Boronic-acid Mediated Carbo-cyanation of Olefins and Vinylation of Alkyl Iodides

Reina Hara, Chahinaz Khiar, Nitin S Dange, Pierre Bouillac, Frédéric Robert, yannick Landais

HAL Id: hal-01790985

https://hal.archives-ouvertes.fr/hal-01790985

Submitted on 14 May 2018

Boronic-acid Mediated Carbo-cyanation of Olefins and Vinylation of Alkyl Iodides

Reina Hara,[a] Chahinaz Khiar,[a][b] Nitin S. Dange,[a] Pierre Bouillac,[a] Frédéric Robert,[a] and Yannick Landais*[a]

Abstract: Phenylboronic acid was shown to mediate the free-radical multicomponent carbo-cyanation of olefins and the addition of alkyl iodides onto vinylsulfones. Reaction of the boronic acid with di-*tert*-butyl hyponitrite generates an aryl radical, which was able to selectively abstract the iodine atom from alkyl iodide precursors to form the key C-centered radical precursor. Arylboronic acids may thus be considered as efficient tin surrogates in these free-radical processes.

Introduction

While transition-metal catalyzed processes[1] constitute a powerful method to build C-C bonds, free-radical strategies offer an attractive alternative, allowing consecutive C-C bond formations through cascade and multicomponent reactions.[2] The addition of alkyl radicals onto C=C bonds provides an effective mean to construct C-C bonds as it is energetically favorable.[3] This addition generates a new radical species, which may then react further with a radical trap, or be oxidized or reduced respectively into carbocation or carbanion species.[4] Unsaturated sulfone derivatives (vinyl-, alkynyl, cyano,…) are well-known efficient radical traps for alkyl radicals, affording, through an addition-elimination process, a new unsaturated system, along with a sulfonyl residue (Figure 1, eq. 1).[5] The power of this strategy has been illustrated earlier with simple addition of alkyl halides to vinylsulfones,[6] and more recently in three-component olefin carbo-alkynylation, alkenylation and cyanation, using the corresponding arylsulfonyl precursors (Figure 1, eq. 2).[5b,7] Depending on the nature of the substituent on the sulfonyl group, the reaction however requires that a tin reagent is present in the medium to sustain the radical chain (Figure 1, (3)). The concomitant need for tin reagents, having perceived toxicity, still hamper the development of C-C bond forming processes using arylsulfonyl derivatives. While several solutions to this problem have been reported in recent time,[8] including the use of alkylsulfonyl analogues,[5a,d][9] there is still a need for environmentally benign alternative methods to promote radical

[a]   R. Hara, C. Khiar, Dr. N. S. Dange, M. P. Bouillac, Dr. F. Robert,
        Prof. Dr. Y. Landais
        Institute of Molecular Sciences, UMR-CNRS 5255
        University of Bordeaux
        351, Cours de la libération
        33405 Talence cedex, France
        E-mail: yannick.landais@u-bordeaux.fr

[b]   C. Khiar
        Laboratoire de Chimie Appliquée et du Génie Chimique (LCAGC)
        Université Mouloud Mammerie de Tizi-Ouzou
        15000, Tizi-Ouzou, Algeria

processes using arylsulfonyl derivatives. Moreover, the synthesis of the latter has been recently studied extensively, making them readily available reagents.[10]

Figure 1. Tin-mediated C-C bond formation using addition of alkyl halides to unsaturated sulfonyl derivatives.

We report here on the development of a "tin-free" strategy, using phenylboronic acids to mediate the three-component carbo-cyanation of olefins and the vinylation of alkyl halides under radical conditions. It is shown that alkyl radicals may be selectively generated through the fast abstraction ($k \sim 10^9$ M^{-1} s^{-1})[11] of iodine atom from alkyl iodides by aryl radicals, issued from the fragmentation of arylboronic acids under oxidative conditions.[12] This fast abstraction outperforms all other competitive processes which might occur in the medium, including the addition to sulfonyl derivatives or the olefin partners.[13] Arylboronic acids are thus stable aryl radical precursors, which may be regarded as useful tin surrogates in above radical processes.

Results and Discussion

Our studies started with the search for an oxidant able to initiate the formation of the desired aryl radical. Preliminary studies were thus carried out using α-iodothioester **2a** as a radical precursor, 2-ethylbutene **3a** as model olefin and p-TsCN as a cyanide source in the presence of PhB(OH)$_2$ **1** in benzene as a solvent. Several oxidants were tested as summarized in Table 1. We first investigated the use of di-*tert*-butyl hyponitrite (DTBHN), as recent studies by Hayashi and co-workers showed that boronic acids reacted cleanly with DTBHN to produce the corresponding aryl radical.[14] Using conditions for the 3-component carbo-cyanation of olefins reported earlier, we were pleased to observe that using DTBHN and replacing (Bu$_3$Sn)$_2$ with 1 eq. of PhB(OH)$_2$ **1** led to the expected **4a** in 44% yield (Table 1, entry 1). The absence of **1** led to no reaction showing the importance of the boronic acid in the transformation (entry 2). Increasing the amount of **1** furnished **4a** in 60% yield (entry 3), while a further increase led to little improvement (entry 4). The amount of DTBHN was also varied and surprisingly, an increase of the hyponitrite did not raise the yield (entries 5-6), while decreasing the quantity to 0.6 eq. had a dramatic effect on the isolated yield of **4a** (entry 7). It is important noticing that in contrast with previous work using (Bu$_3$Sn)$_2$ reagent[7] (see Figure 1, (3)), the PhSO$_2$ radical does not react with the boronic acid.[15] The process is therefore not a chain and requires at least a stoichiometric amount of DTBHN. Although conditions described in entry 3 seemed optimal, a rapid screening of other peroxides was performed as DTBHN is quite expensive. Results summarized in entries 8-12 (Table 1) indicate that only PhCO$_2$$t$-Bu in the presence of a catalytic amount of Cu(II)[16] was able to afford acceptable yields of **4a** (entry 11), albeit inferior to those observed with DTBHN. Surprisingly, a poor yield was obtained with t-BuOOt-Bu, while as in DTBHN a t-BuO radical is generated upon heating at 130°C. Mn(OAc)$_3$ in 1,2-dichloroethane (DCE) was also tested (not shown), as it is known to react efficiently with boronic acids,[17] but it failed to afford traces of **4a**. Using DTBHN as an oxidant, we also varied the amount of **2a** (entry 13), p-TsCN (entry 14) and **3a** (entry 15), showing that the olefin and the cyanide source must be used in excess. Finally, variation of the nature of the solvent was also looked at, using for instance DCE or t-BuOH, which afforded respectively 28% and 3% of **4a**, while CH$_3$CN and acetone did not afford the required compound. The nature of the boron derivative was also varied. For instance, using the phenylpinacolborate instead of **1** led to **4a** in only 19% yield. Modifying the nature of the aryl radical using 4-MeOPhB(OH)$_2$ instead of **1**, led to 50% yield. Amongst the by-products that were formed, we were able to isolate a small quantity of *i* (Table 1), which results from the carbo-cyanation of isobutene, itself likely issued from the decomposition of t-BuOB(OH)$_2$.

**Table 1.** Phenylboronic acid-mediated carbo-cyanation of olefin. Search for an oxidant.

Entry	2a (eq.)	3a (eq.)	1 (eq.)	Oxidant (eq.)	Time (h)	Yield [%][a]
1	1	2	1	DTBHN (1.2)	2	44
2	1	2	0	DTBHN (1.2)	2	0
3	1	2	2	DTBHN (1.2)	2	60
4	1	2	3	DTBHN (1.2)	2	62
5	1	2	2	DTBHN (2)	2	59
6	1	2	2	DTBHN (2)	2	59
7	1	2	2	DTBHN (0.6)	2	13
8[b]	1	2	2	t-BuOOt-Bu (2)	6	6
9	1	2	2	(PhCO$_2$)$_2$ (2) / Cu(acac)	24	10
10	1	2	2	PhCO$_2$$t$-Bu (2)	48	-
11	1	2	2	PhCO$_2$$t$-Bu (2) / Cu(acac)	48	40
12	1	2	2	K$_2$S$_2$O$_8$ (2), AgNO$_3$	15	-
13[c]	2	1	1	DTBHN (1.2)	2	11[d]
14[e]	1	2	1	DTBHN (1.2)	2	16
15	1	3	2	DTBHN (1.2)	2	57
16	1	2	2[f]	DTBHN (1.2)	2	50
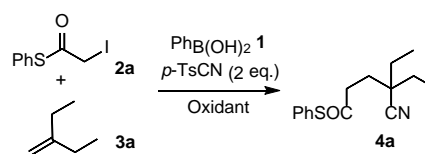
[a] Yield of isolated products. [b] 130°C. [c] 1:1 CH$_2$Cl$_2$/water was used as a solvent. [d] Trace amount of compound *i* below was also isolated. [e] 1.2 eq. of p-TsCN was used. [f] 4-MeOPhB(OH)$_2$ was used instead of **1**.
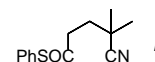

With the optimal conditions set up in entry 3 in hands, we then studied the scope of the reaction, varying first the nature of the olefin (Scheme 1). The process proved to be compatible with a range of functional groups, including ketones, nitrile, phosphonates, but also bromides and carbamates. Yields range from moderate to good. The radical nature of the process is indicated by the formation of nitrile **4j**, generated from carbo-cyanation of β-pinene.[18]
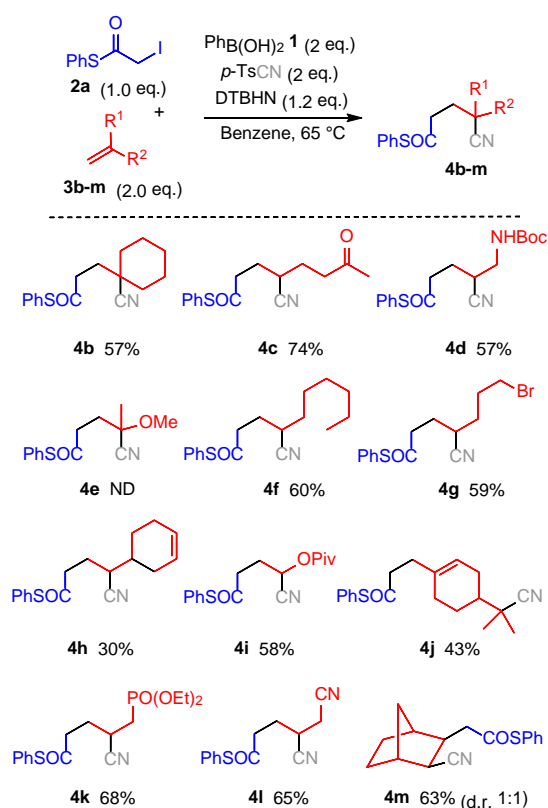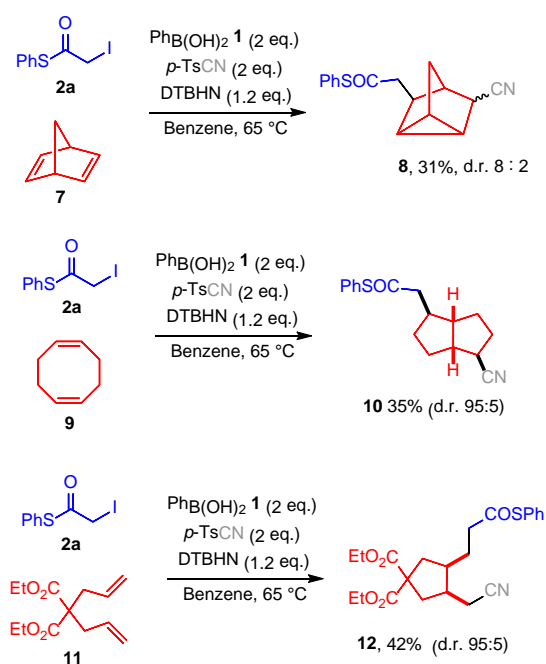
Scheme 1. PhB(OH)$_2$-mediated carbo-cyanation of olefins. Variation of the nature of the olefin.

Scheme 2. PhB(OH)$_2$-mediated carbo-cyanation of olefins. Variation of the nature of the radical precursor.

These preliminary studies were then extended to radical addition varying the nature of the radical precursor **5a-d** (Scheme 2). Several iodides bearing an ester (**5a**), α,α-difluoroester (**5b**), nitrile (**5c**) or sulfone groups (**5d**) were reactive under the above conditions, affording the desired nitriles **6a-g** in moderate to excellent yields. Difference of reactivity between iodides **5a** and **5b** is worth noticing,[19] the former generally leading to higher yields. This observation had already been made previously in carbo-alkenylation reactions.[7e] Several contrasting reports have appeared recently concerning the role of fluorine substituents in C-centered radicals.[20] While the strong electronegativity of the fluorine atom should increase the electrophilicity of radical intermediate **I** (Figure 1 (3)) and thus lead to improved reactivity toward electron-rich olefins, this is not reflected in terms of yield of 3-component adducts (compare **6b**, **6d** with non-fluorinated analogues **6a**, **6c**). A recent report by Dolbier and co-workers[21] showed that difluoroalkyl radicals (RCF$_2$·) reacted faster with the most electron-deficient olefins, as a result of a polarized transition state. Charge transfer from RCF$_2$· to acrylonitrile for instance was shown through computational studies to lead to the development of a positive charge at the RCF$_2$ carbon center stabilized by the electron-donation of fluorine atoms. Although **5b** also bears an additional ester group, the resulting radical species may not be so electrophilic, explaining its moderate reactivity toward electron-rich olefins. Similar observations were done during previous studies with related polyfluoroalkyl radicals.[7e,f] Finally, reaction with electron-rich olefins such as vinyl pivalate led to the desired nitrile **6g-a**, along with the sulfonylcyanation product **6g-b**.
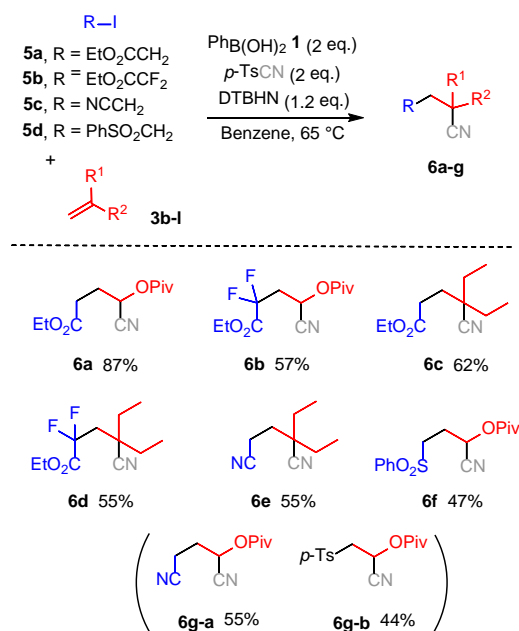
The reaction was also applied to dienes **7**, **9** and **11**, leading to the desired 3-component adducts albeit in moderate yields, but generally good diastereoselectivity (Scheme 3). The stereochemistry of **8**, **10** and **12** were in good agreement with those of related carbo-alkenylation products prepared earlier.[7e]

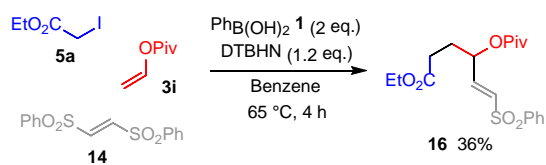**Scheme 3.** PhB(OH)$_2$-mediated carbo-cyanation of dienes.

The cyanation using sulfonylcyanide being efficient, we also extended our investigation to the development of a carbo-alkenylation and vinylation of alkyl halide.[6,8] We first studied the addition of simple alkyl iodides to vinyl disulfone **14**, an efficient radical trap.[6n,7e] Under the same conditions than above, the expected vinylated products were formed in satisfying yields

(Scheme 4). Primary, secondary and tertiary alkyl radicals added efficiently onto **14**. Interestingly, formation of vinylsulfone **15f** occurred with high stereocontrol and inversion of configuration of the neomenthyl iodide precursor **13f**. Finally, other vinylation agents, including diethyl-2-(chloromethylene)malonate),[7e] 1,1,2-trichloroethylene,[22] or (*E*)-ethyl-3-chloro-2-(phenylsulfonyl)acrylate were also tested but led to disappointing results with yields not exceeding 20%.
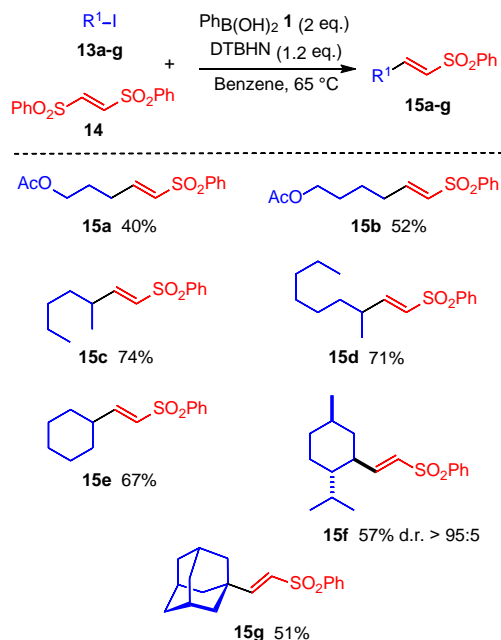

Scheme 4. PhB(OH)$_2$-mediated vinylation of alkyl iodides.

Our efforts to extend the above vinylation to a three-component carbo-alkenylation process[7e] unfortunately met with little success, affording moderate yields of products, as exemplified below with the carbo-alkenylation of vinyl pivalate **3i**, which led to the 3-component adduct **16** in 36% yield (Scheme 5).

Scheme 5. PhB(OH)$_2$-mediated carbo-alkenylation of olefins.

A final experiment was carried out in order to identify the presence of an aryl iodide and thus the formation of an aryl radical as the initiator of the radical process. Carbo-cyanation of *n*-octene **3f** was thus carried out as described above, using functionalized boronic acid **17** instead of **1** to allow for the isolation of the corresponding aryl iodide (Scheme 6). Under these conditions, the carbo-cyanation product **4f** was formed as the major compound, along with the sulfonyl-cyanation product **18** and the expected aryl iodide **19**. As mentioned above, this radical process is not a chain reaction, and the electrophilic sulfonyl radical, formed upon fragmentation of *p*-TsCN, may thus react with excess olefin to generate **18**.
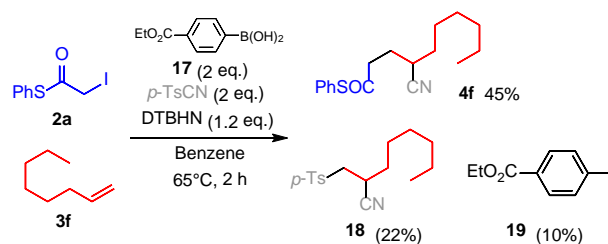
Scheme 6. Boronic acid **17**- mediated carbo-cyanation of n-octene.

Based on these experimental evidences, the mechanism of the above radical processes may be summarized as in Figure 2. Addition of the alkoxy radical (resulting from the thermal decomposition of DTBHN) onto boronic acid **1**, generates the phenyl radical (eq. 1).[14] The latter then abstracts the iodine atom from the alkyl iodide (eq. 2), to form radical **I**, which then reacts with the electron-rich olefin to generate a new nucleophilic radical **II** (eq. 3), being finally trapped by the sulfonyl derivative, leading to the addition product, along with the sulfonyl radical (eq. 4). PhSO$_2$ radical does not react with **1** and thus is not able to propagate the radical chain.[15] This has two consequences: (1) equimolar amount of oxidant is required; (2) the sulfonyl radical accumulates in the medium during the reaction and may, with electron-richer olefins, provides sulfonyl-cyanation products such as **18**.[7f] Fortunately, addition of sulfonyl radicals onto olefins is a reversible (fast) process,[23] so that sulfonyl-cyanation generally does not impede the desired carbo-cyanation pathway.
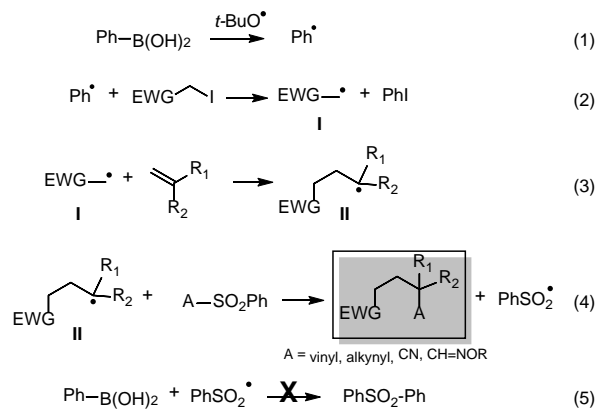

Figure 2. Phenylboronic acid mediated three-component carbo-functionalization of olefins.

Conclusions

As a summary, we have described a "tin-free" carbo-cyanation of olefins and vinylation of alkyl iodides using phenyl boronic acids as radical mediators. The reaction of the *t*-BuO radical, resulting from the decomposition of DTBHN, with the boronic acid generates an aryl radical, which then abstracts the iodine atom from alkyl iodides to form a C-centered radical, finally adding onto the olefin to form a new C-C bond. Moderate to excellent yields of 2- and 3-component adducts are finally obtained, through a methodology, which is operationally simple, using readily available PhB(OH)$_2$.

Experimental Section

General Information: All reactions were carried out under an argon atmosphere with dry solvents under anhydrous conditions. Yields refer to chromatographically and spectroscopically (^{1}H NMR) homogeneous materials. Commercial reagents were used without purification, unless otherwise stated. Silica gel 60M (230-400 mesh ASTM) was used for flash chromatography. In some cases, silica gel was preliminary deactivated by mixing with 5% (v/v) of triethylamine. CH_2Cl_2 was dried over activated alumina columns on MBraun Solvent Purification System (SPS-800). DCE and MeCN were distilled from CaH_2 and benzene was distilled from Na/Benzophenone. ^{1}H-NMR and ^{13}C-NMR were recorded on a Brüker Avance-300 FT (^{1}H: 300 MHz, ^{13}C: 75.5 MHz), a Brüker DPX-400 FT (^{1}H: 400 MHz, ^{13}C: 100.2 MHz) and a Brüker Avance 600 (^{1}H: 600 MHz, ^{13}C: 150.9 MHz) apparatus using $CDCl_3$ as internal reference unless otherwise indicated. The chemical shifts (δ) and coupling constants (J) are expressed in ppm and Hz respectively. FT-IR spectra were recorded on a Perkin-Elmer Spectrum 100 using a diamond ATR accessory. HRMS were recorded with a Waters Q-TOF 2 spectrometer in the electrospray ionization (ESI) mode.

Boronic-acid mediated carbo-cyanation - General procedure. To a solution of iodide precursor **2a** (1 eq.) in dry benzene (1 M), were added olefin **3a-m** (2 eq.), *p*-toluenesulfonyl cyanide (2 eq.) and phenyl boronic acid **1** (2 eq.), and the reaction mixture was degassed for 10 min. Then, the process was initiated by adding slowly DTBHN (1.2 eq) at room temperature. The mixture was then stirred at 65°C and the reaction progress monitored by TLC. After the reaction was completed, the mixture was concentrated under reduced pressure and the residue purified by chromatography on silica gel.

Boronic-acid mediated vinylation of alkyl iodides – General procedure. To a solution of alkyl iodide **13a-g** (1 eq.) in dry benzene (1.0 M), was added (*E*)-1,2-bis(phenyl-sulfonyl)ethene **14** (2 eq.) and phenyl boronic acid **1** (2 eq.). The reaction mixture was then degassed for 10 min under argon, and the process initiated by adding DTBHN (1.2 eq.). The mixture was stirred at 65°C and the reaction progress monitored by TLC. After the reaction was complete, the solvent was concentrated under reduced pressure and the residue purified by chromatography on silica gel.

Keywords: Radicals • C-C coupling • boronic acids • tin-free methodology • sulfones

[1]   (a) A. Ding, H. Guo, *Carbometalation and heterometalation reactions of alkenes, alkynes and allene*s in Comprehensive Organic Synthesis II, Eds P. Knochel, G. A. Molander, Elsevier, 2014, Vol. 4, 891; (b) J. Choi, G. C. Fu, *Science* **2017**, *356*, 152; (c) H. Yang, X. Yang, W. Tang, *Tetrahedron* **2016**, *72*, 6143; (d) A. H. Cherney, N. T. Kadunce, S. E. Reisman, *Chem. Rev.* **2015**, *115*, 9587; (e) M. Garcia-Melchor, X. Solans-Monfort, G. Ujaque, *C-C bond formation* in Comprehensive Organic Synthesis II, Eds J. Reedijk, K. Poeppelmeier, 2013, Vol. 9, 767.

[2]   (a) G. J. Rowlands, *Tetrahedron* **2009**, *65*, 8603 and references cited therein; (b) G. S. C. Srikanth, S. L. Castle, *Tetrahedron* **2005**, *61*, 10377; (c) I. Ryu, *Multicomponent radical reactions*. In Multicomponent Radical Reactions; J. Zhu, H. Bienayme, Eds.; Wiley-VCH: Weinheim, 2005, pp 169-198; (d) V. Liautard, Y. Landais, in *Multicomponent Reactions*, Eds. J. Zhu, Q. Wang, M. X. Wang, Wiley, 2nd Edition. 2014, pp 401-438.

[3]   H. Subramanian, Y. Landais, M. P. Sibi in Comprehensive Organic synthesis, Eds. G. A. Molander, P. Knochel, 2nd ed., Vol. 4, Oxford: Elsevier, **2014**, pp. 699-741.

[4]   Radicals in Organic Synthesis, ed. Renaud, P.; Sibi, M. P. Wiley-VCH, Weinheim, Germany, 2001, vol. 1.

[5]   (a) F. Bertrand, F. Leguyader, L. Liguori, G. Ouvry, B. Quiclet-Sire, S. Seguin, S. Z. Zard, *C. R. Acad. Sci. Paris,* **2001**, *4*, 547; (b) B. Ovadia, F. Robert, Y. Landais, *Chimia* **2016**, *70*, 34; (c) I. J.Rosenstein in Radicals in Organic Synthesis, ed. Renaud, P.; Sibi, M. P. Wiley-VCH, Weinheim, Germany, 2001, vol. 1, pp. 50–71; (d) B. Quiclet-Sire, S. Zard, *Beilstein J. Org. Chem.* **2013**, *9*, 557.

[6]   For selected examples, see : (a) J. Gong, P. L. Fuchs, *J. Am. Chem. Soc.* **1996**, *118*, 4486; (b) J. Xiang, P. L. Fuchs, *J. Am. Chem. Soc.* **1996**, *118*, 11986; (c) J. Xiang, W. Jiang, J. Gong, P. L. Fuchs, *J. Am. Chem. Soc.* **1997**, *119*, 4123; (d) J. Xiang, P. L. Fuchs, *Tetrahedron Lett.* **1996**, *37*, 5269; (e) J. Xiang, W. Jiang, P. L. Fuchs, *Tetrahedron Lett.* **1997**, *38*, 6635; (f) J. Xiang, P. L. Fuchs, *Tetrahedron Lett.* **1998**, *39*, 8597; (g) X. Liu, Z. Wang, X. Cheng, C. Li, *J. Am. Chem. Soc.* **2012**, *134*, 14330; (h) G. Rouquet, F. Robert, R. Méreau, F. Castet, Y. Landais, *Chem. Eur. J.* **2011**, *17*, 13904; (i) J. Lei, X. Wu, Q. Zhu, *Org. Lett.* **2015**, *17*, 2322. (j) J. L. García Ruano, J. Alemán, A. Parra, L. Marzo, *Eur J. Org. Chem.* **2014**, *8*, 1577 and references cited therein; (k) G. A. Russell, P. Ngoviwatchai, H. I. Tastoush, *Organometallics*, **1988**, *7*, 696; (l) G. A. Russell, H. I. Tashtoush, P. Ngoviwatchai, *J. Am. Chem. Soc.* **1984**,*106*, 4622; (m) G. A. Russell, P. Ngoviwatchai, H. I. Tashtoush, A. Pla-Dalmau, R. K. Khanna, *J. Am. Chem. Soc.* **1988**,*110*, 3530; (n) N. Miyamoto, D. Fukuoka, K. Utimoto, H. Nozaki, *Bull. Chem. Soc. Jpn* **1974**, *47*, 503; (o) Y. Amaoka, M. Nagatomo, M. Watanabe, K. Tao, S. Kamijo, M. Inoue, *Chem. Sci.* **2014**, *5*, 4339; (p) T. Hoshikawa, S. Kamijo, M. Inoue, *Org. Biomol. Chem.* **2013**, *11*, 164; (q) G. Rouquet, F. Robert, R. Méreau, F. Castet, P. Renaud, Y. Landais, *Chem. Eur. J.* **2012**, *18*, 940.

[7]   (a) E. Godineau, Y. Landais, *J. Am. Chem. Soc.* **2007**, *129*, 12662; (b) V. Liautard, F. Robert, Y. Landais, *Org. Lett.* **2011**, *13*, 2658; (c) Y. Landais, F. Robert, E. Godineau, L. Huet, N. Likhite, *Tetrahedron* **2013**, *69*, 10073; (d) C. Poittevin, V. Liautard, R. Beniazza, F. Robert, Y. Landais, *Org. Lett.* **2013**, *15*, 2814; (e) R. Beniazza, V. Liautard, C. Poittevin, B. Ovadia, S. Mohammed, F. Robert, Y. Landais, *Chem. Eur. J.* **2017**, *23*, 2439; (f) H. Hassan, V. Pirenne, M. Wissing, C. Khiar, A. Hussain, F. Robert, Y. Landais, *Chem. Eur. J.* **2017**, *23*, 4651.

[8]   (a) A.-P. Schaffner, V. Darmency, P. Renaud, *Angew. Chem., Int. Ed.* **2006**, *45*, 5847. *Angew. Chem.,* **2006**, *118*, 5979; (b) A. Schaffner, K. Sarkunam, P. Renaud, *Helv. Chim. Acta* **2006**, *89*, 2450; (c) S. Kim, S. Kim, *Bull. Chem. Soc. Jpn.* **2007**, *80*, 809; (d) S. Sumino, M. Uno, H.-J. Huang, Y. K. Wu, I. Ryu, *Org. Lett.* **2018**, *20*, 1078.

[9]   (a) F. Le Guyader, B. Quiclet-Sire, S. Seguin, S. Z. Zard, *J. Am. Chem. Soc.* **1997**, *119*, 7410; (b) F. Bertrand, B. Quiclet-Sire, S. Z. Zard, *Angew. Chem., Int. Ed.* **1999**, *38*, 1943. *Angew. Chem.,* **1999**, *111*, 2135; (c) S. Kim, C. J. Lim, *Bull. Korean. Chem. Soc.* **2003**, *24*, 1219; (d) K. Weidner, A. Giroult, P. Panchaud, P. Renaud, *J. Am. Chem. Soc.* **2010**, *132*, 17511; (e) B. Ovadia, F. Robert, Y. Landais, *Org. Lett.* **2015**, *17*, 1958; (f) J. Lei, X. Wu, Q. Zhu, *Org. Lett.* **2015**, *17*, 2322.

[10]   For selected recent examples, see: (a) S. Tang, Y. Wu, W. Liao, R. Bai, C. Liu, A. Lei, *Chem. Commun.* **2014**, *50*, 4496; (b) Z. Huang, Q. Lu, Y. Liu, D. Liu, J. Zhang, A. Lei, *Org. Lett.* **2016**, *18*, 3940; (c) Y. Sun, A. Abdukader, D. Lu, H. Zhang, C. Liu, *Green Chem.* **2017**, *19*, 1255; (d) S. Shaaban, S. Liang, N.-W. Liu, G. Manolikakes, *Org. Biomol. Chem.* **2017**,*15*, 1947; (e) A. Rodríguez, W. J. Moran, *J. Org. Chem.* **2016**, *81*, 2543; (f) A. Garcia-Dominguez, S. Müller, C. Nevado, *Angew. Chem. Int. Ed.* **2017**, *56*, 9949; (g) C. Simon Gloor, F. Denes, P. Renaud, *Angew. Chem. Int. Ed.* **2017**, 56, 13329; (h) A. S. Deeming, E. J. Emmett, C. S. Richards-Taylor, M. Willis, *Synthesis* **2014**, *46*, 2701; (i) J. Zhang, Y. An, J. Wu, *Chem. Eur. J.* **2017**, *23*, 9477.

[11]   M. R. Heinrich, *Chem. Eur. J.* **2009**, *15*, 820 and references cited therein.

[12]   (a) I. B. Seiple, S. Su, R. A. Rodriguez, R. Gianatassio, Y. Fujiwara, A. L. Sobel, P. S. Baran, *J. Am. Chem. Soc.* **2010**, *132*, 13194; (b) Y. Fujiwara, V. Domingo, I. B. Seiple, R. Gianatassio, M. D. Bel, P. S. Baran, *J. Am. Chem. Soc.* **2011**, *133*, 3292; (c) P. P. Singh, S. K. Aithagani, M. Yadav, V. P. Singh, R. A. Vishwakarma, *J. Org. Chem.* **2013**, *78*, 2639; (d) J. Wang, S. Wang, G. Wang, J. Zhang, X.-Q. Yu, *Chem. Commun.* **2012**, *48*, 11769; (e) M. Yan, J. C. Lo, J. T. Edwards, P. S. Baran, *J. Am. Chem. Soc.* **2016**, *138*, 12692.

[13]   Model reactions involving phenylboronic acids and DTBHN in the presence of *p*-TsCN, vinylsulfones or olefins did not provide addition products.

[14]   N. Uchiyama, E. Shirakawa, R. Nishikawa, T. Hayashi, *Chem. Commun.* **2011**, *47*, 11671.

[15]   V. Darmency, P. Renaud, *Top. Curr. Chem.* **2006**, *263*, 71.

[16]   (a) J. Lalevée, J.-P. Fouassier, *Overview of radical Initiation* in Encyclopedia of Radicals in Chemistry, Biology and Materials, 2012 J. Wiley & Sons, Ltd; (b) Z. Xu, Z. Hang, L. Chai, Z.-Q. Liu, *Org. Lett.* **2016**, *18*, 4662.

[17]   (a) A. S. Demir, O. Reis, M. Emrullahoglu, *J. Org. Chem.* **2003**, *68*, 578; (b) M. Tobisu, K. Koh, T. Furukawa, N. Chatani, *Angew. Chem. Int. Ed.* **2012**, *51*, 11363. *Angew. Chem.* **2012**, *124*, 11525; (c) A. Dickschat, A. Studer *Org. Lett.* **2010**, *12*, 3972.

[18]   D. M. Oldroyd, G. S. Fisher, L. A. Goldblatt, *J. Am. Chem. Soc.* **1950**, *72*, 2407.

[19]   (a) E. Godineau, C. Schäfer, Y. Landais, *Org. Lett.* **2006**, *8,* 4871; (b) B. Moreno, C. Quehen, M. Rose-Hélène, E. Leclerc, J. C. Quirion, *Org. Lett.* **2007**, *9*, 2477.

[20]   (a) A. Studer, *Angew. Chem. Int. Ed.* **2012**, *51*, 8950. *Angew. Chem.,* **2012**, *124*, 9082; (b) D. Leifert, A. Studer, *Angew. Chem., Int. Ed.* **2016**, *55*, 11660. *Angew. Chem.* **2016**, *128*, 11832.

[21]   X.-J. Tang, Z. Zhang, W. R. Dolbier, Jr., *Chem. Eur. J.* **2015**, 21, 18961.

[22]   G. Kraus, B. Andersh, Q. Su, J. Shi, *Tetrahedron Lett.* **1993**, *34*, 1741.

[23]   Rate constant for sulfonyl radical addition, see: C. Chatgilialoglu, O. Mozziconacci, M. Tamba, K. Bobrowski, G. Kciuk, M. P. Bertrand, S. Gastaldi, V. I. Timokhin, *J. Phys. Chem. A* **2012**, *116*, 7623. Rate constant for sulfonyl radical β-elimination, see: (a) P. J. Wagner, J. H. Sedon, M. J. Lindstrom, *J. Am. Chem. Soc.* **1978**, *100*, 2579; (b) V. I. Timokhin, S. Gastaldi, M. P. Bertrand, C. Chatgilialoglu, *J. Org. Chem.* **2003**, *68*, 3532.