Heterocycles

Deutsche Ausgabe: DOI: 10.1002/ange.201504603
Internationale Ausgabe: DOI: 10.1002/anie.201504603

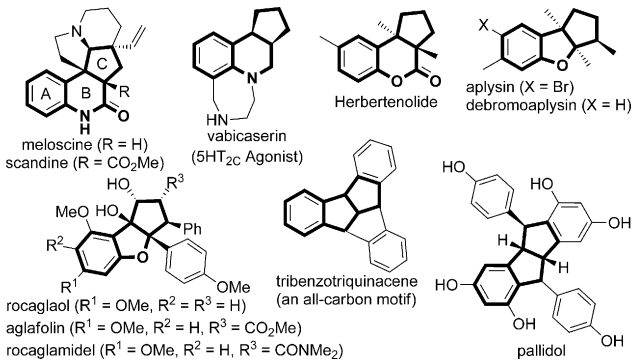
Metal-Free Radical [2+2+1] Carbocyclization of Benzene-Linked 1,*n*-Enynes: Dual C(sp^3)–H Functionalization Adjacent to a Heteroatom**

*Ming Hu, Jian-Hong Fan, Yu Liu, Xuan-Hui Ouyang, Ren-Jie Song, and Jin-Heng Li**

Abstract: *A new metal-free oxidative radical [2+2+1] carbocyclization of benzene-linked 1,n-enynes with two C(sp^3)–H bonds adjacent to the same heteroatom is described. This method achieves two C(sp^3)–H oxidative functionalizations and an annulation, thus providing efficient and general access to a variety of fused five-membered carbocyclic hydrocarbons.*

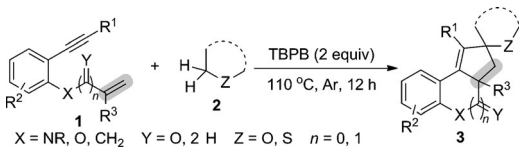
Complex polycyclic hydrocarbons, including carbocyclic compounds containing fused five-membered rings (Scheme 1), are privileged structural elements in chemical biology and material sciences.[1,2] Numerous methods have thus been developed to access these carbocyclic frameworks, but many face limitations associated with the use of unavailable starting materials or require several synthetic steps with low overall yields.[1–3] Therefore, the development of general methods, especially one-pot strategies, of producing these structures from readily available starting materials is strongly desired.

The direct cyclization of 1,*n*-enynes using [2+2+*m*] annulation strategies is one of the most rapid and convenient ways to build diverse fused polycyclic hydrocarbons.[4] Typically, the [2+2+1] carbocyclization of 1,*n*-enynes with a one-carbon unit is an appealing route to the five-membered fused carbocyclic ring systems.[4–6] However, the majority of such transformations focus on the use of CO as a one-carbon unit (the Pauson–Khand-type reaction).[5] C–H oxidative coupling reactions have recently proven to be powerful methods for constructing C–C bonds[6] by oxidative coupling with a C-(sp^3)–H bond in ethers, cycloalkanes, common alkanes, and carbonyl compounds.[7] We reasoned that similar compounds, containing two reactive C(sp^3)–H bonds on the same carbon atom, might be used as a one-carbon unit for 1,*n*-enyne [2+2+1] carbocyclization through a dual C(sp^3)–H functionalization. Herein, we report the first radical [2+2+1] carbocyclization[8] of benzene-linked 1,*n*-enynes ($n = 6, 7$) with two C(sp^3)–H bonds which are adjacent to a heteroatom: The reaction proceeds with *tert*-butyl perbenzoate (TBPB) oxidation under metal-free conditions, thereby providing a general and straightforward means of accessing various fused five-membered carbocyclic hydrocarbons, including cyclopenta[*c*]chromen-4-ones, cyclopenta[*c*]chromenes, cyclopenta[*b*]-benzofuran, and cyclopenta[*a*]indene (Scheme 2). In this transformation, three new C–C bonds and two new rings are constructed in one reaction through a double C(sp^3)–H oxidative functionalization and annulation sequence.



Scheme 1. Examples of compounds containing fused five-membered carbocyclic rings.

Initially, we focused our efforts on optimizing the reaction conditions for the [2+2+1] carbocyclization reaction between *N*-methyl-*N*-(2-(phenylethynyl)phenyl)methacrylamide (**1a**) and 1,4-dioxane (**2a**; Table 1). After a series of trials, treatment of the 1,7-enyne **1a** with **2a** and TBPB at 110 °C for 12 hours afforded the desired cyclopenta[*c*]chromen-4-one **3aa**[9] in the highest yield (entry 1). A number of other oxidants, including *tert*-butyl hydrogenperoxide (TBHP), di-*tert*-butyl peroxide (DTBP), benzoyl peroxide (BPO), dicumylperoxide (DCP), and $PhI(OAc)_2$, were subsequently investigated (entries 2–6), and they were found to be less effective than TBPB (entries 2–5 versus entry 1), and $PhI(OAc)_2$ proved to be an ineffective oxidant for this carbocyclization reaction (entry 6). While a higher amount of TBPB had no effect on the reaction (entry 7), a lower amount of TBPB had a negative effect (entry 8). Screening of the reaction temperatures revealed that using 130 °C afforded **3aa** in the same yield as that using 110 °C (entry 9), but when



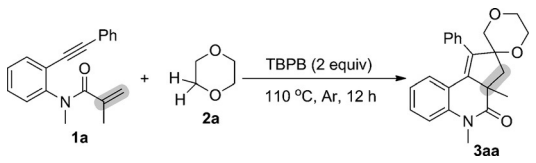
Scheme 2. [2+2+1] carbocyclization through a double C(sp^3)–H oxidative coupling.

[*] M. Hu, J.-H. Fan, Y. Liu, X.-H. Ouyang, Dr. R.-J. Song, Prof. Dr. J.-H. Li
State Key Laboratory of Chemo/Biosensing and Chemometrics, College of Chemistry and Chemical Engineering, Hunan University
Changsha 410082 (China)
E-mail: jhli@hnu.edu.cn
Prof. Dr. J.-H. Li
State Key Laboratory of Applied Organic Chemistry, Lanzhou University, Lanzhou 730000 (China)

[**] We thank the Natural Science Foundation of China (Nos. 21472039 and 21172060) and Hunan Provincial Natural Science Foundation of China (No. 13JJ2018) for financial support.

Supporting information for this article is available on the WWW under http://dx.doi.org/10.1002/anie.201504603.

Table 1: Screening of optimal reaction conditions.[a]

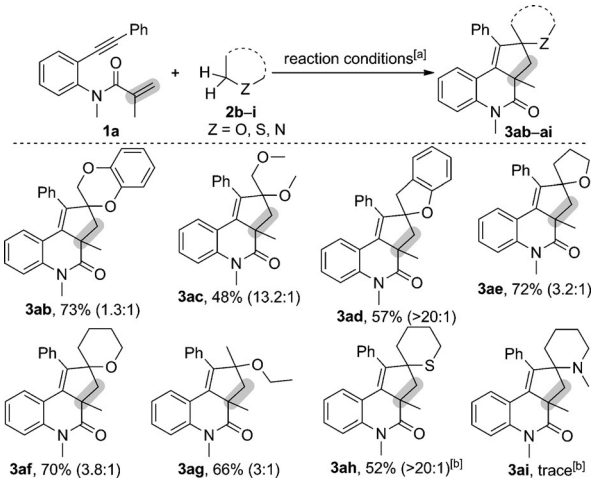


Entry	Variation from the standard reaction conditions	Yield [%][b]
1	none	76
2	TBHP instead of TBPB	53
3	DTBP instead of TBPB	19
4	BPO instead of TBPB	69
5	DCP instead of TBPB	32
6	$PhI(OAc)_2$ instead of TBPB	trace
7	TBPB (3 equiv)	76
8	TBPB (1.5 equiv)	55
9	At 130 °C	74
10	At 100 °C	26
11	**2a** (20 equiv) in benzene (0.5 mL)	76
12[c]	none	71

[a] Reaction conditions: **1a** (0.3 mmol), **2a** (2 mL), TBPB (2 equiv), argon, 110 °C and 12 h. TBHP (5 M in decane). Some by-products, including the vinyl C–N bond-decomposition products, were observed. The d.r. value of the product was 3:1, as determined by ^{1}H NMR spectroscopic analysis of the crude product. [b] Yields of isolated product. [c] **1a** (1 g, 3.64 mmol) and **2a** (6 mL) for 36 h.

the reaction was run at 100 °C the yield was lowered to 26 % (entry 10). Gratifyingly, the reaction could be performed at a loading of 20 equivalents **2a** in benzene (entry 11). A good yield could be achieved for a gram-scale reaction of **1a** (entry 12).

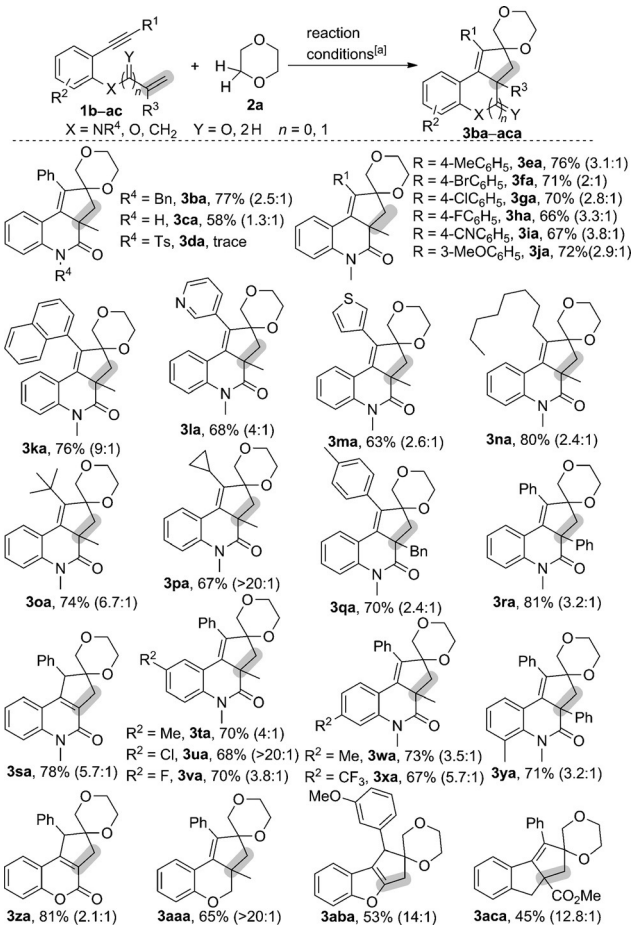
After the optimal reaction conditions were determined, the scope of this [2+2+1] carbocyclization protocol with regard to the two C(sp^3)–H bonds adjacent to a heteroatom (Scheme 3) as well as benzene-linked 1,*n*-enynes (Scheme 4) was exploited. As shown in Scheme 3, a variety of C(sp^3)–H bonds adjacent to an oxygen atom (**2b–g**), a sulfur atom (tetrahydro-2*H*-thiopyran; **2h**), or a nitrogen atom (**2i**) were



Scheme 3. Variation of the C(sp^3)–H bonds adjacent to the heteroatom (**2**). [a] Reaction conditions: **1a** (0.3 mmol), **2** (2 mL), TBPB (2 equiv), argon, 110 °C, and 12 h. The d.r. value is given within parentheses and was determined by ^{1}H NMR spectroscopic analysis of the crude product. [b] At 130 °C for 24 h.

first investigated in the presence of **1a** and TBPB. The optimal reaction conditions were compatible with a wide range of ethers (**2b–g**), thus providing **3ab–ag** in moderate to good yields. For example, 2,3-dihydrobenzo[*b*][1,4]dioxine (**2b**) or 2,3-dihydrobenzofuran (**2d**) were successfully converted into **3ab** (73 %) and **3ad** (57 %), respectively. The acyclic ethers **2c** and **2g** also reacted to give **3ac** and **3ag**[9], respectively, in moderate yields. When using tetrahydrofuran (**2e**) or tetrahydro-2*H*-pyran (**2f**), the reaction afforded high yields of the corresponding **3ae** and **3af**. Gratifyingly, tetrahydro-2*H*-thiopyran (**2h**) reacted with **1a** and TBPB, thus resulting in **3ah** in 52 % yield. Unfortunately, the attempt to cyclize the amine **2i** failed to form **3ai**.

We next set out to investigate the scope of the benzene-linked 1,*n*-enynes (**1**) in reactions with **2a** and TBPB (Scheme 4). The [2+2+1] carbocyclization protocol was applicable to various benzene-linked 1,*n*-enynes, namely aniline-linked 1,7-enynes (**1b–y**), phenol-linked 1,7-enynes (**1z–aa**), the phenol-linked 1,6-enyne **1ab**, and benzene-linked 1,6-enyne **1ac**. First, substitution effects were examined by using the substrates **1b–y**. The 1,7-enynes **1b** and **1c**, having a N-Bn group or a free N-H group, respectively, reacted with **2a** and TBPB to deliver the corresponding products **3ba** and **3ca** in good yields. However, the 1,7-enyne

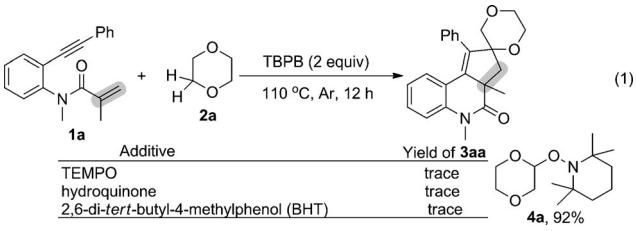


Scheme 4. [2+2+1] Carbocyclization of the 1,*n*-enynes (**1**) with **2a**. [a] See Table 1 and Scheme 3. The d.r. value is given within parentheses and was determined by ^{1}H NMR spectroscopic analysis of the crude product. Ts = 4-toluenesulfonyl.

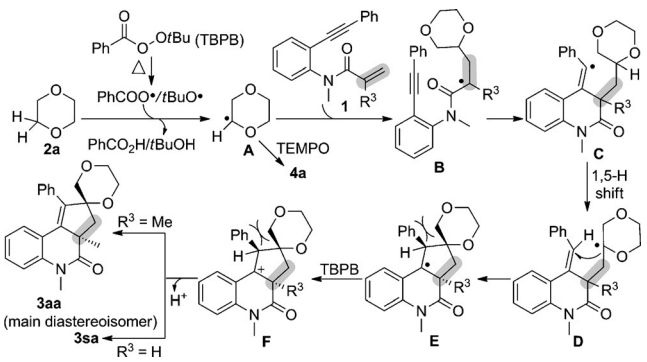
1d, which has an N-Ts group, was unreactive and resulted in no formation of **3da**. These results demonstrated that both aryl and alkyl groups at the alkyne terminus were tolerated under the optimal reaction conditions (**3ea–pa**). It was noted that the electron-rich aryl groups led to a higher reactivity (**3ea** and **3ja**) than the electron-deficient aryl groups (**3fa–ia**). Because the naphthalen-1-yl-, pyridin-3-yl-, and thiophen-3-yl-containing alkynes **1k–m** showed good reactivity, the products **3ka–ma** were obtained in 63–76% yields. When using the aliphatic alkynes **1n–p**, even with a bulky *tert*-butyl or a cyclopropyl group, the reaction still achieved high yields (**3na–pa**). Screening revealed that the 1,7-enynes **1q** and **1r**, having a Bn group and a Ph group, respectively, at the 2-position of the acrylamide moiety were smoothly converted into the corresponding **3qa** and **3ra** in good yields. For the 1,7-enyne **1s**, which has a 2-monosubstituted acrylamide moiety, the chemoselectivity was shifted toward the formation of the spiro[cyclopenta[*c*]quinoline-2,2′-[1,4]dioxan]-4(1*H*)-one **3sa** rather than spiro[cyclopenta[*c*]quinoline-2,2′-[1,4]dioxan]-4-(5*H*)-one. Several substituents, namely Me, Cl, F, and CF_3, on the aromatic ring of the aniline moiety were well-tolerated (**3ta–ya**), and steric bulk has no effect on this reaction (**3ta**, **3wa**,[9] and **3ya**). In the case of the phenol-linked 1,*n*-enynes **1z–ab**, three oxygen-containing polycyclic hydrocarbons, namely the cyclopenta[*c*]chromen-4-one **3za**, cyclopenta[*c*]-chromene **3aaa**, and cyclopenta[*b*]benzofuran **3aba**, were constructed in 53–81% yields. Interestingly, the important cyclopenta[*a*]indene skelecton (**3aca**) could be formed using the benzene-linked 1,6-enyne **1ac**.

Control experiments [Eq (1); TEMPO = 2,2,6,6-tetramethylpiperidin-1-yl)oxyl] showed that the reaction of **1a** with **2a** and TBPB was completely suppressed when a stoichiometric amount of radical inhibitors, including TEMPO, hydroquinone, and BHT, were added. Notably, the product **4a** was formed from **2a** and TEMPO. These results suggest that this [2+2+1] carbocyclization is initiated by the formation of alkyl radicals from ethers **2**.

The mechanism for this [2+2+1] carbocyclization reaction was proposed on the basis of the present results and previous reports (Scheme 5).[6–8,10] Initially, the C(sp^3)–H



bond adjacent to the oxygen atom in **2a** is broken to deliver the alkyl radical **A** by TBPB under heating (supported by the formation of **4a**).[7,8] Subsequently, the addition of **A** across a C–C double bond in the enyne **1** produces the radical intermediate **B**, followed by cyclization with a C–C triple bond to afford the vinyl radical intermediate **C**. The intermediate **C** the undergoes a 1,5-H shift, followed by a radical cyclization with the C–C double bond, mainly through a backside attack of the C(sp^2)–Ph bond to selectively form the radical intermediate **E**.[10] The intermediate **E**



Scheme 5. Possible reaction mechanism.

then reacts with TBPB, thus leading to the cation intermediate **F**.[7,8] Finally, loss of a proton from **F** affords the product **3aa**.

In summary, we have developed a metal-free radical [2+2+1] carbocyclization reaction of benzene-linked 1,*n*-enynes with two C(sp^3)–H bonds adjacent to a heteroatom. THE process involves a dual C(sp^3)–H oxidative functionalization and annulation sequence. Diverse fused five-membered carbocyclic hydrocarbons were assembled in a straightforward manner. This method represents the first example of the oxidative functionalization of two C(sp^3)–H bonds adjacent to a heteroatom by a metal-free radical process. Furthermore, this reaction exhibits a broad substrate scope and excellent functional-group tolerance. Further studies of the enantioselective aspects and applications of 1,*n*-enyne oxidative radical cyclizations are currently underway in our laboratory.

Keywords: carbocycles · enynes · heterocycles · peroxides · radicals

How to cite: *Angew. Chem. Int. Ed.* **2015**, *54*, 9577–9580
Angew. Chem. **2015**, *127*, 9713–9716

[1] a) R. G. Harvey, *Polycyclic Aromatic Hydrocarbons*, Wiley-VCH, Weinheim, **1997**; b) *Carbon-Rich Compounds* (Eds.: M. M. Haley, R. R. Tykwinski), Wiley-VCH, Weinheim, **2006**; c) M. Inoue, *Chem. Rev.* **2005**, *105*, 4379; d) M. Randić, *Chem. Rev.* **2003**, *103*, 3449; e) T. Nakata, *Chem. Rev.* **2005**, *105*, 4314; f) M. Malacria, *Chem. Rev.* **1996**, *96*, 289; g) K. U. Wendt, *Angew. Chem. Int. Ed.* **2005**, *44*, 3966; *Angew. Chem.* **2005**, *117*, 4032.

[2] a) M. A. Lago, J. I. Luengo, C. E. Peishoff, J. D. Elliot, in *Annual Reports in Medicinal Chemistry*, *Vol. 31* (Ed.: J. A. Bristol), Academic Press, San Diego, **1996**, p. 81; Meloscine and scandine: b) K. Bernauer, G. Englert, W. Vetter, E. Weiss, *Helv. Chim. Acta* **1969**, *52*, 1886; c) J. R. Cannon, K. D. Croft, Y. Matsuki, V. A. Patrick, R. F. Toia, A. H. White, *Aust. J. Chem.* **1982**, *35*, 1655; d) J. E. Saxton, in *The Alkaloids*, *Vol. 51* (Ed.: G. A. Cordell), Academic Press, New York, **1998**, p. 1; e) L. F. Szabó, *ARKIVOC (Gainesville, FL, U.S.)* **2007**, *7*, 280; Vabicaserin: f) R. Neelamegam, T. Hellenbrand, F. A. Schroeder, C. Wang, J. M. Hooker, *J. Med. Chem.* **2014**, *57*, 1488; Herbertenolide: g) A. Matsuo, S. Yuki, M. Nakayama, *Chem. Lett.* **1983**, *7*, 1041; h) A. Matsuo, S. Yuki, M. Nakayama, *J. Chem. Soc. Perkin Trans. 1* **1986**, *4*, 701; i) D. Ng, Z. Yang, M. A. Garcia-Garibay, *Org. Lett.* **2004**, *6*, 645; Aplysin and debromoaplysin: j) R. Robinson, *Bull. Soc. Chim. Fr.* **1958**, 125; k) J. C. Craig, A. R. Naik, R.

Pratt, E. Johnson, *J. Org. Chem.* **1965**, *30*, 1573; Rocagaol analogous: l) M. L. King, C.-C. Chiang, H.-C. Ling, E. Fujita, M. Ochiai, A. T. McPhail, *J. Chem. Soc. Chem. Commun.* **1982**, 1150; m) F.-N. Ko, T.-S. Wu, M.-J. Liou, T.-F. Huang, C.-M. Teng, *Eur. J. Pharmacol.* **1992**, *218*, 129; n) F. Ishibashi, C. Satasook, M. B. Isman, G. H. N. Towers, *Phytochemistry* **1993**, *32*, 307; o) J. Hiort, J. H. Chaidir, F. I. Bohnenstengel, B. W. Nugroho, C. Schnieder, V. Wray, L. Witte, P. D. Hung, L. C. Keit, P. Proksch, *J. Nat. Prod.* **1999**, *62*, 1632; a review: p) P. Proksch, R. Edrada, R. Ebel, F. I. Bohnenstengel, B. W. Nugroho, *Curr. Org. Chem.* **2001**, *5*, 923; Pallidole: q) S. A. Adesanya, R. Nia, M.-T. Martin, N. Boukamcha, A. Montagnac, M. Païs, *J. Nat. Prod.* **1999**, *62*, 1694; r) M. A. Khan, S. G. Nabi, S. Prakash, A. Zaman, *Phytochemistry* **1986**, *25*, 1945; s) S. A. Snyder in *Biomimetic Organic Synthesis* (Eds.: E. Poupon, B. Nay), Wiley-VCH, Weinheim, **2011**, pp. 695; Tribenzotriquinacene: t) D. Kuck, *Chem. Rev.* **2006**, *106*, 4885; u) D. Kuck, *Pure Appl. Chem.* **2006**, *78*, 749.

[3] For selected reviews, see: a) J.-C. Wasilke, S. J. Obrey, R. T. Baker, G. C. Bazan, *Chem. Rev.* **2005**, *105*, 1001; b) S. E. Denmark, A. Thorarensen, *Chem. Rev.* **1996**, *96*, 137; c) G. Mehta, A. Srikrishna, *Chem. Rev.* **1997**, *97*, 671; d) H.-C. Guo, J.-A. Ma, *Angew. Chem. Int. Ed.* **2006**, *45*, 354; *Angew. Chem.* **2006**, *118*, 362; e) T. Bach, J. Hehn, *Angew. Chem. Int. Ed.* **2011**, *50*, 1000; *Angew. Chem.* **2011**, *123*, 1032; f) *The Chemistry of Heterocyclic Compounds: Synthetic Applications of 1,3-Dipolar Cycloaddition Chemistry Toward Heterocycles and Natural Products* (Eds.: A. Padwa, W. H. Pearson), Wiley-Interscience, New York, **2002**.

[4] For selected reviews, see: a) P. A. Wender, V. A. Verma, T. H. Paxton, T. H. Pillow, *Acc. Chem. Res.* **2008**, *41*, 40; b) M. Lautens, W. Klute, W. Tam, *Chem. Rev.* **1996**, *96*, 49; c) P. A. Inglesby, P. A. Evans, *Chem. Soc. Rev.* **2010**, *39*, 2791; d) C. Aubert, L. Fensterbank, M. Malacria, *Top. Organomet. Chem.* **2006**, *19*, 259; e) *Advances in Cycloaddition*, *Vols. 1–6*, JAI Press, Greenwich, CT, **1988–1999**; f) Tetrahedron Organic Chemistry Series: W. Carruthers, *Cycloaddition Reactions in Organic Synthesis*, Pergamon, Elmsford, NY, **1990**; g) L. Yet, *Chem. Rev.* **2000**, *100*, 2963; h) *Cycloaddition Reactions in Organic Synthesis* (Eds.: S. Kobayashi, K. A. Jørgensen), Wiley-VCH, Weinheim, **2002**; i) F. López, J. L. Mascareñas, *Beilstein J. Org. Chem.* **2011**, *7*, 1075.

[5] For selected reviews, see: a) J. Blanco-Urgoiti, L. Añorbe, L. Pérez-Serrano, G. Domínguez, J. Pérez-Castells, *Chem. Soc. Rev.* **2004**, *33*, 32; b) Y. K. Chung, *Coord. Chem. Rev.* **1999**, *188*, 297; c) K. Brummond, J. L. Kent, *Tetrahedron* **2000**, *56*, 3263; d) S. E. Gibson, A. Stevenazi, *Angew. Chem. Int. Ed.* **2003**, *42*, 1800; *Angew. Chem.* **2003**, *115*, 1844; e) T. Shibata, *Adv. Synth. Catal.* **2006**, *348*, 2328; f) J. Perez-Castells, *Top. Organomet. Chem.* **2006**, *19*, 207; g) H.-W. Lee, F.-Y. Kwong, *Eur. J. Org. Chem.* **2010**, 789; h) T. Shibata, *Sci. Synth.* **2011**, *3*, 125; i) *The Pauson-Khand Reaction: Scope, Variations and Applications* (Ed.: R. R. Torres), Wiley-VCH, Weinheim, **2012**.

[6] Only one example of the [2+2+1] radical carbocyclization of 1,*n*-enynes has been reported, the disadvantages being that harmful organotin initiators are required and poor selectivity is observed. See: a) T. Fukuyama, N. Nakashima, T. Okada, I. Ryu, *J. Am. Chem. Soc.* **2013**, *135*, 1006; for a paper on the [2+2+2] radical carbocyclization of 1,6-enynes with $ArSO_2Cl$ using photocatalysis, see: b) G.-B. Deng, Z.-Q. Wang, J.-D. Xia, P.-C. Qian, R.-J. Song, M. Hu, L.-B. Gong, J.-H. Li, *Angew. Chem. Int. Ed.* **2013**, *52*, 1535; *Angew. Chem.* **2013**, *125*, 1575; For selected papers on the common radical cyclization of 1,*n*-enynes, see: c) E. Lee, J. S. Tae, C. Lee, C. M. Park, *Tetrahedron Lett.* **1993**, *34*, 4831; d) D. L. J. Clive, S. R. Magnuson, H. W. Manning, D. L. Mayhew, *J. Org. Chem.* **1996**, *61*, 2095; e) I. Ryu, H. Miyazato, H. Kuriyama, K. Matsu, M. Tojino, T. Fukuyama, S. Minakata, M. Komatsu, *J. Am. Chem. Soc.* **2003**, *125*, 5632; f) H. M. Ko, C. W. Lee, H. K. Kwon, H. S. Chung, S. Y. Choi, Y. K. Chung, E. Lee, *Angew. Chem. Int. Ed.* **2009**, *48*, 2364; *Angew. Chem.* **2009**, *121*, 2400; g) S. Mondal, B. Gold, R. K. Mohamed, I. V. Alabugin, *Chem. Eur. J.* **2014**, *20*, 8664; h) J.-Y. Luo, H.-L. Hua, Z.-S. Chen, Z.-Z. Zhou, Y.-F. Yang, P.-X. Zhou, Y.-T. He, X.-Y. Liu, Y.-M. Liang, *Chem. Commun.* **2014**, *50*, 1564; i) L. Zhang, Z. Li, Z.-Q. Liu, *Org. Lett.* **2014**, *16*, 3688; j) Y.-T. He, L.-H. Li, Z.-Z. Zhou, H.-L. Hua, Y.-F. Qiu, X.-Y. Liu, Y.-M. Liang, *Org. Lett.* **2014**, *16*, 3896.

[7] For selected reviews, see: a) C.-J. Li, *Acc. Chem. Res.* **2009**, *42*, 335; b) G. P. Mcglacken, L. M. Bateman, L. Bateman, *Chem. Soc. Rev.* **2009**, *38*, 2447; c) J. A. Ashenhurst, *Chem. Soc. Rev.* **2010**, *39*, 540; d) C. Liu, H. Zhang, W. Shi, A. Lei, *Chem. Rev.* **2011**, *111*, 1780; e) W. Wu, H. Jiang, *Acc. Chem. Res.* **2012**, *45*, 1736; f) Y.-X. Xie, R.-J. Song, J.-N. Xiang, J.-H. Li, *Chin. J. Org. Chem.* **2012**, *32*, 1555; g) C. Zhang, C. Tang, N. Jiao, *Chem. Soc. Rev.* **2012**, *41*, 3464; h) F. Guo, M. D. Clift, R. J. Thomson, *Eur. J. Org. Chem.* **2012**, 4881; i) M. Grzybowski, K. Skonieczny, H. Butenschön, D. T. Gryko, *Angew. Chem. Int. Ed.* **2013**, *52*, 9900; *Angew. Chem.* **2013**, *125*, 10084; j) S. A. Girard, T. Knauber, C.-J. Li, *Angew. Chem. Int. Ed.* **2014**, *53*, 74; *Angew. Chem.* **2014**, *126*, 76; k) R.-J. Song, Y. Liu, Y.-X. Xie, J.-H. Li, *Synthesis* **2015**, *47*, 1195.

[8] For pioneering papers on the oxidative couplings of the $C(sp^3)$–H bonds, see: a) S. Jaegli, J. Dufour, H.-l. Wei, T. Piou, X.-H. Duan, J.-P. Vors, L. Neuville, J. Zhu, *Org. Lett.* **2010**, *12*, 4498; b) T. Wu, X. Mu, G.-S. Liu, *Angew. Chem. Int. Ed.* **2011**, *50*, 12578; *Angew. Chem.* **2011**, *123*, 12786; c) X. Mu, T. Wu, H.-Y. Wang, Y.-L. Guo, G.-S. Liu, *J. Am. Chem. Soc.* **2012**, *134*, 878; d) H. Zhang, P. Chen, G. Liu, *Synlett* **2012**, *23*, 2749; e) W.-T. Wei, M.-B. Zhou, J.-H. Fan, W. Liu, R.-J. Song, Y. Liu, M. Hu, P. Xie, J.-H. Li, *Angew. Chem. Int. Ed.* **2013**, *52*, 3638; *Angew. Chem.* **2013**, *125*, 3726; f) C.-Y. Wang, R.-J. Song, Y. Liu, W.-T. Wei, *Chem. Commun.* **2013**, *49*, 10817; g) Y. Meng, L.-N. Guo, H. Wang, X.-H. Duan, *Chem. Commun.* **2013**, *49*, 7540; h) S.-L. Zhou, L.-N. Guo, H. Wang, X.-H. Duan, *Chem. Eur. J.* **2013**, *19*, 12970; i) H. Wang, L.-N. Guo, X.-H. Duan, *Chem. Commun.* **2013**, *49*, 10370; j) H. Wang, L.-N. Guo, X.-H. Duan, *Org. Lett.* **2013**, *15*, 5254; k) Z. Li, Y. Zhang, L. Zhang, Z.-Q. Liu, *Org. Lett.* **2014**, *16*, 382; l) M.-Z. Lu, T.-P. Loh, *Org. Lett.* **2014**, *16*, 4698; m) W.-T. Wei, R.-J. Song, X.-H. Ouyang, Y. Li, H.-B. Li, J.-H. Li, *Org. Chem. Front.* **2014**, *1*, 484; n) C.-Y. Wang, R.-J. Song, W.-T. Wei, J.-H. Fan, J.-H. Li, *Chem. Commun.* **2015**, *51*, 2361; o) Y. Li, B. Liu, H.-B. Li, Q. Wang, J.-H. Li, *Chem. Commun.* **2015**, *51*, 1024; p) A. Bunescu, Q. Wang, J. Zhu, *Angew. Chem. Int. Ed.* **2015**, *54*, 3132; *Angew. Chem.* **2015**, *127*, 3175; q) C. Chatalova-Sazepin, Q. Wang, G. M. Sammis, J. Zhu, *Angew. Chem. Int. Ed.* **2015**, *54*, 5443–5446; *Angew. Chem.* **2015**, *127*, 5533–5536.

[9] CCDC 1401398 (**3aa**), CCDC 1401399, CCDC 1401400 (two diastereoisomers of **3ae**) and CCDC 1401401 (**3wa**) contain the supplementary crystallographic data for this paper. These data can be obtained free of charge from The Cambridge Crystallographic Data Centre. The diastereoisomers were also determined by 2D NMR analysis of **3ae** and the other possible mechanism was proposed (see the Supporting Information).

[10] For selected papers, see: a) E. Bosch, M. D. Bachi, *J. Org. Chem.* **1993**, *58*, 5581; b) S. Bogen, M. Journet, M. Malacria, *Synlett* **1994**, 958; c) P. J. Crick, N. S. Simpkins, A. Highton, *Org. Lett.* **2011**, *13*, 6472; For a review, see: d) U. Wille, *Chem. Rev.* **2013**, *113*, 813.

Received: May 21, 2015
Published online: June 26, 2015

