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Hypervalent Iodine-Mediated Fluorination of Styrene Derivatives: Stoichiometric and Catalytic Transformation to 2,2-Difluoroethylarenes

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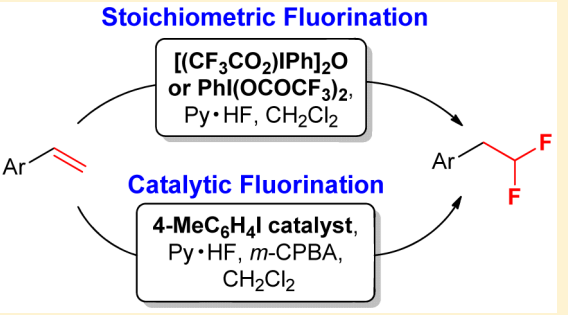
Supporting Information

ABSTRACT: Fluorination of styrene derivatives with a reagent system composed of μ-oxo-bis[trifluoroacetato(phenyl)iodine] and a pyridine·HF complex gave the corresponding (2,2-difluoroethyl)arenes in good yields. Similarly, the reagent of $PhI(OCOCF_3)_2$ and the pyridine·HF complex acted as a fluorinating agent for styrene derivatives. The fluorination of styrene derivatives with the pyridine·HF complex underwent under catalytic conditions using 4-iodotoluene as a catalyst and *m*-CPBA as a terminal oxidant.



INTRODUCTION

Introduction of fluorine atoms into organic molecules strongly affects on the chemical, physical, and biological properties. The unique properties have proven to be important in the pharmaceutical, agrochemical, and materials industries. Especially, trifluoromethyl and the related groups have been used as active components of pharmaceuticals and agrochemicals, and the synthetic methods of fluoroalkylated compounds have been widely investigated so far.[1] Similarly, introduction of a 2,2,2-trifluoroethyl group into organic molecules has been conducted using several methodologies.[2]

On the other hand, it is also expected that the 2,2-difluoroethyl group has the ability to modify the biological properties. Rueeger et al. reported that introduction of a 2,2-difluoroethyl group into an indole derivative enhances the biological activity compared with the corresponding 2,2,2-trifluoroethylated compound.[3] However, a direct introduction of a 2,2-difluoroethyl group has not been conducted before. At present, functional group transformation is a suitable strategy for the construction of a *gem*-difluoroethyl moiety. The synthesis of organic molecules bearing *gem*-difluoroethyl side chains has been conducted by several methods such as (1) fluorination of styrene derivatives using fluorinated hypervalent iodine compounds or iodine/XeF_2,[4] (2) reaction of organozinc reagents and potassium bromodifluoroacetate,[5] (3) fluorination of *gem*-bistriflates and *gem*-dihalides,[6] (4) fluorodecarboxylation of dicarboxylic acids,[7] and (5) chlorodifluoromethylation followed by the elimination of HCl and the migration of a double bond.[8] The outline is shown in Scheme 1.

Among the above methods, the fluorination reaction of styrene-derivative-mediated hypervalent iodine can construct aromatic compounds bearing 2,2-difluoroethyl moieties. This method deserves attention as a direct transformation method of the vinyl group on the aromatic ring into the corresponding 2,2-difluoroethyl group. Although the transformation of a vinyl group into a 2,2-difluoroethyl group accompanies the migration of an aryl group, as shown in Scheme 2, this method is convenient and useful in organic synthesis. The previous procedures for the hypervalent iodine-mediated 2,2-difluoroethyl group construction require (difluoroiodo)arenes or Togni's reagent as a hypervalent iodine-fluorinating reagent. (Difluoroiodo)arenes must be prepared before use, and they cannot be stored for a long time due to their instability. Although Togni's reagent is commercially available, it is expensive. Thus, we studied to find a simple and convenient reagent system for the construction of the 2,2-difluoroethyl group. For this purpose, we prepared in situ a hypervalent iodine reagent and used it for the fluorination of styrene derivatives. This method provided a convenient and practical fluorination reaction, giving 2,2-difluoroethyl-substituted arenes, and served to conduct a catalytic fluorination reaction. Here we report the convenient and practical construction of 2,2-difluoroethylarenes by a hypervalent iodine-mediated fluorination reaction of styrene derivatives. Also, we found that this fluorination proceeded with a catalytic amount of iodoarenes in the presence of *m*-CPBA as a terminal oxidant.

RESULTS AND DISCUSSION

Stoichiometric Fluorination with Hypervalent Iodine/HF Reagents. First, we chose styrene **1a** as the model substrate and the pyridine·HF complex (Py·HF) as the fluorine

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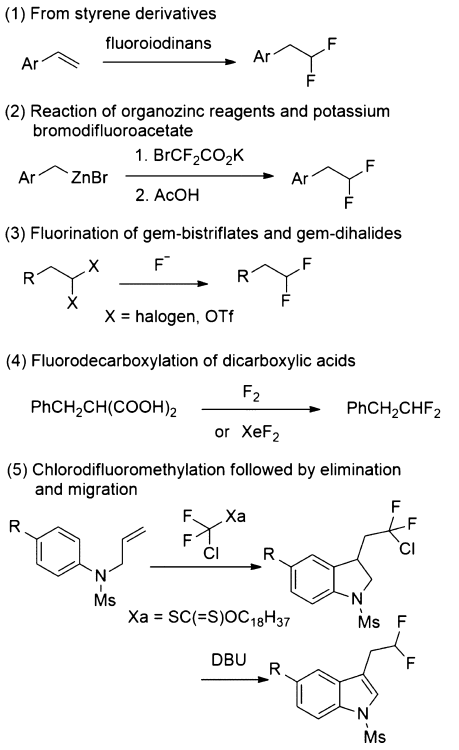
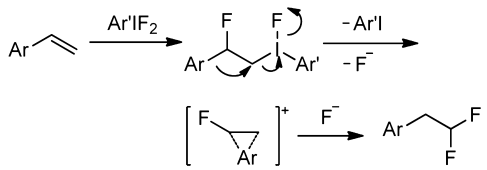
Scheme 1. Known Methods for Construction of a 2,2-Difluoroethyl Group

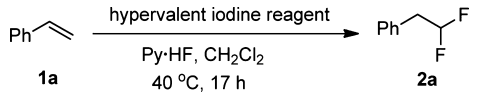


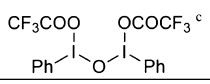
Scheme 2. Hypervalent Iodine-Mediated Transformation of Styrenes to 2,2-Difluoroethylarenes



source for the optimization of reaction conditions. Because a hypervalent iodine reagent was essential as a mediator in the previous fluorination reactions of carbonyl compounds,[9] we started to screen the hypervalent iodine reagents. The results are given in Table 1. When iodosylbenzene (PhIO) was used together with the Py·HF reagent, the reaction of **1a** in CH_2Cl_2 at 40 °C for 17 h gave (2,2-difluoroethyl)benzene (**2a**) in 43% yield (entry 1). Although the use of $PhI(OAc)_2$ increased the yield to 59%, Koser's salt [hydroxyl(tosyloxy)iodobenzene] resulted in a decrease of the yield (entry 3). When a less nucleophilic $PhI(OCOCF_3)_2$ was used as a promoter, the yield was increased to 60% (entry 4). The reaction of **1a** using μ-oxo-bis[trifluoroacetato(phenyl)iodine], $[(CF_3CO_2)IPh]_2O$, gave the highest yield of **2b** (61%) (entry 5). $PhI(OAc)_2$ and $PhI(OCOCF_3)_2$ gave comparable yields, but $PhI(OCOCF_3)_2$ gave a cleaner reaction mixture. Then, we determined to use $[(CF_3CO_2)IPh]_2O$ for further optimization of the reaction conditions.

Table 1. Effect of Hypervalent Iodine Reagents on the Fluorination of Styrene 1a[a]

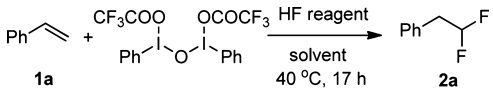


Entry	Reagent	Yield (%)[b]
1	PhIO	43
2	$PhI(OAc)_2$	59
3	PhI(OH)OTs	21
4	$PhI(OCOCF_3)_2$	60
5	 [c]	61

[a]Conditions: **1a** (0.2 mmol), hypervalent iodine reagent (0.24 mmol), pyridine·HF (2 mmol HF), and CH_2Cl_2 (2 mL) at 40 °C for 17 h. [b]Yield was determined by ^{19}F NMR. [c]With 0.12 mmol.

Using $[(CF_3CO_2)IPh]_2O$, HF reagents as the fluorine source were screened again. The results are given in Table 2. Although

Table 2. Effects of HF Reagents and Solvents on the Fluorination of Styrene 1a[a]



entry	HF reagent	solvent	yield (%)[b]
1	55% aq HF	CH_2Cl_2	34
2	TEA·5HF	CH_2Cl_2	46
3	TEA·3HF	CH_2Cl_2	trace
4	KF	CH_2Cl_2	0
5	Py·HF	DCE	52
6	Py·HF	1,2-DCB	53
7	Py·HF	toluene	24
8	Py·HF	other solvents[c]	0

[a]Conditions: **1a** (0.2 mmol), $[(CF_3CO_2)IPh]_2O$ (0.12 mmol), HF reagent (2 mmol HF), and solvent (2 mL). [b]Yield was determined by ^{19}F NMR. [c]MeCN, DMF, DME, diglyme, and THF.

the reaction with the Py·HF reagent provided **2a** in 61% yield, 55% aqueous HF and TEA·5HF reagents decreased the yields to 34 and 46%, respectively (entries 1 and 2). TEA·3HF and KF were not suitable for this fluorination (entries 3 and 4). Next, we examined solvents using the Py·HF reagent, but the yield was not improved (entries 5–8).

Since we found the best reagent system for the fluorination of **1a**, we further optimized the conditions. The results are given in Table 3. When the amount of the Py·HF reagent was increased, the yield of **2a** also increased (entries 1–3). Use of 4 mmol of Py·HF reagent afforded **2a** in 67% yield (entry 3). When the amount of the hypervalent iodine reagent $[(CF_3CO_2)IPh]_2O$ was increased, the highest yield (70%) was obtained in the case of 0.18 mmol (entries 4 and 5). When the reaction time was investigated, it turned out that the reaction was complete within a short time (1 h) (entries 6 and 7). Finally, it was found that the reaction proceeded efficiently even at room temperature or 0 °C (entries 8 and 9).

With the optimized conditions obtained above, a variety of styrene derivatives were tested to determine the scope of the substrates. In these reactions, we also examined the reaction with $PhI(OCOCF_3)_2$ (condition B) as a hypervalent iodine mediator together with $[(CF_3CO_2)IPh]_2O$ (condition A). The results are given in Table 4. The substituted styrenes **1** include 4-methylstyrene (**1b**), 4-*tert*-butylstyrene (**1c**), 4-fluorostyrene (**1d**), 4-bromostyrene (**1e**), 4-acetoxystyrene (**1f**), 2,4,6-trimethylstyrene (**1g**), 3-bromostyrene (**1h**), and 2-bromostyrene (**1i**). The fluorination reaction of the substituted styrenes

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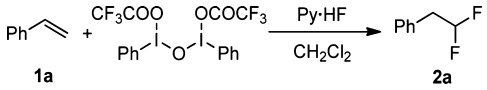
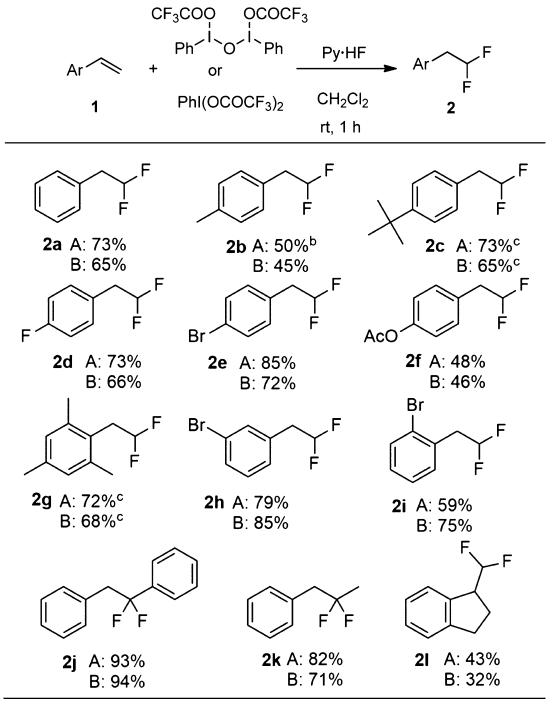
Table 3. Further Optimization of the Fluorination of Styrene 1a[a]



entry	$[(CF_3CO_2)IPh]_2O$ (mmol)	Py·HF (HF mmol)	time (h)	temp (°C)	yield (%)[b]
1	0.12	2	17	40	61
2	0.12	3	17	40	65
3	0.12	4	17	40	67
4	0.18	4	17	40	70
5	0.24	4	17	40	64
6	0.18	4	1	40	70
7	0.18	4	0.5	40	38
8	0.18	4	1	rt	73
9	0.18	4	1	0	72

[a]Conditions: **1a** (0.2 mmol), $[(CF_3CO_2)IPh]_2O$, Py·HF, and CH_2Cl_2 (2 mL). [b]Yield was determined by ^{19}F NMR.

Table 4. Scope of Substrates[a]

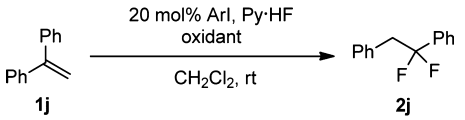


[a]Condition A: **1** (0.2 mmol), $[(CF_3CO_2)IPh]_2O$ (0.18 mmol), Py·HF (4 mmol HF), and CH_2Cl_2 (2 mL) at rt for 1 h. Condition B: **1** (0.2 mmol), $PhI(OCOCF_3)_2$ (0.36 mmol), Py·HF (4 mmol HF), and CH_2Cl_2 (2 mL) at rt for 1 h. Yields were determined by ^{19}F NMR. [b]For 2 h. [c]For 8 h.

1b–**1i** generated the corresponding 2,2-difluoroethylarenes **2b**–**2i** in good to high yields under both conditions A and B. The reaction of 1,1-diphenylethene (**1j**) and 2-phenylpropene (**1k**) afforded 1,1-difluoro-1,2-diphenylethane (**2j**) and 2,2-difluoro-1-phenylpropane (**2k**) in high yields. In the reaction of 1,2-dihydronaphthalene (**1l**), the ring-contracted product, 1-(difluoromethyl)indane (**2l**), was obtained in 32–43% yield. Most products were volatile and had bad separation, with iodobenzene formed from $[(CF_3CO_2)IPh]_2O$. Accordingly, the yields of volatile products were low when they were isolated by column chromatography on silica gel. However, the desired fluorination reaction was not observed in the case of 2-vinylpyridine, *trans*-stilbene, 1-vinylnaphthalene, 2-vinylnaphthalene, 2-(2-propenyl)naphthalene, 4-vinylbiphenyl, or 4-methoxystyrene. In addition, this reaction cannot be applied to styrene derivatives bearing functionalities sensitive to HF, such as alcohols and amines, and to simple alkenes due to low reactivity.

Catalytic Fluorination with an Iodoarene Catalyst. Although a catalytic fluorination of styrenes with an iodoarene as a catalyst has not been studied before, the success of the catalytic fluorination of 1,3-dicarbonyl compounds by iodoarene catalysts[10] suggests that the catalytic fluorination also takes place in the case of styrenes. Thus, we examined the catalytic fluorination by an iodoarene catalyst using 1,1-diphenylethene (**1j**) as the model substrate and Py·HF reagent as the fluorine source. The results are given in Table 5. When the reaction of

Table 5. Optimization of the Catalytic Fluorination of 1,1-Diphenylethene[a]



entry	iodoarene	oxidant	time (h)	yield (%)[b]
1	2-MeOC_6H_4I	*m*-CPBA	17	48
2	2-MeOC_6H_4I	$NaClO{\cdot}5H_2O$	17	0
3	2-MeOC_6H_4I	30% H_2O_2	17	0
4	2-MeOC_6H_4I	*t*-BuOOH	17	0
5	$2,4,6\text{-(MeO)}_3C_6H_2I$	*m*-CPBA	17	1
6	4-MeOC_6H_4I	*m*-CPBA	17	6
7	$2,4,6\text{-Me}_3C_6H_2I$	*m*-CPBA	17	45
8	2-MeC_6H_4I	*m*-CPBA	17	42
9	4-MeC_6H_4I	*m*-CPBA	17	49
10		*m*-CPBA	17	0
11[c]	4-MeC_6H_4I	*m*-CPBA	17	49
12[d]	4-MeC_6H_4I	*m*-CPBA	17	47
13	4-MeC_6H_4I	*m*-CPBA	3	49
14	4-MeC_6H_4I	*m*-CPBA	0.5	50

[a]Conditions: **1j** (0.5 mmol), ArI (0.1 mmol), Py·HF (10 mmol HF), and an oxidant (0.75 mmol) in CH_2Cl_2 (2 mL) at rt. [b]Yields were determined by ^{19}F NMR. [c]Reaction was carried out at 40 °C. [d]*m*-CPBA (1.0 mmol) was used.

1j with Py·HF was conducted in the presence of 1-iodo-2-methoxybenzene (20 mol %) and *m*-CPBA as a terminal oxidant at room temperature for 17 h, the desired difluorinated product **2j** was obtained in 48% yield (entry 1). Although other oxidants such as $NaClO{\cdot}5H_2O$, 30% H_2O_2, and *t*-BuOOH were examined in the fluorination reaction, as for neither of the cases, no difluorinated product **2j** was obtained (entries 2–4). Next, we screened an iodoarene catalyst. We conducted the fluorination reaction using 2-iodo-1,3,5-trimethoxybenzene and 1-iodo-4-methoxybenzene as the catalyst, but the yield of **2j** was very low (entries 5 and 6). When 2-iodo-1,3,5-trimethylbenzene, 1-iodo-2-methylbenzene, and 1-iodo-4-methylbenzene were used as the catalyst, the product was obtained in good yields (42–49%) (entries 7–9). However, the absence of the iodoarene catalyst did not provide the product **2j** at all (entry 10). Increasing the reaction temperature to 40 °C and the amount of *m*-CPBA gave almost the same result (47–49% yield) (entries 11 and 12). Although the reaction time was shortened to 3 and 0.5 h, there was almost no difference in the yield of **2j**. Then, we decided on the optimal time in 0.5 h.

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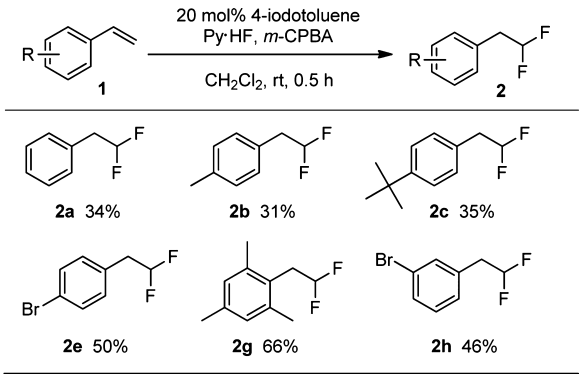
The catalytic fluorination by 4-iodotoluene was examined with several styrene derivatives in order to determine the scope of the substrates. Table 6 shows that the catalytic fluorination

Table 6. Catalytic Fluorination of Styrenes 1 with 2-Iodotoluene[a]



[a]Conditions: **1** (0.5 mmol), 4-MeC_6H_4I (0.1 mmol), Py·HF (10 mmol HF), and *m*-CPBA (0.75 mmol) in CH_2Cl_2 (3 mL) at rt for 0.5 h. Yields were determined by ^{19}F NMR.

provides 2,2-difluoroethylarenes **2** in 31−66% yields. Although the catalytic efficiency in the fluorination of styrenes **1** is not high, the present results indicate that the fluorination of **1** proceeds moderately even under the catalytic conditions using 4-iodotoluene.

CONCLUSION

We have disclosed that the reaction of styrene derivatives **1** with a hypervalent iodine reagent and a pyridine·HF reagent takes place under mild conditions to give (2,2-difluoroethyl)-arenes **2** in good yields. Since the fluorination of styrenes **2** involves 1,2-aryl migration, the present reaction formally provides the method for introducing a 2,2-difluoroethyl group into arenes. Due to the advantages of convenient preparation of fluorinating reagents and efficiency of the reaction, this method is useful for the introduction of a potentially valuable difluoroethyl group into the aromatic ring. Moreover, it has been proven that the present fluorination also proceeds by iodoarene catalysts. Therefore, the present method for transformation of styrenes to (2,2-difluoroethyl)arenes should be considered a convenient and mild alternative to other fluorinating reactions.

EXPERIMENTAL SECTION

General Procedure for the Fluorination of Styrenes 1. Condition A: To a 15 mL Teflon test tube were placed $[(CF_3CO_2)IPh]_2O$ (117 mg, 0.18 mmol), Py·HF (114 mg, 4 mmol), and CH_2Cl_2 (1 mL), and the mixture was stirred for 15 min at room temperature. After styrene **1** (0.2 mmol) and CH_2Cl_2 (1 mL) were added, the test tube was capped with a rubber septum. The mixture was stirred at room temperature for 1 h. The reaction mixture was quenched with a saturated $NaHCO_3$ solution and extracted with ether (10 mL × 3). The combined organic layer was washed with brine, dried over anhydrous Na_2SO_4, and concentrated under reduced pressure. The yield of the product was determined by ^{19}F NMR using hexafluorobenzene as an internal standard. **Condition B:** The reaction was conducted in the same procedure as condition A except for using $PhI(OCOCF_3)_2$ (160 mg, 0.36 mmol) instead of $[(CF_3CO_2)IPh]_2O$. The product isolation was conducted by the reaction of **1** (1 mmol) for 17 h. The product was separated by column chromatography on silica gel (eluent: hexane).

(2,2-Difluoroethyl)benzene (2a).[6a] Using condition A, the fluorinated product **2a** was obtained in 73% yield as determined by ^{19}F NMR of the crude reaction mixture. Due to the volatility, the identity of the product was confirmed by ^1H and ^{19}F NMR and GCMS: ^1H NMR (400 MHz, $CDCl_3$) δ 3.13 (dt, J = 4, 17 Hz, 2H), 5.93 (tt, J = 4, 56 Hz, 1H), 7.24−7.35 (m, 5H); ^{19}F NMR (376 MHz, $CDCl_3$) δ −115.0 (dt, J = 18, 57 Hz) [lit.[6a] −115.3 (dt, J = 17.5, 57 Hz)]; MS (EI) m/z 142 (M^+), 91 ($PhCH_2^+$); HRMS (EI, double focusing) m/z [M^+] calcd for $C_8H_8F_2$ 142.0594; found 142.0592.

1-(2,2-Difluoroethyl)-4-methylbenzene (2b).[11] Using condition A, the fluorinated product **2b** was obtained in 50% yield as determined by ^{19}F NMR of the crude reaction mixture. Due to the volatility, the identity of the product was confirmed by ^1H and ^{19}F NMR: ^1H NMR (400 MHz, $CDCl_3$) δ 2.32 (s, 3H), 3.07 (dt, J = 4, 17 Hz, 2H), 5.86 (tt, J = 4, 57 Hz, 1H), 7.12 (s, 4H); ^{19}F NMR (376 MHz, $CDCl_3$) δ −115.1 (dt, J = 18, 57 Hz); MS (EI) m/z 156 (M^+), 105 ($MeC_6H_4CH_2^+$); HRMS (EI, double focusing) m/z [M^+] calcd for $C_9H_{10}F_2$ 156.0751; found 156.0751.

1-(2,2-Difluoroethyl)-4-(1,1-dimethylethyl)benzene (2c). Using condition B, the fluorinated product **2c** was obtained in 53% yield as determined by ^{19}F NMR of the crude reaction mixture. Further separation by column chromatography on silica gel gave 26 mg (ca. 95% of purity) of **2c** in the reaction for 17 h using **1c** (1 mmol): ^1H NMR (400 MHz, $CDCl_3$) δ 1.31 (s, 9H), 3.11 (dt, J = 4, 17 Hz, 2H), 5.91 (tt, J = 4, 56 Hz, 1H), 7.18 (d, J = 8 Hz, 2H), 7.36 (d, J = 8 Hz, 2H); $^{13}C\{^1H\}$ NMR (100 MHz, $CDCl_3$) δ 31.3, 34.5, 40.4 (t, J = 22 Hz), 116.8 (t, J = 240 Hz), 125.6, 129.33, 129.39, 129.43; ^{19}F NMR (376 MHz, $CDCl_3$) δ −114.9 (dt, J = 17, 56 Hz); HRMS (EI, double focusing) m/z [M^+] calcd for $C_{12}H_{16}F_2$ 198.1220; found 198.1221.

1-(2,2-Difluoroethyl)-4-fluorobenzene (2d).[11] Using condition A, the fluorinated product **2d** was obtained in 73% yield as determined by ^{19}F NMR of the crude reaction mixture. Due to the volatility, the identity of the product was confirmed by ^1H and ^{19}F NMR: ^1H NMR (400 MHz, $CDCl_3$) δ 3.07 (dt, J = 4, 17 Hz, 2H), 5.86 (tt, J = 4, 56 Hz, 1H), 6.97−7.19 (m, 4H); ^{19}F NMR (376 MHz, $CDCl_3$) δ −115.4, −115.5 (dt, J = 18, 56 Hz); MS (EI) m/z 160 (M^+), 109 ($FC_6H_4CH_2^+$); HRMS (EI, double focusing) m/z [M^+] calcd for $C_8H_7F_3$ 160.0500; found 160.0499.

1-Bromo-4-(2,2-difluoroethyl)benzene (2e).[4a] Using condition A, the fluorinated product **2e** was obtained in 85% yield as determined by ^{19}F NMR of the crude reaction mixture. The product **2e** was isolated in 29% yield (64 mg) by column chromatography on silica gel. Further separation by column chromatography on silica gel gave 64 mg (ca. 90% of purity) of **2e** in the reaction for 17 h using **1e** (1 mmol): ^1H NMR (400 MHz, $CDCl_3$) δ 3.09 (dt, J = 4, 17 Hz, 2H), 5.90 (tt, J = 4, 56 Hz, 1H), 7.12 (d, J = 8 Hz, 2H), 7.46 (d, J = 8 Hz, 2H); $^{13}C\{^1H\}$ NMR (100 MHz, $CDCl_3$) δ 40.2 (t, J = 22 Hz), 116.0 (t, J = 240 Hz), 121.6, 131.3, 131.5, 131.8; ^{19}F NMR (376 MHz, $CDCl_3$) δ −115.4 (dt, J = 17, 56 Hz).

1-Acetoxy-4-(2,2-difluoroethyl)benzene (2f). Using condition B, the fluorinated product **2f** was obtained in 46% yield as determined by ^{19}F NMR of the crude reaction mixture. Further separation by column chromatography on silica gel gave 44 mg (ca. 95% of purity) of **2f** in the reaction for 17 h using **1f** (1 mmol): ^1H NMR (400 MHz, $CDCl_3$) δ 2.29 (s, 3H), 3.12 (dt, J = 4, 17 Hz, 2H), 5.90 (tt, J = 4, 56 Hz, 1H), 7.05 (d, J = 7 Hz, 2H), 7.25 (d, J = 7 Hz, 2H); $^{13}C\{^1H\}$ NMR (100 MHz, $CDCl_3$) δ 21.0, 40.2 (t, J = 22 Hz), 116.3 (t, J = 240 Hz), 121.8, 129.9, 130.8, 150.0, 169.4; ^{19}F NMR (376 MHz, $CDCl_3$) δ −115.2 (dt, J = 17, 56 Hz); HRMS (EI, double focusing) m/z [M^+] calcd for $C_{10}H_{10}O_2F_2$ 200.0649; found 200.0650.

1-(2,2-Difluoroethyl)-2,4,6-trimethylbenzene (2g). Using condition B, the fluorinated product **2g** was obtained in 68% yield as determined by ^{19}F NMR of the crude reaction mixture. Further separation by column chromatography on silica gel gave 9.2 mg (ca. 90% of purity) of **2g** in the reaction for 17 h using **1g** (1 mmol): ^1H NMR (400 MHz, $CDCl_3$) δ 2.26 (s, 3H), 2.31 (s, 6H), 3.20 (dt, J = 4, 17 Hz, 2H), 5.88 (tt, J = 4, 57 Hz, 1H), 6.88 (s, 2H); $^{13}C\{^1H\}$ NMR (100 MHz, $CDCl_3$) δ 20.3, 20.8, 34.2 (t, J = 22 Hz), 116.6 (t, J = 240 Hz), 126.5, 129.2, 136.9, 137.5; ^{19}F NMR (376 MHz, $CDCl_3$) δ

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−113.6 (dt, J = 17, 57 Hz); HRMS (EI, double focusing) m/z [M^+] calcd for $C_{11}H_{14}F_2$ 184.1064; found 184.1061.

1-Bromo-3-(2,2-difluoroethyl)benzene (2h).[4a] Using condition B, the fluorinated product **2h** was obtained in 85% yield as determined by ^{19}F NMR of the crude reaction mixture. Further separation by column chromatography on silica gel gave 93 mg (ca. 90% of purity) of **2h** in the reaction for 17 h using **1h** (1 mmol): ^1H NMR (400 MHz, $CDCl_3$) δ 3.11 (dt, J = 4, 17 Hz, 2H), 5.92 (tt, J = 4, 56 Hz, 1H), 7.17−7.21 (m, 2H), 7.42−7.44 (m, 2H); $^{13}C\{^1H\}$ NMR (100 MHz, $CDCl_3$) δ 40.4 (t, J = 22 Hz), 116.1 (t, J = 240 Hz), 122.6, 128.5, 130.2, 130.6, 132.8, 134.5; ^{19}F NMR (376 MHz, $CDCl_3$) δ −115.3 (dt, J = 17, 56 Hz).

1-Bromo-2-(2,2-difluoroethyl)benzene (2i). Using condition B, the fluorinated product **2i** was obtained in 75% yield as determined by ^{19}F NMR of the crude reaction mixture. Further separation by column chromatography on silica gel gave 29 mg (ca. 85% of purity) of **2i** in the reaction for 17 h using **1i** (1 mmol): ^1H NMR (400 MHz, $CDCl_3$) δ 3.33 (dt, J = 4, 16 Hz, 2H), 6.02 (tt, J = 4, 56 Hz, 1H), 7.17 (d, J = 8 Hz, 1H), 7.23−7.29 (m, 2H), 7.58 (d, J = 8 Hz, 1H); $^{13}C\{^1H\}$ NMR (100 MHz, $CDCl_3$) δ 40.9 (t, J = 23 Hz), 115.4 (t, J = 240 Hz), 127.7, 129.3, 132.3, 132.8, 132.9; ^{19}F NMR (376 MHz, $CDCl_3$) δ −115.5 (dt, J = 16, 56 Hz); HRMS (EI, double focusing) m/z [M^+] calcd for $C_8H_7BrF_2$ 219.9699; found 219.9700.

1,1-Difluoro-1,2-diphenylethane (2j).[12] Using condition B, the fluorinated product **2j** was obtained in 94% yield as determined by ^{19}F NMR of the crude reaction mixture. Further separation by column chromatography on silica gel gave 190 mg (>95% of purity) of **2j** in the reaction for 17 h using **1j** (1 mmol): ^1H NMR (400 MHz, $CDCl_3$) δ 3.39 (t, J = 16 Hz, 2H), 7.09−7.37 (m, 10H); $^{13}C\{^1H\}$ NMR (100 MHz, $CDCl_3$) δ 45.8 (t, J = 28 Hz), 121.9 (t, J = 243 Hz), 125.2 (t, J = 6 Hz), 127.2, 128.1, 129.6, 130.6, 132.61, 132.65, 136.8 (t, J = 27 Hz); ^{19}F NMR (376 MHz, $CDCl_3$) δ −95.1 (dt, J = 16 Hz).

2,2-Difluoropropylbenzene (2k).[13] Using condition A, the fluorinated product **2k** was obtained in 82% yield as determined by ^{19}F NMR of the crude reaction mixture. Due to the volatility, the identity of the product was confirmed by ^1H and ^{19}F NMR: ^1H NMR (400 MHz, $CDCl_3$) δ 1.52 (t, J = 18 Hz, 3H), 3.13 (t, J = 16 Hz, 2H), 7.25−7.32 m, 5H); ^{19}F NMR (376 MHz, $CDCl_3$) δ − 89.3 (dt, J = 16, 52 Hz); MS (EI) m/z 156 (M^+), 91 ($PhCH_2^+$); HRMS (EI, double focusing) m/z [M^+] calcd for $C_9H_{10}F_2$ 156.0751; found 156.0750.

1-(Difluoromethyl)-2,3-dihydro-1*H*-indene (2l).[4f] Using condition A, the fluorinated product **2l** was obtained in 43% yield as determined by ^{19}F NMR of the crude reaction mixture. Due to the volatility, the identity of the product was confirmed by ^1H and ^{19}F NMR: ^1H NMR (400 MHz, $CDCl_3$) δ 2.06−2.15 (m, 1H), 2.25−2.34 (m, 1H), 2.88−3.06 (m, 2H), 3.55−3.64 (m, 1H), 5.79 (dt, J = 6, 57 Hz, 1H), 7.18−7.34 m, 4H); ^{19}F NMR (376 MHz, $CDCl_3$) δ −118.9−119.2 (m); MS (EI) m/z 168 (M^+), 117 ($C_9H_9^+$); HRMS (EI, double focusing) m/z [M^+] calcd for $C_{10}H_{10}F_2$ 168.0751; found 168.0750.

General Procedure for Catalytic Fluorination of Styrenes 1. To a Teflon tube were placed 4-iodotoluene (20 mol %), *m*-CPBA (1.5 equiv), Py·HF (20 equiv), and CH_2Cl_2 (1 mL) and stirred for 15 min. After styrene (0.2 mmol) and CH_2Cl_2 (1 mL) were added, the tube was sealed with a rubber septum. The mixture was stirred at room temperature for 30 min. The reaction mixture was treated with aqueous $Na_2S_2O_3$ solution and then neutralized with aqueous $NaHCO_3$ solution. The product was extracted with ether, and the ethereal extract was dried over anhydrous Na_2SO_4 and concentrated under reduced pressure. The product was analyzed by ^{19}F NMR using hexafluorobenzene as an internal standard.

■ ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge on the ACS Publications website at DOI: 10.1021/acs.joc.5b01929.

^1H, ^{19}F, and ^{13}C NMR spectra of isolated products **2** (PDF)

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Notes

The authors declare no competing financial interest.

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