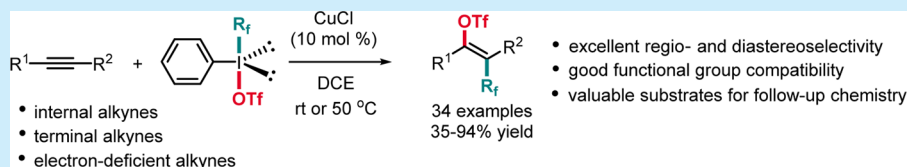


Regio- and Stereoselective Radical Perfluoroalkyltriflation of Alkynes Using Phenyl(perfluoroalkyl)iodonium Triflates

Xi Wang and Armido Studer*^{1b}

Institute of Organic Chemistry, University of Münster, Corrensstrasse 40, 48149 Münster, Germany

S Supporting Information



ABSTRACT: A method for regio- and stereoselective anti-addition of the perfluoroalkyl and the triflate group of phenyl(perfluoroalkyl)iodonium triflates to alkynes is presented. The radical reaction uses cheap CuCl as a smart initiator and can be conducted in gram scale. The perfluoroalkyltriflated products are readily further functionalized, rendering this transformation valuable.

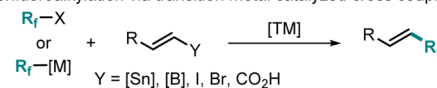
Fluorinated building blocks have been widely used for preparation of pharmaceuticals, agrochemicals, and functional materials.¹ This is due to the unique properties exerted by the F-substituents such as increased lipophilicity, higher metabolic stability, and better bioavailability.² Therefore, the development of methods to introduce perfluoroalkyl groups (R_f) into organic components is important.³

Recently, remarkable developments to attach R_f groups to (hetero)arenes,⁴ benzylic positions,^{5a} allylic positions,^{5b} the α -position of carbonyl groups,^{5c,d} and heteroatoms⁶ have been achieved. Enantioselective perfluoroalkylation was established,⁷ and the synthesis of vinyl perfluoroalkanes is also in high demand. Common strategies to access them involve transition metal catalyzed or mediated cross-coupling of halides or carboxylic acids with organometallic reagents (Scheme 1A).⁸ Nevado disclosed a Pd-catalyzed three-component arylperfluoroalkylation of terminal alkynes (Scheme 1B),^{9a} and the Chaladaj group reported arylperfluoroalkylation of internal alkynes using Pd-catalysis.^{9b} Other straightforward approaches to vinyl perfluoroalkanes include direct radical C–H perfluoroalkylation of alkenes,¹⁰ hydroperfluoroalkylation of alkynes,¹¹ and alkyne perfluoroalkyliodination (Scheme 1C).¹² Notably, *trans*-selective trifluoromethyltriflation of internal alkynes via photoredox catalysis has been developed by Akita and Koike (Scheme 1D).^{13f} Although many valuable methods for the synthesis of vinyl perfluoroalkanes have been developed, some problems still remain to be solved. Most of the reported perfluoroalkylations suffer at least from one of the following limitations: harsh reaction conditions, narrow substrate scope, low *E/Z* selectivity, and moderate yield. Therefore, novel approaches to address these drawbacks are desirable.

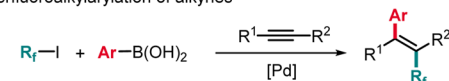
Alkenyl triflates have been intensively applied as vinyl-organometallic precursors in cross-coupling reactions. The traditional route for their preparation proceeds via trapping of a deprotonated ketone with a triflating reagent (usually Trf_2O or PhNTf_2). Such triflates can also be accessed using $\text{HOTf}^{13a,b}$ or

Scheme 1. Synthesis of Vinyl Perfluoroalkanes

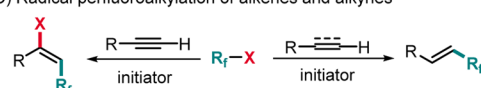
(A) Perfluoroalkylation via transition metal catalyzed cross coupling⁸



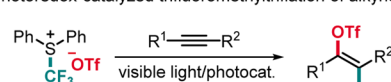
(B) Perfluoroalkylarylation of alkynes⁹



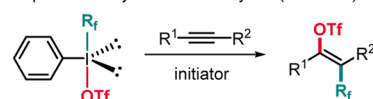
(C) Radical perfluoroalkylation of alkenes and alkynes^{10,11,12}



(D) Photoredox-catalyzed trifluoromethyltriflation of alkynes^{13f}



(E) Radical perfluoroalkyltriflation of alkynes (*this work*)



AgOTf^{13c} as triflate sources. Recently, electrophile induced triflation of alkynes with electrophilic reagents bearing $^- \text{OTf}$ as the counteranion has been developed (aryl and vinyl triflation by Gaunt^{13d} and cyanotriflation by our group^{13e}).

Hypervalent iodine(III) reagents¹⁴ of the benziodoxole type or the iodonium salt type are generally used as electrophiles where only one I(III)-ligand gets transferred to the substrate. Sequential transfer of two ligands from an iodine(III) compound to a carbon–carbon unsaturated bond would certainly improve atom

Received: April 21, 2017

Published: May 18, 2017

economy, but such transformations are rare.^{13d,e,15a–e} For example, the Waser group described an elegant strategy for oxyalkynylation of diazo compounds with alkynylbenziodoxoles.^{15f} We herein report highly regio- and stereoselective perfluoroalkyltriflation of various alkynes with phenyl(perfluoroalkyl)iodonium triflates¹⁶ using radical chemistry (Scheme 1D). The method shows remarkable substrate scope and proceeds under mild conditions. The potential of the sequence is documented by various follow-up transformations and by the successful preparation of a fluorinated drug.

Initial screening was performed with ethyl 4-(pent-1-yn-1-yl)benzoate **1a** and 1.0 equiv of iodine(III) reagent **2a** (PhI(C₃F₇)OTf) in various solvents at room temperature for 4 h. Pleasingly, we found that in dichloroethane (DCE) the perfluoroalkylated triflate **3a** was obtained in 49% yield with complete regio- and *E*-selectivity (Table 1, entry 6). The relative

Table 1. Reaction Optimization

entry ^a	additive	2a (equiv)	solvent	time (h)	yield (%) ^b
1	none	1.0	MeOH	4	0
2	none	1.0	Et ₂ O	4	0
3	none	1.0	MeCN	4	11
4	none	1.0	DCM	4	40
5	none	1.0	CHCl ₃	4	25
6	none	1.0	DCE	4	49
7	none	1.0	DCE	15	53
8	none	1.7	DCE	15	69
9	pyridine (1.7 equiv)	1.7	DCE	15	86
10	K ₂ CO ₃ (1.7 equiv)	1.7	DCE	15	78
11	BF ₃ ·Et ₂ O (1.7 equiv)	1.7	DCE	15	75
12	TfOH (1.7 equiv)	1.7	DCE	15	53
13	TBAI (10 mol %)	1.7	DCE	15	86
14	CuCl (10 mol %)	1.7	DCE	15	91
15 ^d	CuCl (10 mol %)	1.7	DCE	15	96 (94) ^c

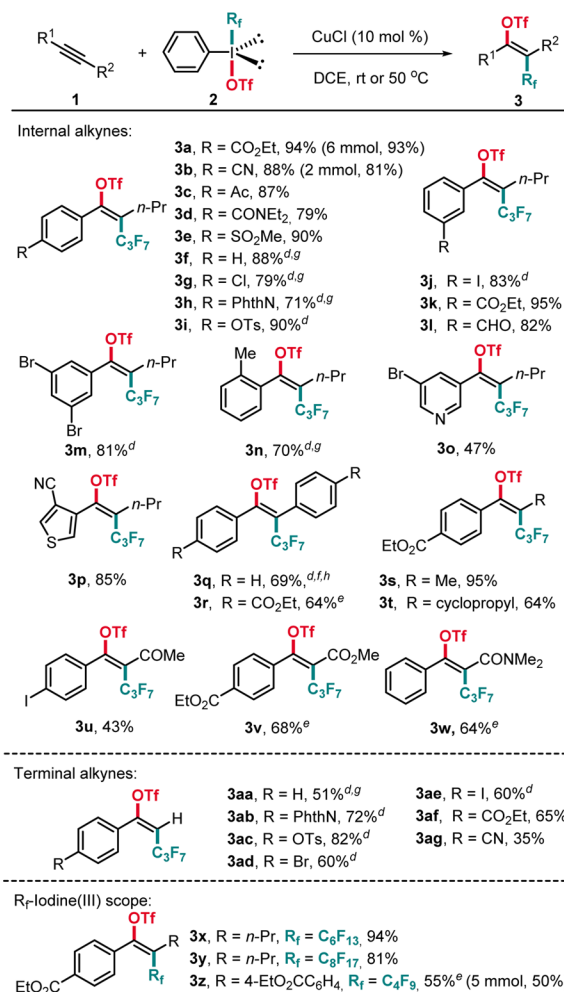
^aReaction conditions: **1a** (0.10 mmol, 1.0 equiv), reagent **2a**, additive, solvent (1 mL), room temperature. ^bYield determined by ¹⁹F NMR analysis using PhCF₃ as an internal standard; isomer ratio determined by ¹⁹F NMR and GC-MS analysis on the crude product, *E/Z* > 20:1. ^cIsolated yield. ^dConducted at 50 °C.

configuration of **3e**, **3r**, and **3v** (see below) was assigned by NOE experiments, and all other compounds were assigned in analogy. Reaction did not work in MeOH or Et₂O, and lower yields were achieved in MeCN, dichloromethane (DCM), and CHCl₃ (Table 1, entries 1–5). Prolonging the reaction time to 15 h slightly improved the yield (Table 1, entry 7), and increasing the amount of **2a** from 1.0 to 1.7 equiv let to a better result (Table 1, entry 8). The yield was further improved upon adding 1.7 equiv of a base such as pyridine or K₂CO₃ providing the target product **3a** in 86% and 78% yield, respectively (Table 1, entries 9–10). A similar effect was achieved with BF₃·Et₂O as an additive (Table 1, entry 11), whereas perfluoroalkyltriflation in the presence of TfOH was lower yielding (Table 1, entry 12). Both tetrabutylammonium iodide (TBAI) and CuCl as additives (10 mol %), which are often used for SET reduction of iodine(III) reagents,¹⁷ enhanced reaction efficiency (Table 1, entries 13–14). The highest yield

was obtained at 50 °C using 10 mol % of CuCl to afford **3a** in 94% isolated yield (Table 1, entry 15).

Having established the optimized conditions, we first explored the scope with respect to the alkyne component and investigated internal alkynes (Scheme 2). Various 1-aryl-1-pentynes bearing

Scheme 2. Alkyne and I(III)-Reagent Scope^{a,b,c}



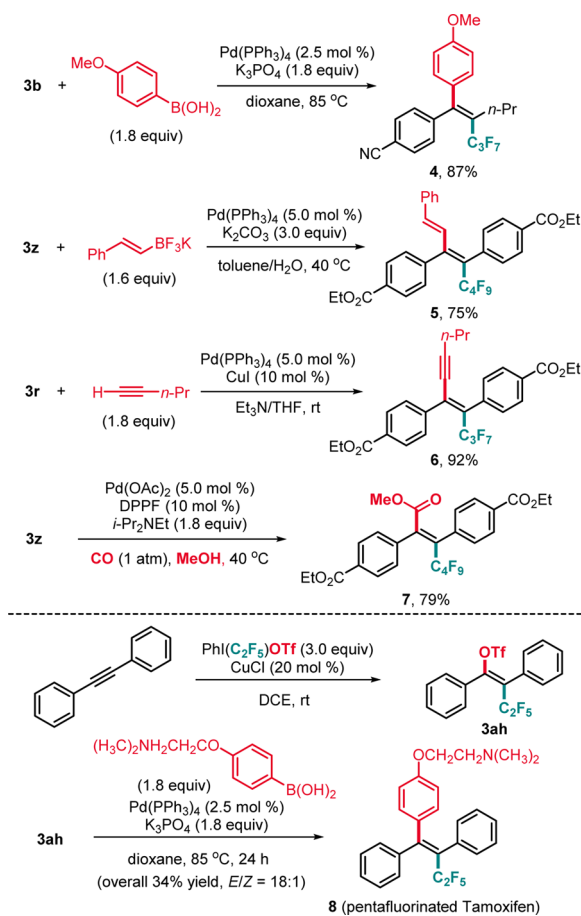
^aReaction conditions: **1** (0.10 mmol, 1.0 equiv), **2** (0.17 mmol, 1.7 equiv), CuCl (0.01 mmol, 10 mol %), DCM (1 mL), 45 °C, 15 h. ^bIsolated yield. ^c*E/Z* isomer ratio determined by ¹⁹F NMR analysis and GC-MS analysis on the crude product. Unless noted otherwise, *E/Z* > 20:1. ^d**1** (0.10 mmol, 1.0 equiv), **2** (0.15 mmol, 1.5 equiv), CuCl (0.01 mmol, 10 mol %), and DCM (1 mL), room temperature, 24 h. ^eAfter 15 h, renewed CuCl (0.01 mmol, 10 mol %), **2** (0.17 mmol, 1.7 equiv), and DCM (1 mL) addition and continued stirring at 45 °C for another 15 h. ^fAfter 24 h, renewed CuCl (0.01 mmol, 10 mol %), **2** (0.15 mmol, 1.5 equiv), and DCM (1 mL) addition and continued stirring at room temperature for another 24 h. ^gYield determined by ¹⁹F NMR analysis using PhCF₃ as an internal standard. ^h*E/Z* = 17:1.

substituents at the para-, ortho-, and meta-position of the aryl group were successfully converted in good yields with excellent regio- and stereoselectivity (**3a–n**). Heteroaryl substituents such as pyridyl and thienyl are tolerated, and **3o** and **3p** were obtained in moderate to high yields. Symmetrical diaryl alkynes are suitable substrates as documented by the preparation of **3q** and **3r**. Complete regioselectivity and *E*-selectivity were also observed with methyl (**3s**) and cyclopropyl (**3t**) aryl alkynes.

Although functionalization of electron-deficient alkynes with electrophilic reagents is challenging our method proved to be applicable to such alkynes as documented by the successful transformation of an ynone (**3u**), a propiolic ester (**3v**), and a propiolic amide (**3w**). We next attempted to expand the newly established method to the conversion of terminal alkynes and could show that arylacetylenes bearing either electron-withdrawing or -donating groups reacted efficiently to afford the corresponding perfluoroalkyltriflation products with complete *E*-selectivity in moderate to good yields (**3aa–3ag**). Unfortunately, reactions with dialkyl alkynes failed and starting materials remained unreacted. Notably, our reaction can be conducted on gram scale without compromising the yield (**3a**, **3b**, **3z**). We found that the perfluoroalkyl group in the I(III) reagent can be readily varied as shown for the perfluorobutyl, perfluorohexyl, and perfluorooctyl congeners in the reaction with the alkyne **1a**. The corresponding products **3x–z** were obtained in good yields and excellent selectivities.

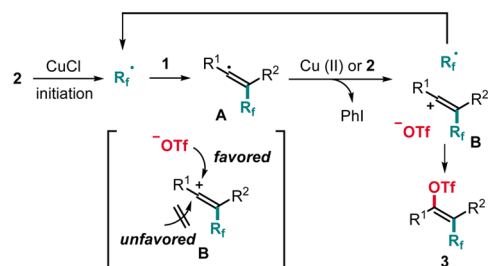
To demonstrate the synthetic value of the method, we investigated follow-up chemistry and could show that compounds of type **3** engage in various stereospecific Pd-catalyzed cross-coupling reactions, including alkenyl-aryl and alkenyl-alkenyl Suzuki couplings (**4**, **5**), the Sonogashira reaction (**6**), and methoxycarbonylation (**7**) (Scheme 3). Moreover, pentafluorinated Tamoxifen **8** was prepared in acceptable overall yield and high *E/Z* selectivity via a pentafluoroethyltriflation/Suzuki coupling sequence.¹⁸

Scheme 3. Further Functionalization of Perfluoroalkyltriflated Products



The suggested mechanism is depicted in Scheme 4. Initiation likely occurs by SET reduction of **2** with CuCl to give the R_f -

Scheme 4. Suggested Mechanism



radical along with $\text{Cu}(\text{II})\text{ClOTf}$.^{16,17} R_f -radical addition to the alkyne leads to the vinyl radical **A** which further reacts via SET oxidation by the I(III)-reagent **2** to form the vinylic cation **B** along with PhI and the R_f -radical sustaining the chain. The observation that without a Cu -salt reaction proceeds in acceptable yields clearly shows that oxidation of **A** with reagent **2** is rather efficient, and hence the sequence belongs to an electron-catalyzed process¹⁹ where the Cu -salt acts as a smart initiator.^{19b} Thus, regeneration of the initiating $\text{Cu}(\text{I})$ -complex is occurring via occasional reaction of **A** with the $\text{Cu}(\text{II})$ -salt. Trapping of **B** with the triflate anion eventually affords **3**. The high *E*-selectivity can be explained by the larger steric hindrance of the R_f group as compared to the R^2 substituent and by the electrostatic repulsion of the R_f -substituent and the incoming triflate during trapping.^{13f,20}

In summary, we have demonstrated a general and practical protocol for direct vicinal alkyne perfluoroalkyltriflation. Prominent features of this process include mild reaction conditions, compatibility with both internal and terminal alkynes, excellent *E*-selectivity and complete regioselectivity, generally high yields, and easy scale up. Various follow-up reactions document that the tetrasubstituted vinyl triflates obtained as products are valuable building blocks in synthesis.

■ ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge on the ACS Publications website at DOI: 10.1021/acs.orglett.7b01215.

Experimental procedures and characterization data (PDF)

■ AUTHOR INFORMATION

Corresponding Author

*E-mail: studer@uni-muenster.de.

ORCID

Armido Studer: 0000-0002-1706-513X

Notes

The authors declare no competing financial interest.

■ ACKNOWLEDGMENTS

This work was supported by the Alexander von Humboldt Foundation (postdoctoral fellowship to X.W.) and the European Research Council (ERC Advanced Grant Agreement No. 692640).

REFERENCES

- (1) (a) Uneyama, K. *Organofluorine Chemistry*; Blackwell: Oxford, U.K., 2006. (b) Müller, K.; Faeh, C.; Diederich, F. *Science* **2007**, *317*, 1881–1886. (c) Bégué, J. P.; Bonnet-Delpon, D. *Bioorganic and Medicinal Chemistry of Fluorine*; Wiley-Interscience: Hoboken, NJ, 2008. (d) Ojima, I. *Fluorine in Medicinal Chemistry and Chemical Biology*; Wiley-Blackwell: Chichester, U.K., 2009.
- (2) (a) Purser, S.; Moore, P. R.; Swallow, S.; Gouverneur, V. *Chem. Soc. Rev.* **2008**, *37*, 320–330. (b) Roy, S.; Gregg, B. T.; Gribble, G. W.; Le, V.; Roy, S. *Tetrahedron* **2011**, *67*, 2161–2195. (c) Tomashenko, O.; Grushin, V. V. *Chem. Rev.* **2011**, *111*, 4475–4521.
- (3) For reviews, see: (a) Umamoto, T. *Chem. Rev.* **1996**, *96*, 1757–1777. (b) Prakash, G. K. S.; Yudin, A. K. *Chem. Rev.* **1997**, *97*, 757–786. (c) Liang, T.; Neumann, C. N.; Ritter, T. *Angew. Chem., Int. Ed.* **2013**, *52*, 8214–8264.
- (4) (a) Kobayashi, Y.; Kumadaki, I. *Tetrahedron Lett.* **1969**, *10*, 4095–4096. (b) McLaughlin, V. C. R.; Thrower, J. *Tetrahedron* **1969**, *25*, 5921–5940. (c) Morimoto, H.; Tsubogo, T.; Litvinas, N. D.; Hartwig, J. F. *Angew. Chem., Int. Ed.* **2011**, *50*, 3793–3798. (d) Litvinas, N. D.; Fier, P. S.; Hartwig, J. F. *Angew. Chem., Int. Ed.* **2012**, *51*, 536–539. (e) Popov, I.; Lindeman, S.; Daugulis, O. *J. Am. Chem. Soc.* **2011**, *133*, 9286–9289. (f) Qi, Q.; Shen, Q.; Lu, L. *J. Am. Chem. Soc.* **2012**, *134*, 6548–6551. (g) Zhang, B.; Mück-Lichtenfeld, C.; Daniliuc, C. G.; Studer, A. *Angew. Chem., Int. Ed.* **2013**, *52*, 10792–10795. (h) Nagase, M.; Kuninobu, Y.; Kanai, M. *J. Am. Chem. Soc.* **2016**, *138*, 6103–6106.
- (5) (a) Kuninobu, Y.; Nagase, M.; Kanai, M. *Angew. Chem., Int. Ed.* **2015**, *54*, 10263–10266. (b) Kawamura, S.; Sodeoka, M. *Angew. Chem., Int. Ed.* **2016**, *55*, 8740–8743. (c) Su, X.; Huang, H.; Yuan, Y.; Li, Y. *Angew. Chem., Int. Ed.* **2017**, *56*, 1338–1341. (d) Kawamoto, T.; Sasaki, R.; Kamimura, A. *Angew. Chem., Int. Ed.* **2017**, *56*, 1342–1345.
- (6) (a) Feiring, A. E. *J. Fluorine Chem.* **1984**, *24*, 191–203. (b) Koshechko, V. G.; Kiprianova, L. A.; Fileleeva, L. I. *Tetrahedron Lett.* **1992**, *33*, 6677–6678. (c) Boiko, V. N.; Shchupak, G. M. *J. Fluorine Chem.* **1994**, *69*, 207–212. (d) Kiss, L. E.; Rábai, J.; Varga, L.; Kövesdi, I. *Synlett* **1998**, 1998, 1243–1245. Kawaguchi, S.-i.; Minamida, Y.; Ohe, T.; Nomoto, A.; Sonoda, M.; Ogawa, A. *Angew. Chem., Int. Ed.* **2013**, *52*, 1748–1752.
- (7) (a) Nagib, D. A.; Scott, M. E.; MacMillan, D. W. C. *J. Am. Chem. Soc.* **2009**, *131*, 10875–10877. (b) Herrmann, A. T.; Smith, L. L.; Zakarian, A. *J. Am. Chem. Soc.* **2012**, *134*, 6976–6979. (c) Woźniak, Ł.; Murphy, J. J.; Melchiorre, P. *J. Am. Chem. Soc.* **2015**, *137*, 5678–5681.
- (8) (a) Matsubara, S.; Mitani, M.; Utimoto, K. *Tetrahedron Lett.* **1987**, *28*, 5857–5860. (b) Lishchynskiy, A.; Grushin, V. V. *J. Am. Chem. Soc.* **2013**, *135*, 12584–12587. (c) Serizawa, H.; Aikawa, K.; Mikami, K. *Org. Lett.* **2014**, *16*, 3456–3459. (d) Saijo, H.; Ohashi, M.; Ogoshi, S. *J. Am. Chem. Soc.* **2014**, *136*, 15158–15161. (e) Lishchynskiy, A.; Mazloomi, Z.; Grushin, V. V. *Synlett* **2014**, 26, 45–50. (f) Aikawa, K.; Nakamura, Y.; Yokota, Y.; Toya, W.; Mikami, K. *Chem. - Eur. J.* **2015**, *21*, 96–100. (g) Lai, Y.-L.; Lin, D.-Z.; Huang, J.-M. *J. Org. Chem.* **2017**, *82*, 597–605.
- (9) (a) Li, Z.; García-Domínguez, A.; Nevado, C. *J. Am. Chem. Soc.* **2015**, *137*, 11610–11613. (b) Domański, S.; Chaladaj, W. *ACS Catal.* **2016**, *6*, 3452–3456. (c) Li, Z.; Merino, E.; Nevado, C. *Top. Catal.* **2017**, DOI: 10.1007/s11244-017-0743-y.
- (10) (a) Yajima, T.; Jahan, I.; Tono, T.; Shinmen, M.; Nishikawa, A.; Yamaguchi, K.; Sekine, I.; Nagano, H. *Tetrahedron* **2012**, *68*, 6856–6861. (b) Lin, Q.-Y.; Xu, X.-H.; Qing, F.-L. *J. Org. Chem.* **2014**, *79*, 10434–10446. (c) Sladojevich, F.; McNeill, E.; Bçrgel, J.; Zheng, S.-L.; Ritter, T. *Angew. Chem., Int. Ed.* **2015**, *54*, 3712–3716. (d) Straathof, N. J. W.; Cramer, S. E.; Hessel, V.; Noël, T. *Angew. Chem., Int. Ed.* **2016**, *55*, 15549–15553.
- (11) (a) Hu, C.-M.; Qiu, Y.-L. *J. Fluorine Chem.* **1991**, *55*, 113–115. (b) Long, Z.-Y.; Chen, Q.-Y. *J. Org. Chem.* **1999**, *64*, 4775–4782.
- (12) (a) Ishihara, T.; Kuroboshi, M.; Okada, Y. *Chem. Lett.* **1986**, *15*, 1895–1896. (b) Huang, W.-Y.; Hu, L.-Q. *J. Fluorine Chem.* **1989**, *44*, 25–44. (c) Takeyama, Y.; Ichinose, Y.; Oshima, K.; Utimoto, K. *Tetrahedron Lett.* **1989**, *30*, 3159–3162. (d) Abou-Ghazaleh, B.; Laurent, Ph.; Blancou, H.; Commeyras, A. *J. Fluorine Chem.* **1994**, *68*, 21–24. (e) Nakamura, T.; Yorimitsu, H.; Shinokubo, H.; Oshima, K. *Synlett* **1998**, 1998, 1351–1352. (f) Jennings, M. P.; Cork, E. A.; Ramachandran, P. V. *J. Org. Chem.* **2000**, *65*, 8763–8766. (g) Amato, C.; Naud, C.; Calas, P.; Commeyras, A. *J. Fluorine Chem.* **2002**, *113*, 55–63. (h) Motoda, D.; Kinoshita, H.; Shinokubo, H.; Oshima, K. *Adv. Synth. Catal.* **2002**, *344*, 261–265. (i) Tsuchii, K.; Imura, M.; Kamada, N.; Hirao, T.; Ogawa, A. *J. Org. Chem.* **2004**, *69*, 6658–6665. (j) Takagi, T.; Kanamori, T. *J. Fluorine Chem.* **2011**, *132*, 427–429. (k) Slodowicz, M.; Barata-Vallejo, S.; Vázquez, A.; Nudelman, N. S.; Postigo, A. *J. Fluorine Chem.* **2012**, *135*, 137–143. (l) Xu, T.; Cheung, C. W.; Hu, X. *Angew. Chem., Int. Ed.* **2014**, *53*, 4910–4914. (m) Choi, S.; Kim, Y. J.; Kim, S. M.; Yang, J. W.; Kim, S. W.; Cho, E. *J. Nat. Commun.* **2014**, *5*, 4881. (n) Beniazza, R.; Atkinson, R.; Absalon, C.; Castet, F.; Denisov, S. A.; McClenaghan, N. D.; Lastécouères, D.; Vincent, J.-M. *Adv. Synth. Catal.* **2016**, *358*, 2949–2961.
- (13) (a) Alonso, P.; Pardo, P.; Galván, A.; Fañanás, F. J.; Rodríguez, F. *Angew. Chem., Int. Ed.* **2015**, *54*, 15506–15510. (b) Wu, J.-J.; Xu, J.; Zhao, X. *Chem. - Eur. J.* **2016**, *22*, 15265–15269. (c) Al-huniti, M. H.; Lepore, S. D. *Org. Lett.* **2014**, *16*, 4154–4157. (d) Suero, M. G.; Bayle, E. D.; Collins, B. S. L.; Gaunt, M. J. *J. Am. Chem. Soc.* **2013**, *135*, 5332–5335. (e) Wang, X.; Studer, A. *J. Am. Chem. Soc.* **2016**, *138*, 2977–2980. (f) Tomita, R.; Koike, T.; Akita, M. *Angew. Chem., Int. Ed.* **2015**, *54*, 12923–12927.
- (14) Reviews: (a) Zhdankin, V. V.; Stang, P. J. *Chem. Rev.* **2008**, *108*, 5299–5358. (b) Yoshimura, A.; Zhdankin, V. V. *Chem. Rev.* **2016**, *116*, 3328–3435.
- (15) (a) Celik, M.; Alp, C.; Coskun, B.; Gültekin, M. S.; Balci, M. *Tetrahedron Lett.* **2006**, *47*, 3659–3663. (b) Egami, H.; Shimizu, R.; Sodeoka, M. *Tetrahedron Lett.* **2012**, *53*, 5503–5506. (c) Egami, H.; Shimizu, R.; Usui, Y.; Sodeoka, M. *J. Fluorine Chem.* **2014**, *167*, 172–178. (d) Janson, P. G.; Ghoneim, I.; Ilchenko, N. O.; Szabó, K. J. *Org. Lett.* **2012**, *14*, 2882–2885. (e) Wang, Y.; Jiang, M.; Liu, J.-T. *Adv. Synth. Catal.* **2014**, *356*, 2907–2912. (f) Hari, D. P.; Waser, J. *J. Am. Chem. Soc.* **2016**, *138*, 2190–2193.
- (16) ArI(R)₂OTf: (a) Umamoto, T.; Kuriu, Y. *Tetrahedron Lett.* **1981**, *22*, 5197–5200. (b) Umamoto, T.; Kuriu, Y.; Shuyama, H.; Miyano, O.; Nakayama, S.-I. *J. Fluorine Chem.* **1982**, *20*, 695–698. (c) Umeoto, T.; Kuriu, Y.; Nakayama, S.-i. *Tetrahedron Lett.* **1982**, *23*, 1169–1172. (d) Umamoto, T.; Kuriu, Y.; Miyano, O. *Tetrahedron Lett.* **1982**, *23*, 3579–3582. (e) Umamoto, T.; Gotoh, Y. *Bull. Chem. Soc. Jpn.* **1986**, *59*, 439–445.
- (17) For SET reduction of hypervalent iodine (III) reagents, see: (a) Dohi, T.; Ito, M.; Morimoto, K.; Iwata, M.; Kita, Y. *Angew. Chem., Int. Ed.* **2008**, *47*, 1301–1304. (b) Dohi, T.; Ito, M.; Yamaoka, N.; Morimoto, K.; Fujioka, H.; Kita, Y. *Angew. Chem., Int. Ed.* **2010**, *49*, 3334–3337. (c) Wang, X.; Ye, Y.; Zhang, S.; Feng, J.; Xu, Y.; Zhang, Y.; Wang, J. *J. Am. Chem. Soc.* **2011**, *133*, 16410–16413. (d) Parsons, A. T.; Buchwald, S. L. *Angew. Chem., Int. Ed.* **2011**, *50*, 9120–9123. (e) Mejía, E.; Togni, A. *ACS Catal.* **2012**, *2*, 521–527. (f) Li, Y.; Studer, A. *Angew. Chem., Int. Ed.* **2012**, *51*, 8221–8224. (g) Zhang, B.; Mück-Lichtenfeld, C.; Daniliuc, C. G.; Studer, A. *Angew. Chem., Int. Ed.* **2013**, *52*, 10792–10795. (h) Wang, Y.; Zhang, L.; Yang, Y.; Zhang, P.; Du, Z.; Wang, C. *J. Am. Chem. Soc.* **2013**, *135*, 18048–18051. (i) Moteki, S. A.; Usui, A.; Selvakumar, S.; Zhang, T.; Maruoka, K. *Angew. Chem., Int. Ed.* **2014**, *53*, 11060–11064. (j) Jia, K.; Zhang, F.; Huang, H.; Chen, Y. *J. Am. Chem. Soc.* **2016**, *138*, 1514–1517.
- (18) (a) Salih, A. K.; Fentiman, I. S. *Cancer Treat. Rev.* **2001**, *27*, 261–273. (b) Jordan, V. C. *J. Med. Chem.* **2003**, *46*, 883–908.
- (19) (a) Studer, A.; Curran, D. P. *Nat. Chem.* **2014**, *6*, 765–773. (b) Studer, A.; Curran, D. P. *Angew. Chem., Int. Ed.* **2016**, *55*, 58–102.
- (20) (a) Lemay, A. B.; Vulic, K. S.; Ogilvie, W. W. *J. Org. Chem.* **2006**, *71*, 3615–3618. (b) Ide, M.; Yauchi, Y.; Shiogai, R.; Iwasawa, T. *Tetrahedron* **2014**, *70*, 8532–8538. (c) Yauchi, Y.; Ide, M.; Shiogai, R.; Chikugo, T.; Iwasawa, T. *Eur. J. Org. Chem.* **2015**, 2015, 938–943. (d) Sproul, K. C.; Chalifoux, W. A. *Org. Lett.* **2015**, *17*, 3334–3337.