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A HMPA−H₂O mediated oxygenative carbocyclization of 2-alkynylphenyl-substituted *p*-quinone methides to indenones†

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Herein, we report a transition-metal and base-free protocol to access a wide range of functionalized indenone derivatives through a HMPA–H₂O-mediated oxygenative annulation of 2-alkynylphenyl-substituted *p*-quinone methides. This method worked effectively for most of the *p*-QMs investigated and the corresponding indenone derivatives were obtained in moderate to good yields. This methodology was further extended to the formal synthesis of one of the resveratrol based natural products, (±)-isopaucifloral F.

Introduction

Indenone is considered a privileged core that is an integral part of many natural products and also serves as an important structural motif in pharmaceutical chemistry and materials science.[1] Besides, indenone derivatives also serve as synthons/intermediates in the preparation of many important organic compounds including drug candidates.[2] Fig. 1 shows some indenone derivatives that show potential biological activities such as antitumor,[3] COX-2 inhibition,[4] and estrogen binding[5] activities.

The traditional method for indenone synthesis relies on intramolecular Friedel–Crafts type cyclization that often suffers from the need for harsh reaction conditions and a limited substrate scope.[6] Besides, some radical and other synthetic approaches have also been developed to produce indenone derivatives.[7] In recent years, transition metal catalysis has gained much attention in organic transformations and, to this end, many transition metal based protocols have also been documented in the literature for the synthesis of indenones,[8] which include catalytic annulations of alkynes with

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ortho-functionalized aromatic aldehydes, esters or nitriles (**a** & **b**, Scheme 1).[8b,c] However, the use of expensive transition metal catalysts such as Pd and Rh limits their synthetic utility. Recently, Yao and co-workers reported a transition metal free tandem annulation of 2-alkynylbenzaldehydes with phenols for the synthesis of 2,3-diarylindenones (**c**, Scheme 1).[9] However, their protocol is effective only for electron-poor aryl-substituted 2-alkynyl benzaldehydes. Moreover, both the regioisomers were formed in their method; of course, one would be the major product depending on the reaction conditions (**c**, Scheme 1). Considering the importance of indenone scaffolds in various fields, the development of more efficient and practical metal-free protocols to access these indenone derivatives are highly desirable.

In recent years, the synthetic utilities of *p*-quinone methides (*p*-QMs) have been widely explored.[10] Our group was also involved in the synthesis of various triarylmethanes,[11] carbocycles[12] and heterocycles[13] using *p*-QMs as synthons. Herein, we report a transition-metal and base-free HMPA-mediated oxygenative carbocyclization of 2-alkynylated *p*-QMs[14] to access substituted indenones (**d**, Scheme 1). In this
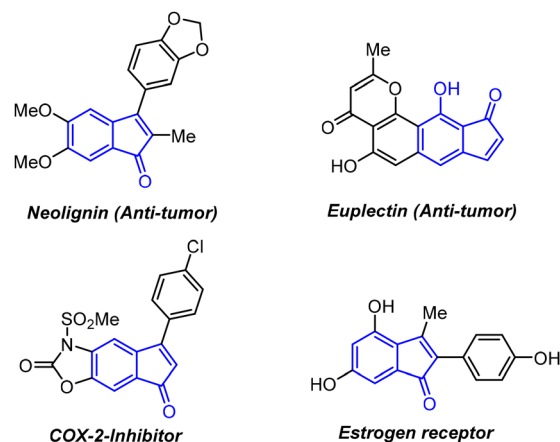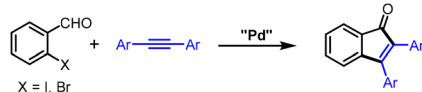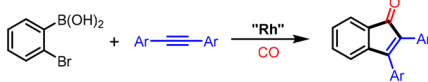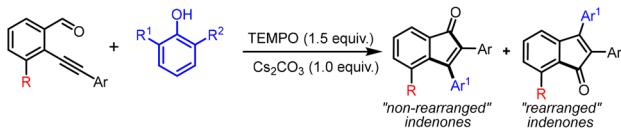

Fig. 1 Indenone-based bio-active molecules.

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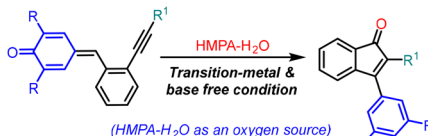
Scheme 1 Selected reported protocols and our hypothesis.

context, it should be noted that although HMPA has been utilized as an additive in many organic transformations[15] including in SmI$_2$ chemistry,[16] only a handful of reports are available in the literature on HMPA-mediated organic transformations, which include regioselective additions of organolithium reagents to enones and enals, conjugate additions of (phenylthio/phenylseleno)allyllithium reagents to cyclopentenones, retro-aldol reactions, arylations of indenes, etc.[17]

Results and discussion

To find out the best reaction conditions, the 2-alkynylphenyl-substituted p-QM **1a** was chosen as the model substrate, and it was subjected to the cyclization reaction under different conditions (Table 1). Initially, we decided to use Au-based catalysts, as they are well known for activating the alkynes, and DMSO as the oxygenating source. However, the cyclization of **1a** with AuCl in DMSO did not yield the expected product **2a** even after 24 hours at room temperature (entry 1). Interestingly, when the reaction temperature was increased to 100 °C, the starting material **1a** was completely consumed (as observed by TLC) after 24 h, and product **2a** was isolated in 60% yield (entry 2). The structure of **2a** was unambiguously confirmed by NMR and X-ray analysis (CCDC 2307508†). Upon changing the catalyst from gold(I) chloride to AuCl$_3$, a slight decrease in the yield of **2a** was observed (entry 3). Later, a couple of other gold-based catalysts such as (PPh$_3$)AuCl and PPh$_3$AuNTf$_2$ were examined (entries 4 & 5), and in these cases, only trace amounts of **2a** was observed. In addition, one reaction was conducted using a combination of gold and silver catalysts (entry 6); however, unfortunately, in that case too, only a

Table 1 Optimization study[a]

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Entry	Catalyst (10 mol%)	Solvent	Temp. [°C]	Time [h]	Yield of **2a**[b] [%]
1	AuCl	DMSO	RT	24	0
2	AuCl	DMSO	100	24	60
3	AuCl$_3$	DMSO	100	12	40
4	(PPh$_3$)AuCl	DMSO	100	24	Trace
5	PPh$_3$AuNTf$_2$	DMSO	100	24	Trace
6	AuCl (5 mol%) AgOTf (5 mol%)	DMSO	100	24	Trace
7[c]	AuCl	HMPA	100	8	53
8[c]	—	HMPA	100	24	60
9[c]	—	HMPA	140	8	78
10	—	DMSO	130	48	0
11[d]	—	HMPA	140	24	0
12	—	H$_2$O	150	24	0
13	—	HMPA : H$_2$O (3 : 1)	140	24	30
14	—	NMP	130	24	10
15[c,e]	—	HMPA	140	8	75

[a] Reaction conditions: reactions were carried out with 0.10 mmol of **1a**. [b] Yields reported are isolated yields. [c] Non-anhydrous and commercially available HMPA with 98.5% purity (remaining 1.5% was water) was used as solvent. [d] Dry HMPA was used as solvent. [e] Reaction was carried out under a N$_2$ atmosphere. (HMPA = hexamethylphosphoramide; NMP = N-methylpyrrolidone).

trace amount of product formation was seen. When the reaction was performed using AuCl in commercially available HMPA (98.5% HMPA + 1.5% water) as a solvent, **2a** was obtained in 53% yield in 8 hours (entry 7). Excited by this result, further optimization experiments were conducted in HMPA. To our surprise, the reaction of **1a** in HMPA at 100 °C without any Au-catalyst also yielded the same product **2a** in 60% yield (entry 8). We found this result very interesting as the reaction worked without any external oxygenating source and it hinted that HMPA is probably promoting the reaction and also acting as an oxygenating agent. Since HMPA has not been utilized as a promoter for any cyclization reactions, including the cyclization of **1a** to **2a**, we became interested in investigating this transformation in detail. We found that reaction temperature plays an important role in the cyclization of **1a**. For example, increasing the temperature to 140 °C significantly improved the yield of **2a** to 78% (entry 9). Another experiment was conducted in DMSO at 130 °C without the Au-catalyst and, in that case, **2a** was not detected at all (entry 10). Interestingly, no product formation was observed when the reaction was conducted either in dry HMPA (entry 11) or in H$_2$O (entry 12) under reflux conditions. However, when a 3 : 1 mixture of dry HMPA and water was used as a solvent, **2a** was obtained in 30% yield (entry 13). Another experiment was also conducted

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using the commercially available *N*-methylpyrrolidone (NMP); however, the desired product **2a** was formed only in 10% yield (entry 14). To exclude the effect of atmospheric oxygen on the outcome of the reaction, a reaction was conducted under inert conditions (entry 15) and in that case also, the product was obtained in 75% yield, clearly indicating that atmospheric oxygen is not playing any role in this transformation.
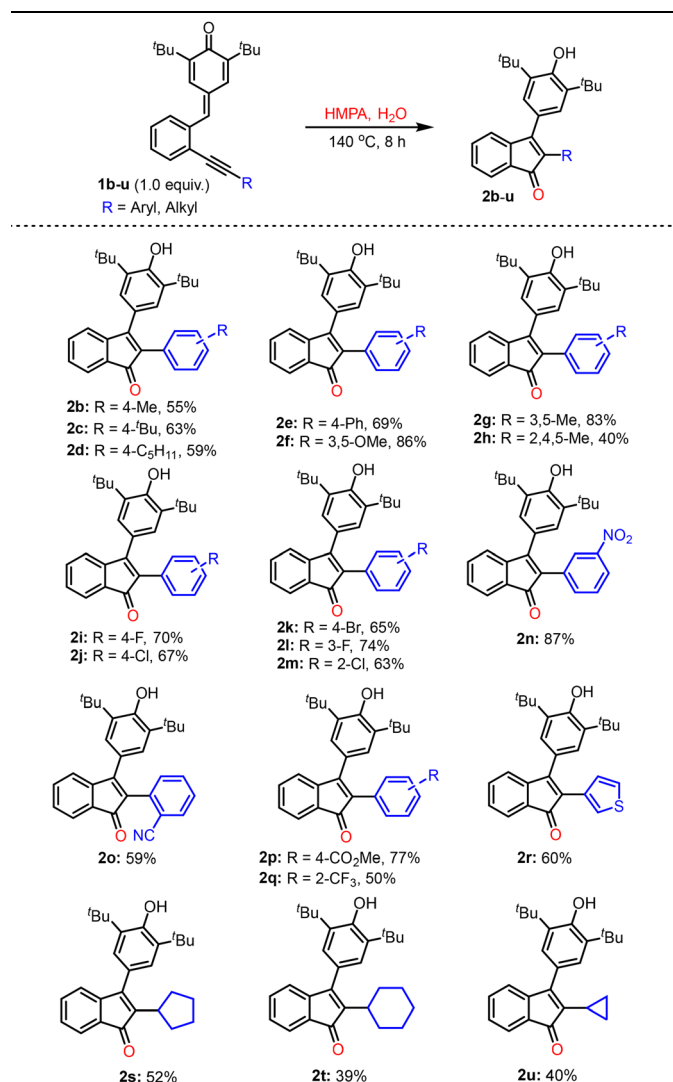
Next, the optimal reaction conditions (entry 9, Table 1) were employed to investigate the scope and limitations of this transformation (Table 2). The *para*-quinone methides (*p*-QMs) **1b–h**, where the alkyne was substituted with electron-rich arenes, produced the desired products **2b–h** in 40–86% yields. The halo-aryl alkyne-substituted *p*-QMs, **1i–m**, also reacted smoothly and afforded the desired products **2i–m** in 63–74% yields. In addition, the *p*-QMs **1n–q**, substituted with electron-withdrawing groups, also underwent cyclization under the optimal conditions and provided the corresponding products

2n–q in the range of 50–87% yields. The 3-thienyl alkyne-substituted precursor **1r** afforded the desired product **2r** in 60% yield. The reaction also worked well with *p*-QMs **1s–u**, having cycloalkyl substituents (such as cyclopropyl, cyclopentyl, and cyclohexyl) on the alkyne, and in these cases, the desired products **2s–u** were isolated in 39–52% yields.

Later, the substrate scope investigation was extended to various substituted *p*-QMs **1v–1aa** and the results are summarized in Table 3. The *p*-QMs **1v–x**, having electron-rich substituents (–Me, –OMe, and 3,5-dimethoxy) on the aryl ring, afforded the corresponding products **3a–c** in yields ranging from 53–61%. The halo-arene-substituted *p*-QMs **1y** and **1z** also reacted under the standard reaction conditions and produced the desired indenones **3d** and **3e** in 35 and 60% yields, respectively. The indenone **3f** was isolated in 54% yield when the corresponding synthon **1aa** was subjected to oxygenative cyclization under standard conditions. The isopropyl containing 2-alkynylphenyl-substituted *p*-QM **1ab** also worked well under the optimized conditions and afforded product **3g** in 80% yield.

To show the feasibility of this methodology, a relatively large-scale reaction of **1a** was carried out under the standard reaction conditions, and in this case, **2a** was obtained in 62% yield (Scheme 2).

To demonstrate the practical applicability of this transformation, we targeted the formal synthesis of one of the resveratrol-derived natural products, isopaucifloral F (**8**),[18] starting from *p*-QM **4**.[12a] Upon treatment with the terminal alkyne **5**, *p*-QM **4** afforded the 2-alkynylphenyl-substituted *p*-QM **6** under Sonogashira conditions (Scheme 3). *p*-QM **6** was then sub-
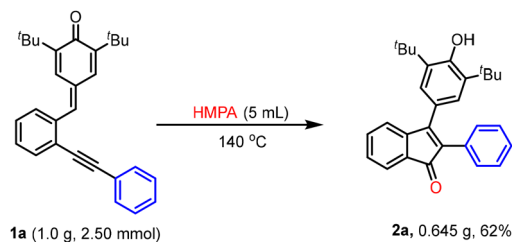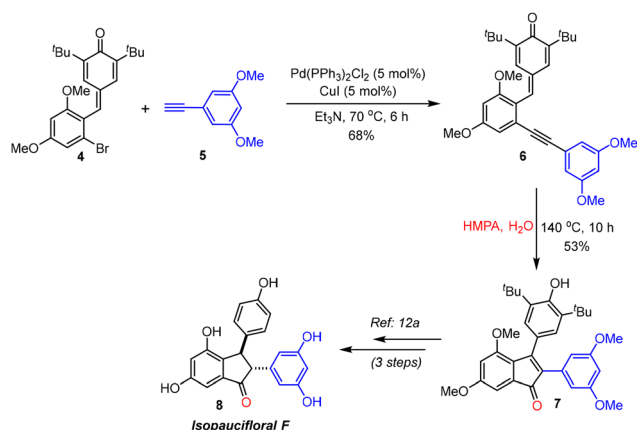
Table 2 Substrate scope[a]

2b: R = 4-Me, 55%
2c: R = 4-*t*Bu, 63%
2d: R = 4-C$_5$H$_{11}$, 59%

2e: R = 4-Ph, 69%
2f: R = 3,5-OMe, 86%

2g: R = 3,5-Me, 83%
2h: R = 2,4,5-Me, 40%

2i: R = 4-F, 70%
2j: R = 4-Cl, 67%

2k: R = 4-Br, 65%
2l: R = 3-F, 74%
2m: R = 2-Cl, 63%

2n: 87%

2o: 59%

2p: R = 4-CO$_2$Me, 77%
2q: R = 2-CF$_3$, 50%

2r: 60%

2s: 52%

2t: 39%

2u: 40%

[a] Reactions were carried out at the 50 mg scale with **1b–u** in 1.0 mL of HMPA. Yields reported are isolated yields.
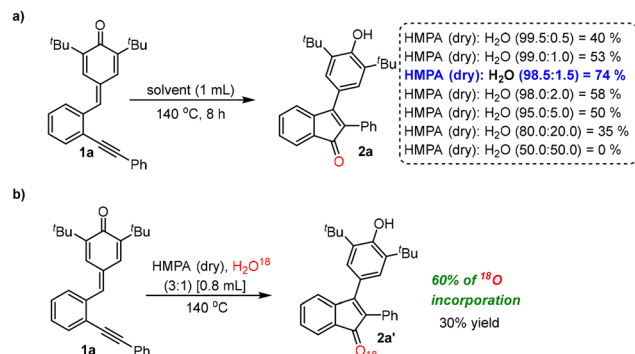
Table 3 Substrate scope[a]

3a: 61%

3b: 53%

3c: 55%

3d: X = F, 35%
3e: X = Cl, 60%

3f: 54%

3g: 80%
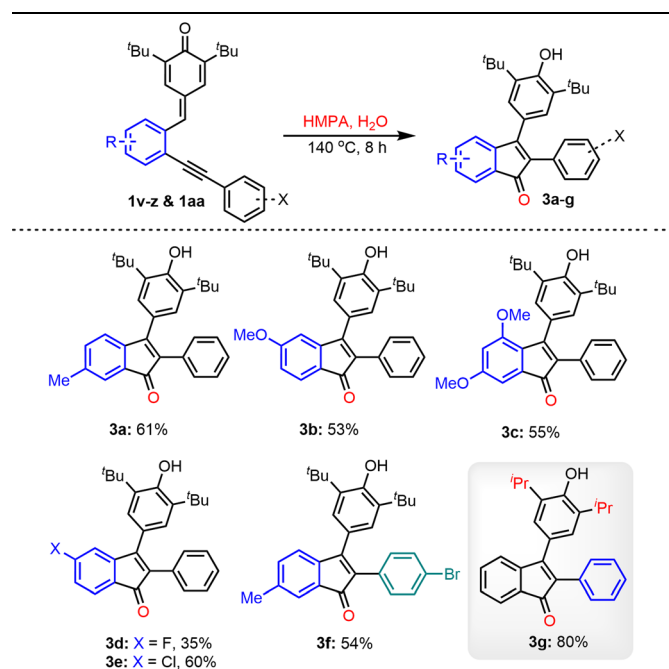
[a] Reactions were carried out at the 50 mg scale with **1v–1aa** in 1.0 mL of HMPA. Yields reported are isolated yields.

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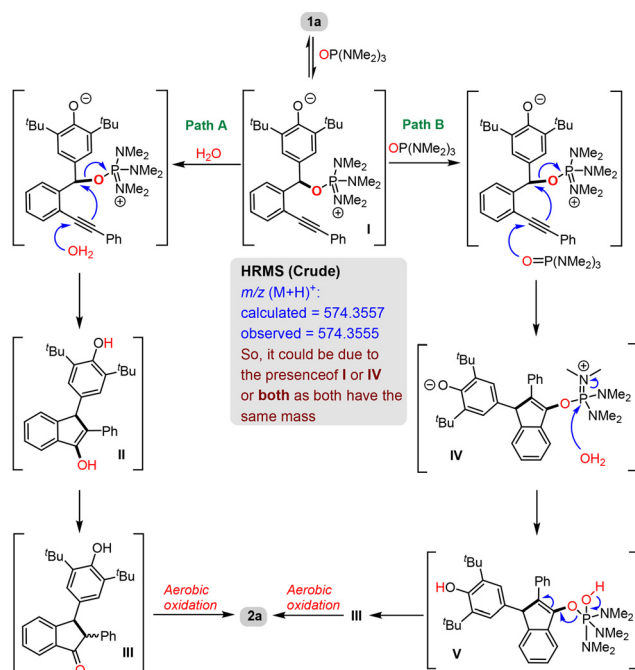
HMPA reacts with **1a** in a 1,6-fashion to generate intermediate **I**. Now, there are two possibilities: (i) the attack of water on the alkyne moiety of **I** followed by cyclization with the expulsion of HMPA would lead to another intermediate **II**, which subsequently undergoes tautomerization (*via* **III**) followed by aerobic oxidation to generate product **2a** (Path A) or (ii) the attack of another molecule of HMPA on the alkyne of **I** followed by intramolecular cyclization would lead to intermediate **IV**, which then reacts with water to generate another intermediate **V**. The expulsion of HMPA from intermediate **V** would lead to **III**, which upon aerobic oxidation produces product **2a** (Path B). The HRMS analysis of the crude reaction mixture indicated the presence of either **I** or **IV** or both during the reaction as a peak was found at m/z $(M + H)^+$ = 574.3555, which corresponds to **I** and/or **IV**. So, based on this observation and the control experiment (Scheme 5), we assume that both the pathways (Paths A & B) are simultaneously operating during the reaction.

Conclusions

In conclusion, we have developed a HMPA–H_2O mediated simple method for the synthesis of functionalized indenone derivatives through the oxygenative carbocyclization of 2-alkynylphenyl-substituted *p*-QMs. Many indenone derivatives could be accessed in moderate to good yields using this protocol. In addition, this transformation was also extended to the formal synthesis of isopaucifloral F. Considering the importance of indenones in medicinal chemistry, we believe that this protocol will definitely find some applications in the synthesis of other indenone-based natural products in the near future.

Data availability

The data supporting this article have been included as part of the ESI.†

Conflicts of interest

There are no conflicts to declare.

Acknowledgements

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