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Phosphine-promoted intramolecular Rauhut–Currier/Wittig reaction cascade to access (hetero)arene-fused diquinanes†

Jay Prakash Maurya, Subham S. Swain and S. S. V. Ramasastry *

We describe the first phosphine-promoted intramolecular Rauhut–Currier reaction that triggers an intramolecular Wittig process assembling new classes of diquinanes. The one-pot strategy provides ready access to simple diquinanes and various (hetero)arene-fused diquinanes incorporated with up to two contiguous all-carbon quaternary centers under metal-free and neutral conditions. We showcased the generality of the method on a broad range of substrates and demonstrated its synthetic utility in accessing various advanced intermediates relevant to natural product synthesis and material science.

Benzannulated diquinanes (cyclopenta[*a*]indenes) are the key structural elements of many bioactive natural products and medicinally important molecules (Fig. 1).[1] Therefore, several synthetic protocols have been developed to synthesize cyclopenta[*a*]indene derivatives.[2] While most of them are metal-promoted strategies, the only metal-free approach to our knowledge is Ghorai's work on constructing benzannulated diquinanes employing a tandem iminium and enamine catalysis.[3] Here, we report the first organophosphine-promoted Rauhut–Currier/Wittig reaction sequence to synthesize complex diquinane analogues.

The Rauhut–Currier (RC) reaction is a versatile carbon–carbon bond-forming reaction between two electron-deficient olefins promoted by an organic nucleophilic base.[4] Since the RC reaction is atom-economic and organocatalytic, it has extensive applications in accessing diverse classes of highly functionalized molecules.[5] Recently, several Lewis base-promoted intramolecular cascade transformations triggered by the RC reaction have been developed to create various cyclic structures.[4,6] However, to our knowledge, the RC reaction is yet to be explored in assembling an valuable diquinane scaffold. This manuscript describes an efficient approach to simple diquinanes and (hetero)arene-fused diquinanes and demonstrates its utility in preparing some advanced intermediates relevant to natural product synthesis.

To assemble cyclopenta[*a*]indenes by incorporating the mechanistic features of the RC reaction, the tethered bis-enone **A** was designed in such a way that the phospha-Michael addition preferentially occurs to the β-unsubstituted enone leading to the formation of the zwitterionic intermediate **B**, Scheme 1. The role of R^1 is to discourage a cross-RC reaction since activated α- and β-unsubstituted olefins tend to dimerize or oligomerize under the RC conditions. The enolate-mediated displacement of phosphine could generate dihydroindeno[2,1-*c*]pyran-9-one **C**. On the other hand, we expected that a proton transfer event might generate the phosphorous ylide **D**, which is poised to undergo an intramolecular Wittig reaction to deliver the benzo-fused diquinane **E**. At this stage, we do not rule out the phospha-Michael addition to the β-substituted

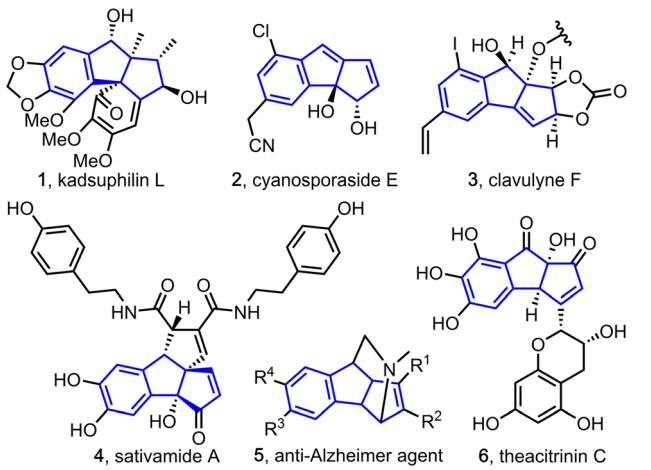
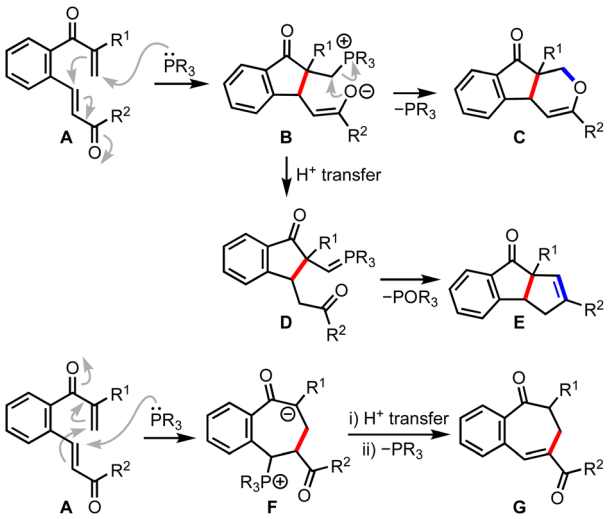


Fig. 1 Representative bioactive natural products possessing cyclopenta[*a*]indene core.

Department of Chemical Sciences, Indian Institute of Science Education and Research (IISER) Mohali, Sector 81, S. A. S. Nagar, Punjab 140306, India. E-mail: ramsastry@iisermohali.ac.in

† Electronic supplementary information (ESI) available: Experimental details and characterisation data for new compounds. CCDC 2325678 [for **8m**] and 2327817 [for **17a**]. For ESI and crystallographic data in CIF or other electronic format see DOI: https://doi.org/10.1039/d4ob00984c

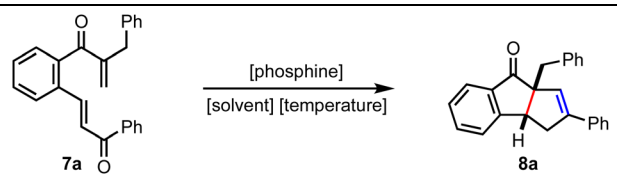


Scheme 1 Substrate design for cyclopenta[*a*]indenes and the possible mechanistic scenarios with a phosphine.

enone generating the zwitterionic species **F**, a subsequent 1,3-proton transfer and an enolate-induced elimination of phosphine providing benzo-fused cycloheptenone **G**.

Although the substrate design (**A**) allows different mechanistic pathways leading to **C**, **E** or **G**, we prepared the bis-enone **7a** to ascertain the preferred product under experimental conditions, Table 1. Since no reaction was observed under catalytic conditions, we exposed **7a** to stoichiometric amounts of PPh_3 and PPh_2Et, but the starting material remained as such (entries 1 and 2). Interestingly, a more nucleophilic trialkylphosphine such as PCy_3 gave **8a** over the other expected products, although in poor yields (entries 3–5). However, better results were achieved with PBu_3 as the Lewis base. An initial reaction of **7a** with PBu_3 in DMF at room temperature delivered **8a** in a good yield (entry 6). During the solvent screening, we realized that the yield of **8a** improved in *tert*-butanol medium (entries 7–9). A few variations in the temperature with PBu_3 as the Lewis base and *tert*-butanol as the solvent gave **8a** in an excellent yield (entries 10–12). We were delighted that we could establish the first synthesis of benzo-fused diquinanes, such as **8a**, under the RC set up.

Table 1 Optimization of reaction parameters[a,b]



Entry	PR_3 (1.2 equiv.)	Solvent	Temperature (°C)	Time (h)/yield[c] (%)
1	PPh_3	DMF	30	48/—
2	PPh_2Et	DMF	30	48/—
3	PCy_3	DMF	30	2/28
4	PCy_3	Toluene	30	2/14
5	PCy_3	MeCN	30	2/32
6	PBu_3	DMF	30	1/64
7	PBu_3	MeCN	30	2/56
8	PBu_3	DMSO	30	1/62
9	PBu_3	*t*-BuOH	30	2/73
10	PBu_3	*t*-BuOH	50	2/78
11	PBu_3	*t*-BuOH	70	1/87
12	PBu_3	*t*-BuOH	80	1/81

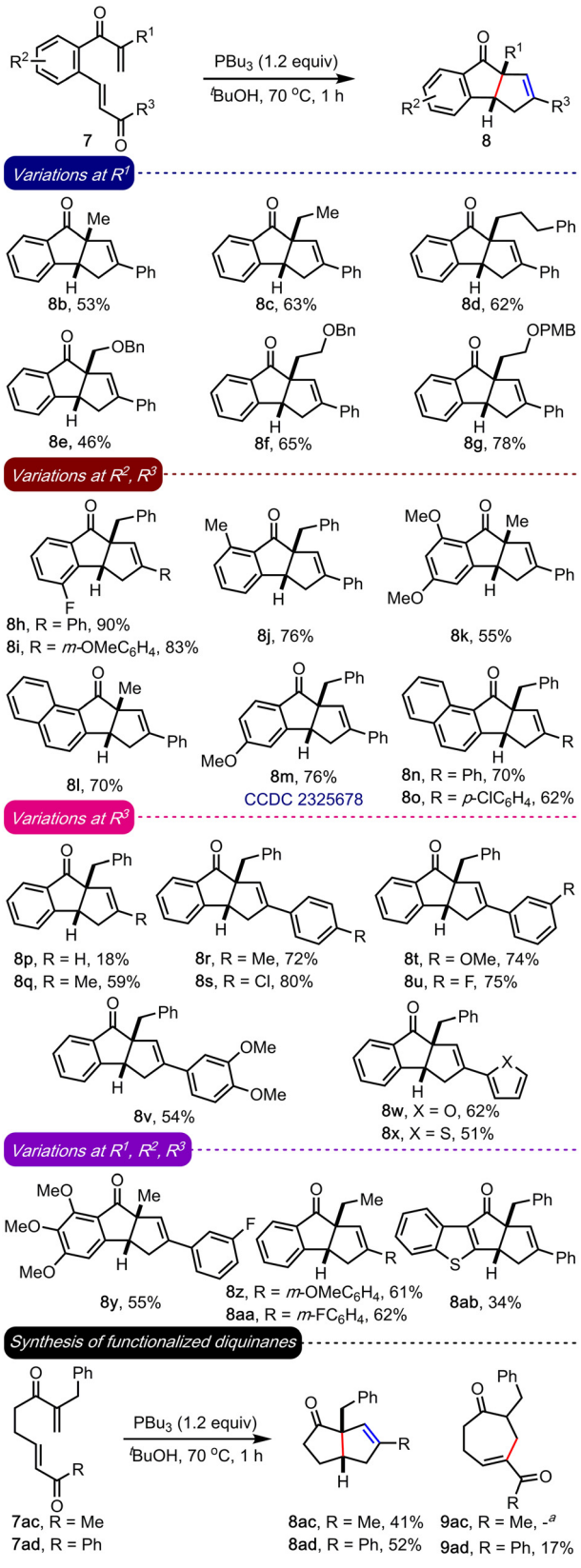
[a] See the ESI† for a detailed procedure. [b] The reactions were performed on a 0.1 mmol scale. [c] Isolated yields after column chromatography.

Encouraged by the result, we evaluated the generality of the method under optimized conditions, Scheme 2. An array of benzannulated diquinanes (**8b–8aa**) and a heteroarene-fused diquinane (**8ab**) were assembled in good yields. The reaction fared well across a wide range of substrates irrespective of the electronic or steric nature of R^1, R^2 or R^3. Different types of alkyl groups can be accommodated at R^1 (**8b–8g**, **8k**, **8l**, **8y**, **8z** and **8aa**), and various kinds of electron-donating (methyl, and mono-, di- and trimethoxy) and marginally electron-withdrawing (fluoro) substituents were well-tolerated at R^2. Apart from the phenyl backbone, substrates with naphthyl (**8l**, **8n** and **8o**) and a benzothiophene backbone (**8ab**) were prepared in moderate to good yields. We could conveniently prepare a diverse range of cyclopenta[*a*]indenes possessing non-aryl (**8p** and **8q**), aryl groups (**8i**, **8o**, **8r–8v**, **8y–8aa**), and heteroaryl substituents (**8w** and **8x**) at R^3. The structure of a representative example (**8m**) was confirmed by the single crystal X-ray diffraction analysis (CCDC 2325678†). The poor yields in case of **8p** and **8ab** are attributed to the partial decomposition of the respective starting compounds leading to unidentifiable products.

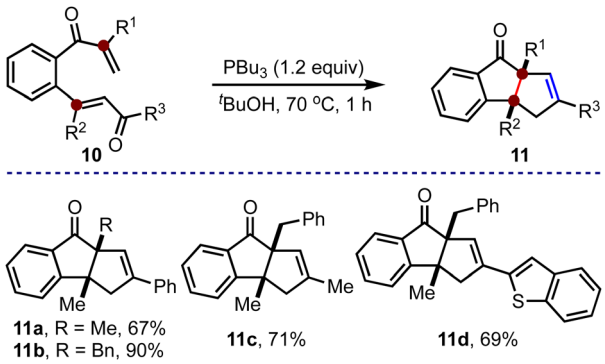
It is worth highlighting that the method can also be extended to synthesizing functionalized diquinanes such as **8ac** and **8ad** in moderate yields, Scheme 2. The intramolecular RC adduct **9ad** was isolated, but **9ac** was not observed. Accessing a fully alkyl-substituted diquinane **8ac** significantly enhances the scope of the work. Further, these structures are amenable to further synthetic manipulations and the prevalence of numerous di- and triquinane-based bioactive natural products make it an attractive strategy.[7]

This method was also extended to synthesizing cyclopenta[*a*]indenes with two contiguous quaternary carbons, Scheme 3. The substituents at R^1 and R^2 in **10** would eventually translate to the quaternary carbons in **11**. Accordingly, the required bis-enones **10** were prepared. By subjecting **10a–10d** to the optimized conditions, we accessed **11a–11d** in good to excellent yields. All the examples accommodated alkyl groups at R^1 and R^2, and aryl (**11a** and **11b**), alkyl (**11c**) and heteroaryl (**11d**) groups at R^3. Notably, a cyclopenta[*a*]indene derivative with all-alkyl substituents (**11c**) at R^1, R^2 and R^3 can also be synthesized.

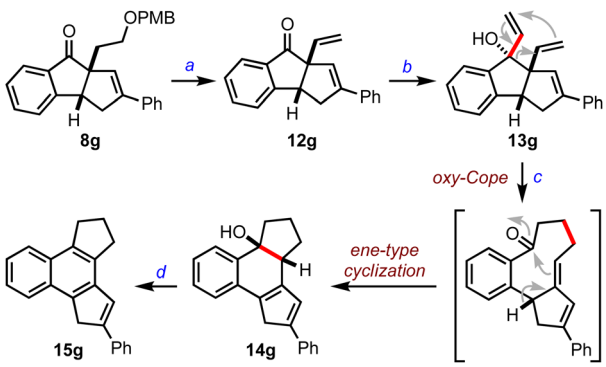
Next, we focused on establishing the synthetic utility of the benzannulated diquinanes accessed herein. We transformed **8g** to **12g** *via* PMB deprotection followed by dehydration of the primary alcohol, Scheme 4. To undertake an oxy-Cope rearrangement, we converted **12g** to the allyl vinyl carbinol **13g** by the addition of the vinyl Grignard reagent, which, upon exposure to potassium hydride, prompted a cascade oxy-Cope rearrangement and intramolecular ene-type cyclization[8] to



Scheme 2 Substrate scope. See the ESI† for a detailed procedure. The reactions were performed on 0.1–0.2 mmol scale and the yields reported are after isolation by column chromatography [a]Not detected.



Scheme 3 Synthesis of cyclopenta[*a*]indenes with two contiguous quaternary carbons.

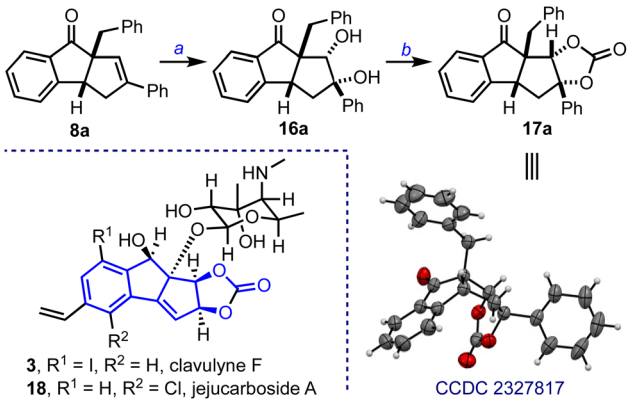


Scheme 4 Elaboration of **8g** to **15g** *via* oxy-Cope and an ene-type cyclization sequence. Reagents and conditions: (a) (i) DDQ (1.5 equiv.), DCM : water (9 : 1), RT, 2 h. (ii) 2-Nitrophenyl selenocyanate (3 equiv.), PBu_3 (3 equiv.), anh. THF, RT, 4 h, then H_2O_2, 2 h, 65% (over two steps). (b) CH_2=CHMgBr (3 equiv.), anh. THF, 0 °C, 2 h, 95%. (c) KH (1.2 equiv.), 18-C-6 (1.1 equiv.), anh. THF, 0 °C-RT, 30 min, 54%. (d) *p*-TSA (0.1 equiv.), toluene, RT, 5 h, 72%.

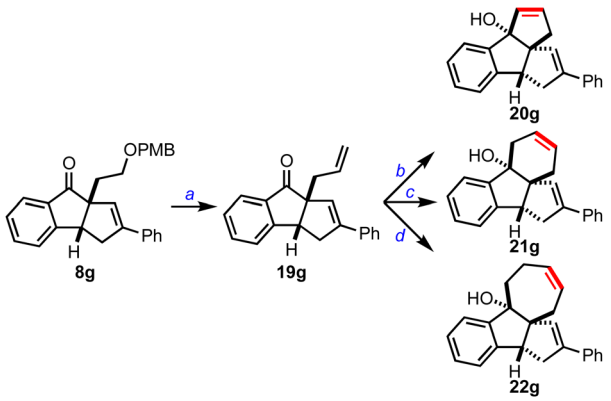
generate an unexpected octahydrobenzo[*e*]-*as*-indacene **14g** in 54% yield. Further, **14g** was converted to the tetrahydrobenzo [*e*]-*as*-indacene **15g** under acidic conditions. Indacenes such as **15** can exhibit interesting medicinal and photophysical properties.[9]

The cyclopenta[*a*]indenes were also extended to synthesizing natural product-like polycyclic cyclopentanoids. For example, the benzo-fused diquinane **8a** was converted to the diol **16a** under OsO_4-catalyzed dihydroxylation conditions, Scheme 5. Transforming the diol **16a** to the cyclic carbonate **17a** represents the construction of the tetracyclic framework of clavulyne[1c] and jejucarboside family of natural products.[10]

We also planned to extend cyclopenta[*a*]indenes **8** to other polycyclic structures, Scheme 6. Accordingly, we converted **8a** to **19g** *via* PMB deprotection, IBX oxidation of the primary alcohol, and a methylene Wittig reaction of the resulting aldehyde. Next, **19g** was treated with the vinyl Grignard reagent to achieve the respective allyl vinyl carbinol, which was subjected to ring-closing metathesis reaction using the Grubbs' 2nd generation catalyst and isolated the dicyclopenta[*a*,*b*]indene **20g**.



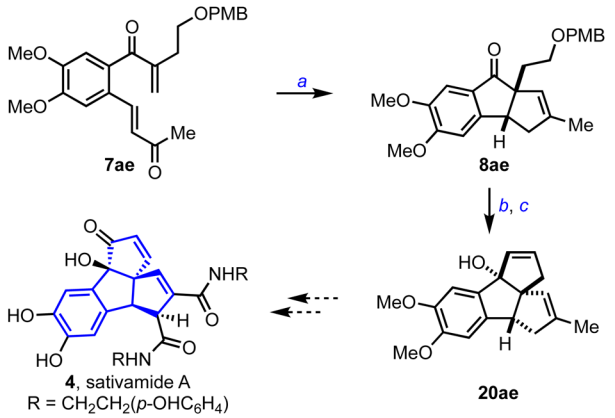
Scheme 5 Elaboration of **8a** to the tetracyclic framework of clavulyne and jejucarboside family of natural products. Reagents and conditions: (a) OsO_4 (10 mol%), NMO (2.5 equiv.), THF : water (5 : 1), RT, 24 h, 90%. (b) CDI (2 equiv.), Et_3N (2 equiv.), dry DCM, RT, 6 h, 86%.



Scheme 6 Elaboration of **8g** to various tetracyclic structures. Reagents and conditions: (a) (i) DDQ (1.5 equiv.), DCM : water (9 : 1), RT, 2 h, 79%. (ii) IBX (1.2 equiv.), DMSO, RT, 1 h, 81%. (iii) $CH_2{=}PPh_3$ (1.5 equiv.), anh. THF, 0 °C, 2 h, 89%. (b) (i) $CH_2{=}CHMgBr$ (3 equiv.), anh. THF, 0 °C, 2 h. (ii) Grubbs' 2nd generation catalyst (G-II, 5 mol%), dry DCM, reflux, 1 h, 88% (over two steps). (c) (i) $CH_2{=}CHCH_2MgCl$ (3 equiv.), anh. THF, 0 °C, 2 h, dr = 5 : 1. (ii) G-II (5 mol%), dry DCM, reflux, 1 h, 85% (over two steps), dr = 5 : 1. (d) (i) $CH_2{=}CHCH_2CH_2MgBr$ (3 equiv.), anh. THF, 0 °C, 2 h. (ii) G-II (5 mol%), dry DCM, reflux, 1 h, 82% (over two steps).

Similarly, we accessed cyclopenta[*k*]fluorene **21g** and benzo[*a*]cyclopenta[*c*]azulene **22g**, which are part structures of several pharmaceutically relevant molecules and materials.[1d,11]

Sativamide A **4** possesses a unique 6-5-5-5 tetracyclic rearranged nor-lignan carbon skeleton and exhibits potential neuroprotective activity on several cell models, Scheme 7.[1d] To assemble the core structure of **4**, we prepared the bis-enone **7ae**, subjected it to the optimized conditions described in Scheme 3, and obtained the respective cyclopenta[*a*]indene **8ae** in 46% yield. Then, we transformed **8ae** to **20ae** in five steps following the synthetic protocol described for **20g**. With the presence of 6-5-5-5 core and the required functionalities in place, **20ae** represents an advanced precursor for synthesizing sativamides.



Scheme 7 Synthesis of an advanced intermediate **20ae** to synthesize sativamide A. Reagents and conditions: (a) PBu_3 (1.2 equiv.), ^tBuOH, 70 °C, 1 h, 46%. (b) (i) DDQ (1.5 equiv.), DCM : water (9 : 1), RT, 2 h. (ii) IBX (1.2 equiv.), DMSO, RT, 1 h. (iii) $CH_2{=}PPh_3$ (1.5 equiv.), anh. THF, 0 °C, 2 h, 55% over three steps. (c) (i) $CH_2{=}CHMgBr$ (3 equiv.), anh. THF, 0 °C, 2 h. (ii) Grubbs' 2nd generation catalyst (G-II, 5 mol%), dry DCM, reflux, 1 h, 81% over two steps.

In summary, we developed a phosphine-promoted Rauhut–Currier/Wittig reaction cascade[12] to assemble diquinanes and a wide range of arene- and heteroarene-fused diquinanes. The scope and generality of the method were quite broad. The utility of the concept was thoroughly exemplified by synthesizing several complex cyclopentanoids and various advanced intermediates for natural product synthesis and materials chemistry. A few other merits of this strategy are (i) neutral and metal-free conditions, (ii) easily accessible starting compounds, and (iii) the occurrence of numerous bioactive molecules with the kind of molecular architectures accessed herein. We are applying this method to synthesize complex bioactive natural products, and the results will be communicated in due course.

Conflicts of interest

The authors declare no competing financial interest.

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