vinylmagnesium bromide.

Our journey began with the preparation of the key building block, the 3-vinyl tricyclic ketone **7**, from commercially available *endo*-dicyclopentadiene by following a three-step synthetic sequence.[18f,20] Having prepared a substantial amount of the starting material **7**, we subjected it to regioselective methylation to deliver the *gem*-dimethyl derivative **11** (91%; Scheme 1). This compound was then treated with allyl bromide in the presence of sodium hexamethyldisilazide (NaHMDS) to furnish the correspond-

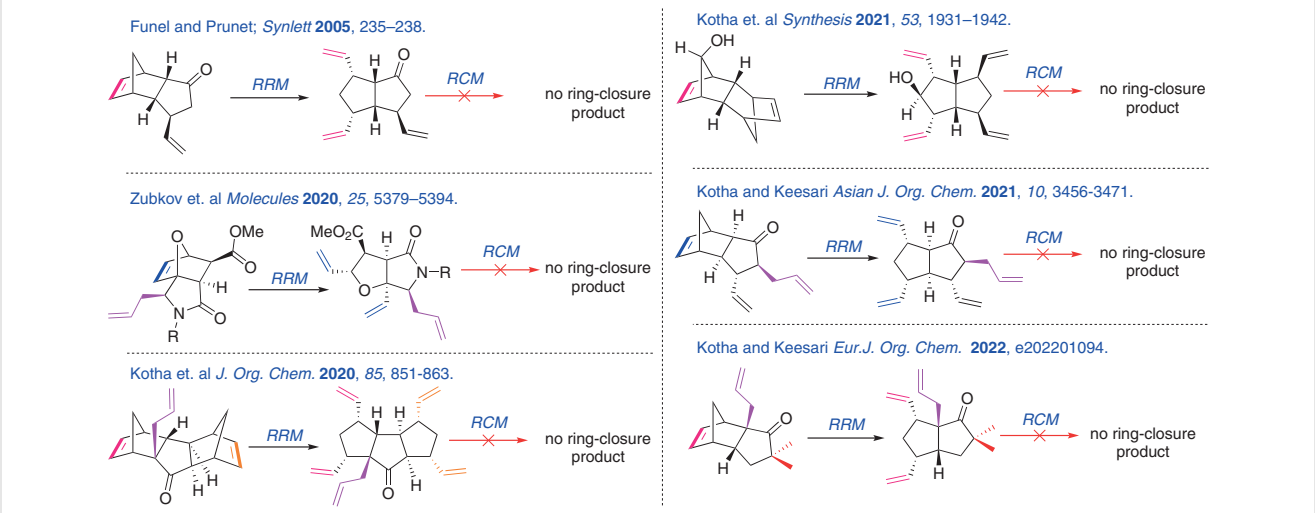


Figure 3 Previous reports on ring-closing metathesis of 1,2-, and 1,3-*trans*-disposed olefinic moieties

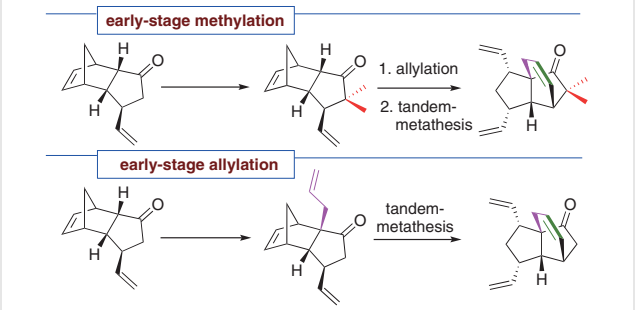


Figure 4 An overview of the present work

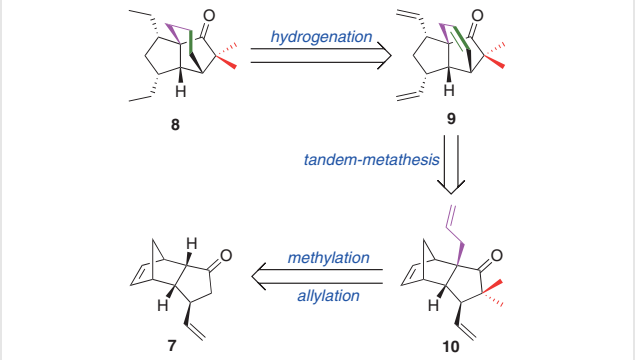
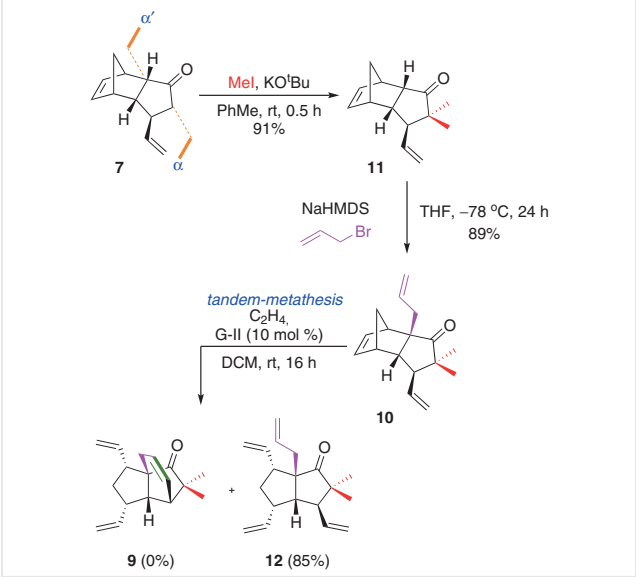


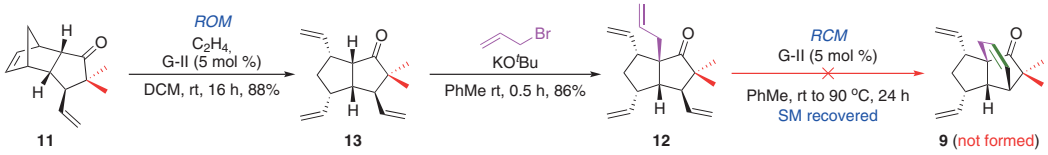
Figure 5 Retrosynthetic analysis to tricyclic ketone **7**



Scheme 1 Attempted synthesis of tricyclic ketone **9** by a tandem metathesis route

ing ring-junction-allylated derivative **10** (89%).[18f] Next, this compound was subjected to tandem metathesis with the aid of the Grubbs II (G-II) catalyst (10 mol%) under an ethylene atmosphere in an attempt to obtain the 5/5/6-tricyclic compound **9**. Instead, however, the tandem metathesis precursor **10** delivered the ring-opening metathesis product **12** (85%) instead of the desired tricyclic compound **9** (Scheme 1).

Alternatively, compound **12** might be obtained by a two-step sequence involving ROM and allylation of the *gem*-dimethyl derivative **11** (Scheme 2). To this end, the diquinane derivative **13** (88%) was obtained by exposing the norbornene derivative **11** to G-II catalyst (5 mol%) under an ethylene atmosphere. Next, compound **13** was allylated at the ring-junction carbon in the presence of allyl bromide and *t*-BuOK to obtain the corresponding allyldiquinane **12** (86%). However, when this compound was subjected to RCM with the aid of the G-II catalyst (10 mol%), the ring-closure product **9** was not obtained, even when the reaction was carried out under heated conditions for a prolonged reaction time, and the starting material was recovered.[18k]



Scheme 2 Attempted synthesis of tricyclic ketone **9** by a ROM/RCM sequence.

Because early-stage methylation (Figure 5) failed to give the desired tricyclic system **9**, we could not proceed further with a synthesis of the target compound **8**. We therefore revised our retrosynthetic strategy to one involving a late-stage methylation to quadranoid skeleton **8** (Figure 6). The target compound **8** might be synthesized from the tricyclic ketone **14**. The key intermediate **14** might, in turn, be assembled by tandem metathesis of ring-junction-allylated derivative **15**, which could be synthesized from vinyl derivative **7** by regio- and stereoselective allylation.

To realize this strategy, compound **7** was subjected to a regio- and stereoselective allylation at the α′-position (i.e., the ring-junction carbon) of the tricyclic system in the presence of a base to deliver the ring-junction-allylated derivative **15**. For this purpose, we screened several reaction conditions by changing the base (mild → strong and small → bulky) and its loading at various temperatures (Scheme 3 and Table 1). Initially, when we used potassium carbonate (K_2CO_3) as a base, the allylation did not occur at any position of compound **7**, and the starting material was recovered. With 1.2 to 2.0 equivalents of potassium *tert*-butoxide (*t*-BuOK), the α-monoallyl product **16** was formed as a diastereomeric mixture (Table 1, entries 1 and 2). When the amount of this base was increased to 4.0 equivalents by adding it in two portions at 0.5 hour intervals, the *gem*-diallyl derivative **17** (major) was also formed along with compound **16** (minor), and 10% of the starting material was recovered (entry 3). At this stage, conventional column chromatography failed to separate these compounds. However, when lithium diisopropylamide (LDA), freshly prepared from BuLi and diisopropylamine (DIPA), was used as a base at a low temperature (–78 °C) and the reaction mixture was stirred for three hours, the reaction merely initiated, and no further progress was observed. We therefore screened several reaction conditions by changing the amount of base and the reaction temperature (entries 4–9).[18e]

When the reaction temperature was slowly increased to –30 °C by stirring the mixture for various times, monoallylation occurred at the desired α′-position, and the corresponding ring-junction-allylated product **15** (21%) was obtained exclusively, along with 68% recovery of the starting material (Table 1; entry 4). Although the conversion improved to 69% on increasing the reaction temperature and reaction time, compound **15** and compound **16** were formed as a chromatographically inseparable mixture in 52% yield (entry 5). However, with the use of HMPA solvent as an additive, both the conversion and the yield of the desired allyl derivative **15** were improved to a certain extent (entries 6–9). We therefore carefully screened several reaction conditions by increasing the loading of the base in the presence of HMPA as an additive at various reaction temperatures and time intervals. Eventually, the desired compound **15** was obtained in a 42% yield under the optimized reaction conditions (entry 8). From these results, we concluded that the amount of base does not affect the regioselectivity whereas the reaction temperature does influence the regioselectivity to yield the requisite allyl product **15**.[18e]

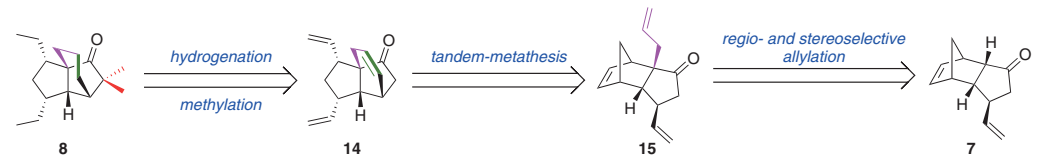
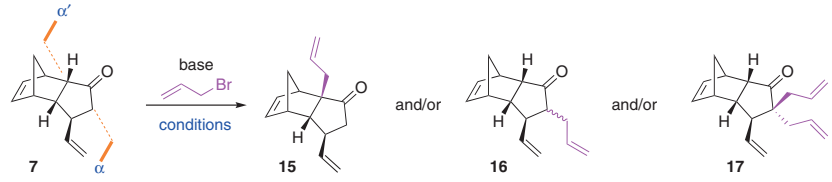


Figure 6 Revised retrosynthetic analysis toward the quadranoid skeleton **8**



Scheme 3 Synthesis of allyl Derivative **15** by regio- and stereoselective allylation of compound **7**

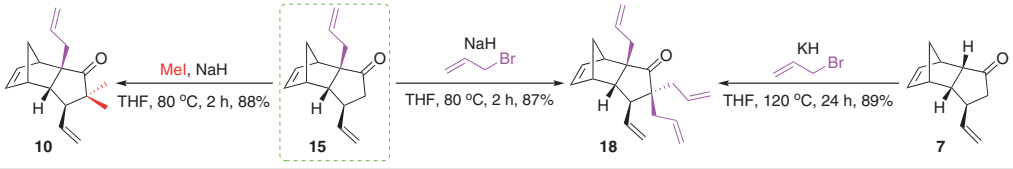
Table 1 Screened Reaction Conditions for Monoallylation of **15**[a]

Entry	Base	Equiv	AllBr[b] (Equiv)	Temp (°C)	Time (h)	Conv[c] (%)	Yield[d] (%)		
							15	**16**	**17**
1	*t*-BuOK	1.5	1.2	rt	0.5	42	–	21	–[e]
2	*t*-BuOK	2.0	2.2	rt	1.0	63	0	38	–[e]
3	*t*-BuOK	4.0	3.2	rt	3.0	90	0	11	66[e]
4	BuLi/DIPA	1.1/1.2	1.4	–78	4	32	21	trace	–
				–50	2				
				–30	2				
5	BuLi/DIPA	1.1/1.2	1.4	–78	3	69	52 (**15** + **16**)		–
				–40	2				
				–20	2				
				rt	12				
6	BuLi/DIPA/HMPA	2.2/2.4/2.2	2.8	–78	2	40	28	trace	–
				–50	2				
				–20	2				
				–10	2				
7	BuLi/DIPA/HMPA	3.0/3.2/3.0	3.0	–78	2	52	36	trace	–
				–45	2				
				–20	2				
				–10	2				
8	BuLi/DIPA/HMPA	3.0/3.2/3.0	3.0	–78	2	63	42	trace	–
				–10	3				
9	BuLi/DIPA/HMPA	3.0/3.2/6.0	3.0	–78	2	78	32	12	16
				–10	3				
				0	6				

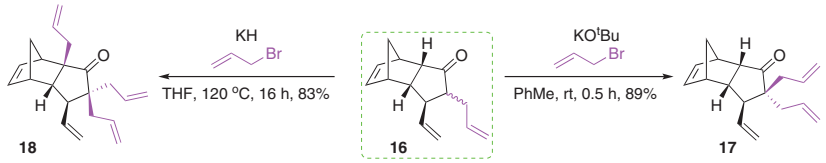
[a] All reactions were carried out in anhyd THF under N_2 unless otherwise stated.
[b] Freshly distilled allyl bromide.
[c] Conversion of based on recovery of the starting material.
[d] Isolated yield.
[e] Toluene was used as the solvent.

At this point, the formation of compounds **15** and **16** and their structures were initially confirmed by NMR analyses. The structure of **15** was confirmed, as it exhibited five CH_2 and eight CH signals in the DEPT-135 NMR spectrum, whereas the structure of **16** was confirmed as it showed four CH_2 and ten CH signals in the DEPT-135 NMR spectrum.

Later, the structures of **15** and **16** were also confirmed by various chemical transformations. When compound **15** was subjected to a methylation sequence, the *gem*-dimethyl derivative **10** was obtained. Furthermore, compound **15** also gave the triallyl derivative **18** upon allylation with allyl bromide in the presence of NaH. Here, the triallyl compound **18** was identical to the compound obtained from the vinyl derivative **7** (Scheme 4).



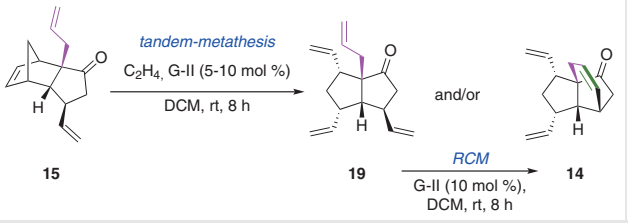
Scheme 4 Structure-confirmation studies for compound **15**



Scheme 5 Structure-confirmation studies for compound **16**

Along similar lines, when **16** was subjected to allylation sequence delivered the same compounds, i.e. the diallyl derivative **17** and the triallyl derivative **18** (Scheme 5). When the ring-junction-allylated derivative **15** was exposed to the Grubbs I catalyst (G-I catalyst; 10 mol%) under an ethylene atmosphere overnight, only the ROM product **19** was obtained, along with 75% of the starting material (by NMR: 3:1 ratio, 69%). Unfortunately, compound **19** could not be isolated in a pure form at this stage by using conventional column chromatography. However, compound **15** furnished the rearranged product **14**, along with 10% of the ROM product **19** (by NMR: 9:1 ratio, 86%) on treatment with the G-II catalyst (5 mol%) under an ethylene atmosphere overnight. A complete conversion was achieved by using 10 mol% of G-II catalyst in a comparatively short reaction time, giving the tricyclic ketone **14** in a good yield (88%).[21]

Later, mixtures of **15** and **19** and of **14** and **19** were also converted into the ring-closure product **14** in yields of 66% and 82%, respectively, by using 10 mol% of G-II catalyst (Scheme 6).



Scheme 6 Tandem metathesis route to a key intermediate, the tricyclic ketone **14**

Next, the keto derivative **14** was subjected to methylation in the presence of MeI and *t*-BuOK in an attempt to prepare the *gem*-dimethyl derivative **20**; however, this compound was not formed and, instead, a complex mixture was obtained. Alternatively, when compound **14** was subjected to an allylation sequence in the presence of KH and allyl bromide under reflux conditions, the rearranged product **22** was obtained instead of the *gem*-diallyl derivative **21** (Scheme 7). As a result, we could not proceed further with a synthesis of compound **8** or its spiro analogue **23** by following this route. However, compounds **8** and **23** might be accessible from tricyclic compound **14** by hydrogenation followed by alkylation and/or an RCM sequence.[18e] These studies will be reported in due course.

We have successfully assembled the propellane-type 5/5/6-carbocyclic framework **14** in a good yield by employing early-stage regio- and stereoselective allylation, followed by a tandem metathesis sequence. Compound **14** could act as a key intermediate to access target compounds **8** and **23**. The present strategy involves commercially available inexpensive starting materials and operationally simple reactions. Consequently, this methodology might be useful in medicinal chemistry to design various drug-like molecules. Further investigations into the synthesis of quadrone natural products would be a useful exercise.

Conflict of Interest

The authors declare no conflict of interest.

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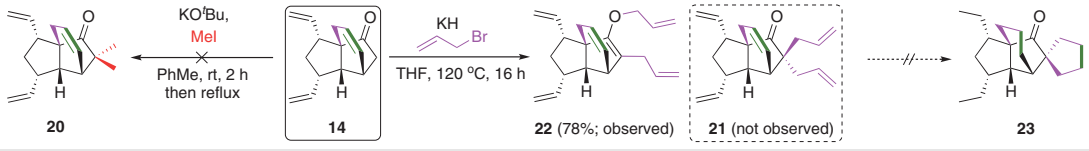
Supporting Information

Supporting information for this article is available online at https://doi.org/10.1055/a-2236-0803.



Scheme 7 Attempted synthesis of dimethyl and diallyl derivatives **20** and **21**

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(21) **(1*S*,2*R*,4*S*,5*S*,6*S*)-2,4-Divinyltricyclo[4.3.2.0^{1,5}]undec-7-en-10-one (14)**

A stirred solution of compound **15** (50 mg, 0.233 mmol) in CH_2Cl_2 (50 mL) was purged sequentially with N_2 gas and ethylene gas for 10 min each. G-II catalyst (20 mg, 0.023 mmol; 10 mol%) was added in one portion at rt under an ethylene atmosphere, and purging was continued for another 5–10 min. The mixture was then stirred at rt under ethylene for 8 h. When the reaction was complete (TLC), the volatiles were removed under reduced pressure, and the crude product was purified by column chromatography (silica gel, 1.0–1.5% EtOAc–PE) to give a colorless liquid; yield: 44 mg (88%); R_f = 0.61 (silica gel-coated 4.0 × 2.0 cm glass TLC plate, 2.0% EtOAc–PE; double run).

IR (neat): 3074, 3026, 2923, 2877, 1737, 1636, 1454, 1429, 1412, 1325, 1156, 1098, 1070, 995, 955, 911, 775, 752, 721, 700, 676, 521 cm^{-1}. ^1H NMR (400 MHz, $CDCl_3$): δ = 6.25 (tdd, *J* = 17.83, 11.78, 8.52 Hz, 1 H), 6.12–6.08 (m, 1 H), 5.99 (ddd, *J* = 16.81, 10.58, 6.00 Hz, 1 H), 5.52 (ddd, *J* = 9.31, 3.77, 2.58 Hz, 1 H), 5.09–5.04 (m, 4 H), 3.04–2.95 (m, 1 H), 2.77 (t, *J* = 5.94 Hz, 1 H), 2.62 (d, *J* = 11.99 Hz, 1 H), 2.52–2.45 (m, 1 H), 2.39–2.31 (m, 2 H), 2.18 (dq, *J* = 17.70, 2.48 Hz, 2 H), 2.04 (ddd, *J* = 13.16, 7.61, 5.92 Hz, 1 H), 1.45 (dd, *J* = 23.92, 12.70 Hz, 1 H). $^{13}C\{^1H\}$ NMR (100 MHz, $CDCl_3$): δ = 223.2 (CO), 139.1 (CH), 137.4 (CH), 136.4 (CH), 126.1 (CH), 115.5 (CH_2), 115.4 (CH_2), 61.2 (C), 54.1 (CH), 51.8 (CH), 49.3 (CH_2), 41.1 (CH), 38.4 (CH_2), 38.3 (CH_2), 34.3 (CH). HRMS (ESI, Q-ToF): *m/z* $[M + K]^+$ calcd for $C_{15}H_{18}KO$: 253.0989; found 253.0989.