Water-assisted metal-free catalyzed cyclization of 2-alkynylarylketones: a facile approach to indenones†

Shuai Zhang, Xue-Ting Bai, Dan-Yun Chen, Pei Chen, Qian-Qian Zhang and Yan-Bo Wang

A simple and directed synthetic strategy starting from 2-alkynylarylketones was developed for the construction of various indenones under metal-free and water-assisted conditions. This intramolecular cyclization reaction could well tolerate a wide range of functional groups, and the corresponding functionalized indenones were obtained in moderate to excellent yields (up to 94%). In addition, the possible mechanism of this reaction may involve isobenzofuranium intermediates.

Introduction

Indenones, prevalent in natural products and materials science, have drawn a considerable amount of attention (Fig. 1). Because of the importance of indenones, various synthetic methods for substituted indenones have already been reported. The traditional synthesis of functional indenones included multistep intramolecular Friedel–Crafts acylation or use organometallic reagents. The use of transition metal species including Rh, Co, Pd or other metals as a catalyst has been developed by intermolecular or intramolecular cyclization reactions in recent decades. In contrast, metal-free synthetic strategies for constructing indenones have been less elucidated. Methyl trifluoromethanesulfonate (MeOTf)-mediated annulation of arylnitriles or isothiocyanates with aromatic alkynes to synthesize indenones has been demonstrated under mild conditions by Xi and coworkers. An efficient acid catalyzed rearrangement of a tetrahalo-7,7-dimethoxybicycle[2.2.1]heptenyl system leading to indenones was described by Khan et al. Superacid-induced intramolecular cyclization of 1,3-diarylpropynones was described for the synthesis of indenones. An efficient I2-catalyzed access to the synthesis of indenones from 2-alkynylbenzyl alcohols has been studied by Li et al. Benzoyl peroxide (BPO)-promoted radical cyclizations were also reported. Although the above elegant metal-free methods have been made to date, the development of a simple and efficient metal-free synthetic approach to indenones is highly desirable.

2-Alkynylarylketones as an important class of substrates were widely investigated due to their convenient synthesis via the Sonogashira reaction and functionalized transformations to corresponding cyclic compounds. Usually, the intramolecular cyclization of 2-alkynylarylketones infer to two active intermediates isobenzopyrylium I and isobenzofuranium II (Scheme 1). Owing to the aromatization of the heterocyclic ring, isobenzopyrylium ions as stable oxonium cations has been extensively studied in both nucleophilic addition reactions and cycloaddition reactions. However, the reactivity of isobenzofuranium intermediates has been less explored. Based on the above studies, great interest has been aroused to further explore isobenzofuranium intermediates involved in the reaction. Herein, we are the first time to report a simple and effective access to various indenones by water-assisted metal-free catalyzed intramolecular cyclization of 2-alkynylarylketones under mild reaction conditions, and the possible path of this reaction may involve in isobenzofuranium intermediates.

Fig. 1 Representative examples of bioactive and naturally occurring important indenones.
Results and discussion

At the outset of our study, 2-alkynylarylketone 1a was chosen as a model substrate to optimize the reaction conditions and the experimental results are summarized in Table 1. When the intramolecular cyclization of 2-alkynylarylketones 1a using one equivalent amount of CH$_3$COOH or CF$_3$COOH as catalyst and 3 equiv. H$_2$O in CH$_3$CN under 30 °C was attempted, no desired product 2a was obtained (Table 1, entries 1 and 2). Treatment of 1a with $p$-CH$_3$C$_6$H$_4$SO$_3$H, CH$_3$SO$_3$H or CF$_3$SO$_3$H under same conditions afforded product 2a in 18%, 33%, or 40% yields, respectively (Table 1, entries 3–5). To our delight, a simple and typical inorganic acid HCl (4N in 1,4-dioxane) was used as catalyst for the intramolecular cyclization of 1a to give a yield of 85% at 30 °C (Table 1, entry 6). However, using another inorganic acid H$_2$SO$_4$ as catalyst led to a highly decreased yield (Table 1, entry 7). These observations clearly indicate that the properties of the acid play an important role in this transformation. Encouraged by the above results, further condition optimization of reaction solvents was conducted. In high polar solvents such as DMF or DMSO, no product 2a was obtained (Table 1, entries 8 and 9). Other solvents such as 1,4-dioxane, THF and CH$_3$Cl$_2$ afforded the product 2a in 43%, 36% or 44% yield, respectively (Table 1, entries 10–12). A slight decline in the yield of 2a appeared when the loading of HCl was decreased from 1.0 to 0.5 equiv. (Table 1, entry 13). In addition, the loading of H$_2$O was decreased from 3.0 to 1.0 equiv. to give an apparent decline in the yield of 2a (Table 1, entry 14). On the contrary, increasing the loading of H$_2$O from 3.0 to 5.0 equiv. can accelerate the reaction and a satisfying 91% yield of 2a was obtained (Table 1, entry 15). Thus, the optimal reaction conditions were obtained as follows: 0.3 mmol 1a, 1 equiv. HCl, 5 equiv. H$_2$O in 2.0 mL CH$_3$CN at 30 °C.

With the optimized conditions established, various substituted substrates for this intramolecular cyclization promoted by HCl were investigated and the results were shown in Scheme 2. It is clear that the electronic property of substituents on the phenyl ring in the R$^1$ group exerts an obvious influence on the product yield. Substrates 1b–d with electron-withdrawing 4-Cl, 4-F and 4-CF$_3$ groups showed higher reactivity in comparison with substrates 1e–f with electron-donating 4-$\text{E}$Bu and 4-Me groups. The corresponding products 2g, 2h and 2i were obtained in middle yields, when the alkyl-substituted alkylenes 1g, 1h and 1i were as substrates. The cyclization reactions of substrates having 4-F (1j or 1k) substituents on the phenyl ring in the R$^1$ group were efficiently catalyzed to give the corresponding products 2j–k in high yields. In addition, substrate having 3-OH (1l) substituent on the phenyl ring in the R$^1$ group was smoothly transformed into the corresponding product 2l in excellent yield. The steric effect of the R$^2$ group on the reaction was also investigated. The reaction of substrate 1m...
intermediate C by protonation of the oxygen atom of isobenzofuran B. Subsequently, the intermediate D can be obtained via an intramolecular ring-closing reaction of the intermediate C. Finally, after elimination of H$_2$O in the presence of HCl, the product indenone is released together with the regenerated catalyst HCl for finishing a catalyst cycle. Furthermore, ESI-HRMS detection of the reaction mixture using 1a as substrate with 1 h was conducted to capture the information of reaction intermediates. The species of m/z 221.0961 ascribed to the intermediate A ($\text{R}^1 = \text{Ph}$, $\text{R}^2 = \text{H}$, $\text{R}^3 = \text{Me}$; $[\text{MC} + \text{H}]^+$) and the species of m/z 239.1067 ascribed to the intermediates B, C and D ($\text{R}^1 = \text{Ph}$, $\text{R}^2 = \text{H}$, $\text{R}^3 = \text{Me}$; $[\text{MB} + \text{H}]^+$, $[\text{MC} + \text{H}]^+$ and $[\text{MD} + \text{H}]^+$) were observed (see ESI Fig. S1$^\dagger$ for details).

Conclusions

In summary, a simple and efficient HCl mediated water-assisted method to the construction of useful indenones by the intramolecular cyclization reaction of 2-alkynylarylketones is described under mild conditions. Various functional substrates could smoothly apply to this cyclization reaction. The reaction process may be initiated by 5-exo-dig cyclization of the carbonyl group with the alkyne triple bond, leading to isobenzofuranium intermediates.

Experimental

All chemicals and reagents were purchased from commercial suppliers without further purification unless otherwise stated. NMR spectra were recorded with tetramethylsilane as the internal standard. NMR spectra were recorded on a Bruker Avance II 400M type ($^1$H NMR, 400 MHz; $^{13}$C NMR, 100 MHz) spectrometer. High resolution mass spectra (HRMS) were recorded on a Q-Q TOF mass spectrometry (Micromass, Wythenshawe, UK) equipped with Z-spray ionization source. Infrared spectra (IR) was measured using a Nicolet NEXUS FT-IR spectrophotometer. Substrates 2-alkynylarylketones were prepared by Sonogashira coupling reaction of corresponding 2-bromoaacetophenones with alkyne according to the literature.

Representative experimental procedure for the intramolecular cyclization of 2-alkynylarylketones

Taking the intramolecular cyclization of 2-1-(2-(phenylethynyl))phenylketone (1a) as example: A 10 mL vial was charged with 1-(2-(phenylethynyl))phenylketone 1a (66.1 mg, 0.30 mmol) and acetonitrile (2 ml), then H$_2$O (27.0 mg, 1.5 mmol) and 0.30 mmol HCl (4N in 1,4-dioxane) was sequentially added into above solution. The vial was sealed and the reaction mixture was stirred at 30$^\circ$C for 24 h. After cooling to room temperature, the resulting mixture was diluted with ethyl acetate (10 mL) and washed with brine (10 mL). The aqueous phase was extracted with ethyl acetate (2 $\times$ 10 mL). The combined organic layers were dried over anhydrous Na$_2$SO$_4$, filtered and concentrated in vacuo. The crude reaction mixture was purified by column chromatography on silica gel (PE/EtOAc) to give 2a in 91% yield.
3-Methyl-2-phenyl-1H-inden-1-one (2a). This compound was obtained as a brown oil (91% yield), \(^1^H\) NMR (400 MHz, CDCl\(_3\)) \(\delta\) (ppm): 7.46 (d, \(J = 6.8\) Hz, 1H), 7.37–7.44 (m, 5H), 7.30–7.34 (m, 1H), 7.21–7.25 (m, 1H), 7.14 (d, \(J = 7.2\) Hz, 1H), 2.29 (s, 3H); \(^1^C\) NMR (100 MHz, CDCl\(_3\)) \(\delta\) (ppm): 196.51, 154.79, 145.93, 133.70, 133.43, 131.24, 130.44, 124.69, 128.97, 128.36, 127.76, 122.16, 119.53, 12.67; IR (film, \(cm^{-1}\)) 3398, 3056, 2964, 1715, 1600, 1457, 1380, 1262, 1179, 1084, 1028, 916, 854, 804, 797, 699, 660, 597, 514; HRMS (ESI-TOF) calcd for C\(_{16}\)H\(_{12}\)O\(_2\) \([M + H]^+\): 235.1117, found: 235.1116.

2-Cyclopentyl-3-methyl-1H-inden-1-one (2g). This compound was obtained as a yellow solid (44% yield), mp 81.6–82.8; \(^1^H\) NMR (400 MHz, CDCl\(_3\)) \(\delta\) (ppm): 7.29–7.34 (m, 2H), 7.15 (dt, \(J = 7.2, 0.8\) Hz, 1H), 6.99 (d, \(J = 7.2, 1H\)), 2.81–2.90 (m, 1H), 1.22 (s, 3H), 1.76–1.87 (m, 6H), 1.60–1.65 (m, 2H); \(^1^C\) NMR (100 MHz, CDCl\(_3\)) \(\delta\) (ppm): 198.17, 153.26, 146.28, 137.35, 133.30, 131.07, 128.12, 121.41, 118.54, 35.74, 31.74, 26.39, 11.67; IR (film, \(cm^{-1}\)) 3389, 2952, 2868, 1704, 1610, 1455, 1383, 1228, 1150, 1083, 1022, 952, 753, 716, 649, 546; HRMS (ESI-TOF) calcd for C\(_{16}\)H\(_{12}\)F\(_3\)O\(_2\) \([M + H]^+\): 213.1274, found: 213.1273.

2-Butyl-3-methyl-1H-inden-1-one (2h). This compound was obtained as a yellow solid (52% yield), mp 60.2–62.2; \(^1^H\) NMR (400 MHz, CDCl\(_3\)) \(\delta\) (ppm): 7.30–7.36 (m, 2H, 7.15 (dt, \(J = 7.2, 0.8\) Hz, 1H), 7.01 (d, \(J = 7.2, 1H\)), 2.27 (t, \(J = 7.2, 2H\)), 2.11 (s, 3H), 1.28–1.47 (m, 4H), 0.91 (t, \(J = 7.2, 3H\)); \(^1^C\) NMR (100 MHz, CDCl\(_3\)) \(\delta\) (ppm): 198.35, 153.91, 146.46, 135.31, 133.34, 130.96, 128.14, 121.60, 118.63, 31.33, 22.78, 22.57, 14.04, 11.59; IR (film, \(cm^{-1}\)) 3395, 2957, 2930, 2858, 1707, 1609, 1457, 1384, 1287, 1159, 1083, 1016, 937, 756, 715, 632, 526; HRMS (ESI-TOF) calcd for C\(_{16}\)H\(_{12}\)O\(_2\) \([M + H]^+\): 201.1274, found: 201.1264.

3-Methyl-2-phenethyl-1H-inden-1-one (2i). This compound was obtained as a yellow solid (61% yield), mp 63.1–64.9; \(^1^H\) NMR (400 MHz, CDCl\(_3\)) \(\delta\) (ppm): 7.37 (d, \(J = 7.2\) Hz, 1H), 7.28–7.32 (m, 2H), 7.22–7.26 (m, 2H), 7.13–7.18 (m, 4H), 6.94 (d, \(J = 7.2\) Hz, 1H), 2.75 (t, \(J = 7.2\) Hz, 2H), 2.56 (t, \(J = 7.6\) Hz, 2H), 1.79 (s, 3H); \(^1^C\) NMR (100 MHz, CDCl\(_3\)) \(\delta\) (ppm): 198.14, 155.04, 146.19, 141.64, 133.68, 133.38, 130.86, 128.74, 128.42, 128.28, 126.02, 121.62, 118.81, 35.13, 25.19, 11.20; IR (film, \(cm^{-1}\)) 3392, 3061, 3027, 2926, 2856, 1706, 1603, 1455, 1384, 1311, 1316, 1148, 1083, 1030, 957, 861, 754, 706, 632, 564; HRMS (ESI-TOF) calcd for C\(_{16}\)H\(_{12}\)O \([M + H]^+\): 249.1274, found: 249.1274.

5-Fluoro-3-methyl-2-phenyl-1H-inden-1-one (2j). This compound was obtained as a reddish brown solid (72% yield), mp 93.4–95.2; \(^1^H\) NMR (400 MHz, CDCl\(_3\)) \(\delta\) (ppm): 7.43–7.46 (m, 2H), 7.38–7.41 (m, 2H), 7.21 (dd, \(J = 7.2, 2.4\) Hz, 1H), 7.04–7.13 (m, 2H), 2.32 (s, 3H); \(^1^C\) NMR (100 MHz, CDCl\(_3\)) \(\delta\) (ppm): 194.85, 163.81 (d, \(J_{CF} = 248.6\) Hz), 154.96 (d, \(J_{CF} = 2.0\) Hz), 141.37 (d, \(J_{CF} = 3.2\) Hz), 133.94 (d, \(J_{CF} = 4.6\) Hz), 132.93 (d, \(J_{CF} = 7.1\) Hz), 131.02, 129.54, 128.46, 127.93, 120.64 (d, \(J_{CF} = 7.8\) Hz), 118.86 (d, \(J_{CF} = 22.9\) Hz), 110.01 (d, \(J_{CF} = 24.7\) Hz), 12.87; IR (film, \(cm^{-1}\)) 3399, 3095, 3061, 2963, 2925, 2853, 1707, 1447, 1442, 1375, 1311, 1262, 1222, 1098, 1027, 892, 841, 796, 737, 701, 577, 522; HRMS (ESI-TOF) calcd for C\(_{16}\)H\(_{12}\)FO \([M + H]^+\): 239.0867, found: 239.0867.

2-(4-tet-Butylphenyl)-5-fluoro-3-methyl-1H-inden-1-one (2k). This compound was obtained as a reddish brown solid (75% yield), mp 106.1–108.0; \(^1^H\) NMR (400 MHz, CDCl\(_3\)) \(\delta\) (ppm): 7.46 (d, \(J = 8.4\) Hz, 2H), 7.35 (d, \(J = 8.4\) Hz, 2H), 7.20...
Notes and references


