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Fluorination with ionic liquid EMIMF(HF)$_{2.3}$ as mild HF source

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Abstract

Hydrogen fluoride is a basic fluorinating reagent, but handling it is difficult. For this reason, some modified fluorinating reagents such as HF-pyridine, Et_3N-HF, and poly(hydrogen fluoride) complex have been developed. Those reagents, however, still require aqueous work-up procedures which generate hydrogen fluoride. Recently, ionic liquids have received much attention because of the ease in handling them and the possibility of non-aqueous work-up. An ionic liquid, 3-ethyl-1-methyimidazolium oligo hydrogen fluoride (EMIMF(HF)$_{2.3}$), which is stable in air and moisture, can be used as a hydrogen fluoride equivalent for some fluorination reactions; it does not require an aqueous work-up.

Keywords: Ionic liquid; Hydrogen fluoride; Halofluorination; Fluorohydrin

1. Introduction

Organofluorine compounds have received much attention because of their interesting chemical and physical properties or biological activities [1]. Introduction of a fluorine atom into organic molecules dramatically changes such physical properties and biological activities. Thus, a development of convenient and efficient fluorinating methods has been desired. Hydrogen fluoride is the most basic nucleophilic fluorinating reagent [2], but it has a drawback due to difficulties in its handling. HF-pyridine (Olah's reagent) [3], Et_3N-HF [4], and poly(hydrogen fluoride) complex [5] are available as alternative stable hydrogen fluoride sources. Those reagents, however, still require an aqueous work-up which generates hydrogen fluoride. Recently, ionic liquids have attracted much attention as reaction media because of the possibility of non-aqueous work-up, especially in the field of green chemistry and combinatorial chemistry [6]. Ionic liquids are not miscible with organic solvents, and form biphase systems. After the reaction, the products in the organic phase can be easily isolated by decantation. Ionic liquid 3-ethyl-1-methy-imidazolium oligo hydrogen fluoride (EMIMF(HF)$_{2.3}$), which is stable in air and moisture, might be used as such a reaction medium with a hydrogen fluoride source.

2. Results and discussion

2.1. EMIMF(HF)$_{2.3}$ (EMI: 1-ethyl-3-methylimidazolium, **1**)

EMIMF(HF)$_{2.3}$ (**1**) was prepared by a direct reaction of 1-ethyl-3-methylimidazolium chloride and anhydrous hydrogen fluoride according to the reported procedure [7]. This ionic liquid is stable against moisture and air. It consists of 1-ethyl-3-methylimidazolium cation and F(HF)$_{2.3}$ anion. In the F(HF)$_{2.3}$ anion, a rapid exchange of HF between F(HF)$_2$ anion and F(HF)$_3$ anion occurs (Fig. 1). The value "2.3" was decided by the results of elemental analysis.

2.2. Halofluorination of alkenes with EMIMF(HF)$_{2.3}$ (**1**)

We examined the halofluorination of 1-dodecene using this ionic liquid as shown in Table 1 [8]. Reactions were carried out in tall polypropylene tubes that are easy to handle for decantation in the work-up process. To a mixture of substrate

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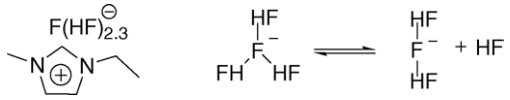
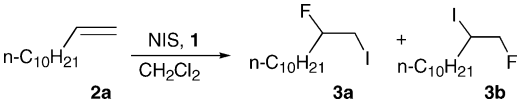


Fig. 1. EMIMF(HF)$_{2.3}$.

Table 1
lodofluorination of 1-dodecene



Entry	NIS (eq.)	Temperature (°C)	Time (h)	Yield (%)		
				2a	**3a**	**3b**
1	1	25	3	60	38	–
2	1	25	36	30	67	–
3	2	25	3	7	90	2
4[a]	2	60	1	5	87	7

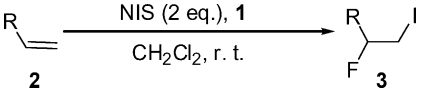
[a] Solvent, $ClCH_2CH_2Cl$.

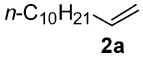
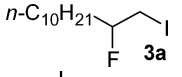
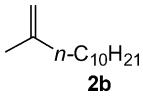
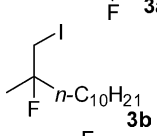
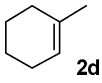
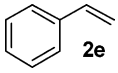
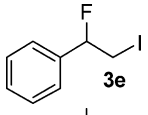
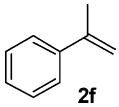
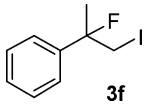
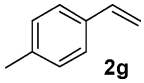
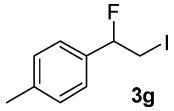
dissolved in CH_2Cl_2, ionic liquid was added to form a biphase (Fig. 2A). To the resulting mixture, *N*-iodosuccinimide (NIS) was added in several portions. The mixture gradually became first clear and then yellow (Fig. 2B and C). When the reaction was finished, hexane was added to the reaction mixture. The resulting mixture became a biphase (Fig. 2D). Decantation of the upper phase gave a hexane solution of the produced β-halofluoride. After the solution was passed through a short silica-gel column, it was concentrated in vacuo to obtain the products. In this procedure, no aqueous was included. When one equivalent of NIS was used, 30% of starting material was recovered in spite of the longer reaction time (Table 1, Entries 1 and 2). The reaction proceeded smoothly by employing two equivalents of NIS (Entry 3). Furthermore, the reaction was accelerated by heating at 60 °C, but regioselectivity was decreased (Entry 4). From these results, we employed the condition in Entry 3.

Various alkenes were iodofluorinated as shown in Table 2. In all cases, products were obtained in good yields and with high regioselectivity.

Bromofluorination of alkenes was also performed with *N*-bromosuccinimide (NBS) and the ionic liquid **1**. Results are summarized in Table 3. *vic*-Bromofluoroalkanes **4** were also obtained in good yields.

Table 2
lodofluorination of alkenes



Entry	Alkene	Time (h)	Product	Yield (%)
1	 **2a**	3	 **3a**	90
2	 **2b**	1	 **3b**	91
3	 **2c**	1	 **3c**	95
4	 **2d**	1	 **3d**	98
5	 **2e**	1	 **3e**	70
6	 **2f**	1	 **3f**	88
7	 **2g**	1	 **3g**	78

As shown in Scheme 1, chlorofluorination of alkenes with *N*-chlorosuccinimide (NCS) and the ionic liquid **1** was also examined. The products were not obtained in good yield and most of the starting alkene was recovered, although a longer reaction time compared to those needed for the bromo- and iodoalkenation was required.

2.3. Ring opening fluorination of epoxides [9]

To styrene oxide (**6a**) in CH_2Cl_2 was added EMIMF(HF)$_{2.3}$ (**1**) at room temperature and the mixture was stirred vigorously to obtain 2-fluoro-2-phenyl-ethanol (**7a**) in 72% yield (Table 4, Entry 1). The reaction mixture is a biphase that consists of CH_2Cl_2 phase and ionic liquid phase. In this reaction, the regio isomer 1-fluoro-2-phenyl-2-ethanol was not detected by ^{1}H and

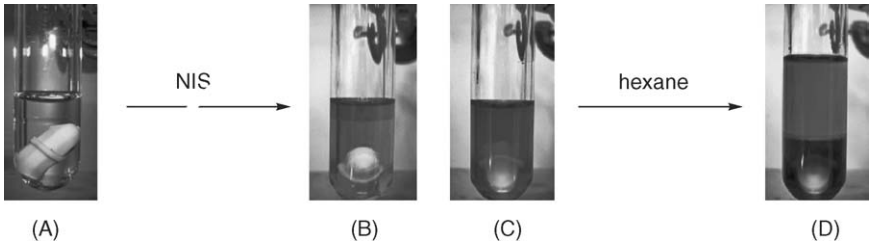
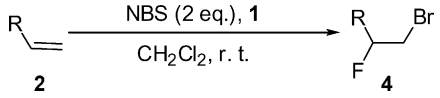
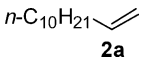
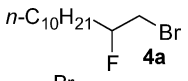
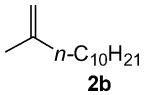
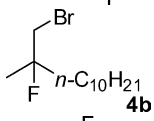
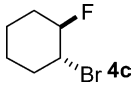
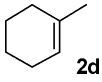
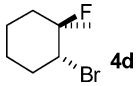
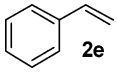
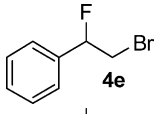
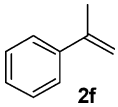
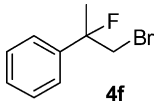
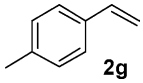
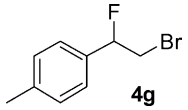


Fig. 2. lodofluorination of alkenes with EMIMF(HF)$_{2.3}$.

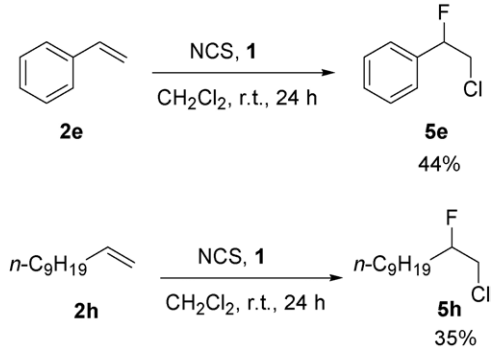
Table 3
Bromofluorination of alkenes



Entry	Alkene	Time (h)	Product	Yield (%)
1	 **2a**	3	 **4a**	86
2	 **2b**	1	 **4b**	90
3	 **2c**	1	 **4c**	90
4	 **2d**	1	 **4d**	95
5	 **2e**	1	 **4e**	81
6	 **2f**	1	 **4f**	87
7	 **2g**	1	 **4g**	93

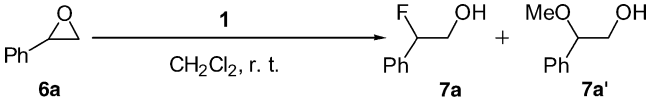
^{19}F NMR in the obtained crude product. An addition of catalytic amount of methanol increased the rate of the reaction. Increasing the amount of methanol resulted in the formation of methoxyalkanol **7a′** which was formed by acid-catalyzed ring opening of epoxide with methanol (Entries 3 and 4).

Ring opening fluorinations of various epoxides with EMIMF(HF)$_{2.3}$ and methanol catalyst are summarized in Table 5. In all cases, the high regioselectivity was observed. An epoxide of terminal mono substituted alkene (**6h**) was recovered even for the longer reaction period.



Scheme 1.

Table 4
Ring opening fluorination of styrene oxide

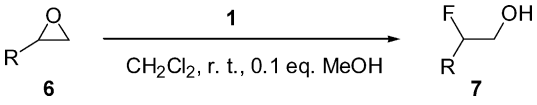


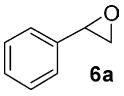
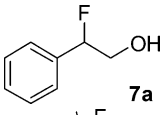
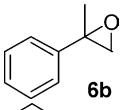
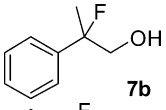
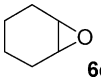
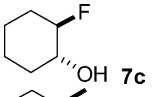
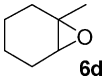
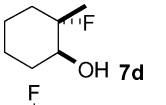
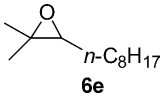
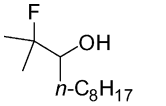
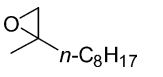
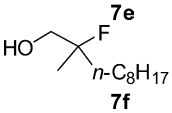
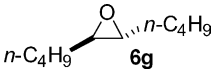
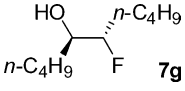
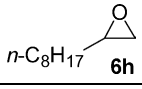
Entry	Solvent	Time (h)	**7a** (%)	**7á** (%)
1	CH_2CI_2	24	72	–
2	CH_2CI_2/0.1 eq. MeOH	16	81	–
3	CH_2CI_2/1.0 eq. MeOH	12	74	17
4	MeOH	4	4	75

2.4. Deprotection of silyl ether

A silyl group is one of the most useful protecting groups for a hydroxy group [10]. Silyl ethers are readily cleaved by mild acidic hydrolysis [11] or by a fluoride ion generated by TBAF [12]. Hydrogen fluoride (4% solution of 95% HF aq. in CH_3CN) is also useful as a mild reagent [13]. Ionic liquid **1** should be

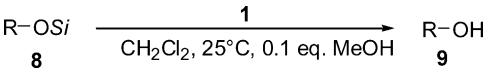
Table 5
Ring opening flouorination of various epoxides



Entry	Epoxide	Time (h)	Product	Yield (%)
1	 **6a**	16	 **7a**	81
2	 **6b**	16	 **7b**	74
3	 **6c**	16	 **7c**	55
4	 **6d**	6	 **7d**	65
5	 **6e**	24	 **7e**	37[a]
6	 **6f**	24	 **7f**	28[b]
7	 **6g**	48	 **7g**	7[c]
8	 **6h**	120	–	0[d]

[a] 50% of starting material was recovered.
[b] 47% of starting material was recovered.
[c] 83% of starting material was recovered.
[d] Starting material was only recovered.

Table 6
Deprotection of silyl ethers



Entry	Protected alcohol	Time (h)	Product	Yield (%)
1	*n*-C_7H_{14}-OTMS **8a**	0.5	*n*-C_7H_{14}-OH **9a**	99
2	*n*-C_6H_{13} OTMS **8b**	1.5	*n*-C_6H_{13} OH **9b**	99
3	OTMS OTMS **8c**	1	OH OH **9c**	76
4	TMS—≡—$(CH_2)_4$—OTBDMS **8d**	2	TMS—≡—$(CH_2)_4$—OH **9d**	94
5	O O$(CH_2)_4$OTBDMS **8e**	1	O O$(CH_2)_4$OH **9e**	90
6	O $(CH_2)_8$OTBDMS **8f**	1	O $(CH_2)_8$OH **9f**	93

useful as mild desilylating reagent as shown in Table 6. To a catalytic amount of methanol and EMIMF(HF)$_{2.3}$, 1-trimethylsiloxyheptene (**8a**) in CH_2Cl_2 was added at room temperature and the mixture was stirred to obtain 1-hexanol (**9a**) in 99% yield. Alkynyl silane, which is cleaved by TBAF or KF [14], was not affected in this condition (Entry 4). THP ether was not cleaved in this condition (Entry 5). Mono alkyl substituted epoxide was tolerated during desilylation, whereas the ring opening oligomerization proceeded under treatment of **8f** with hydrogen fluoride aq. methanol solution.

3. Conclusion

We demonstrated the possibilities of an ionic liquid, 3-ethyl-1-methyimidazolium oligo hydrogen fluoride (EMIMF(HF)$_{2.3}$) (**1**), to act as a stable and useful substitute for hydrogen fluoride in fluorination of organic compounds. Although the availability of **1** is a still a limitation of these transformation, the high reactivity and the ease of the procedure will compensate the difficulty.

4. Experimental

All solvents were used as obtained from commercial suppliers. Chromatographic purification of products was accomplished using forced-flow chromatography on Kanto Chemical Co., Inc. Silica-gel 60 N (spherical, neutral). The polypropylene tube used was a centrifuge tube (15 ml) with a screw cap, and is available from Corning. EMIMF(HF)$_{2.3}$ was prepared according to the literature [7]. ^{1}H, ^{13}C, ^{19}F NMR spectra were recorded on Varian Mercury (300, 75 and 282 MHz, respectively) instruments and are internally referenced to residual solvent signals (for ^{1}H and ^{13}C) and $CFCl_3$ (for ^{19}F). Data for ^{1}H NMR are reported as chemical shifts (δ ppm), multiplicity (s, singlet; d, doublet; t, triplet; q, quartet; m, multiplet), coupling constant (Hz), and integration. Data for ^{13}C NMR are reported as chemical shifts. High resolution mass spectra were generated by JEOL Mstation 700 spectrometer. The elemental analyses were carried out at the Elemental Analysis Center of Kyoto University.

5. General procedure for halofluorination

In a 15 ml polypropylene tube, CH_2Cl_2 (500 μl) solution of alkene (1.0 mmol) and EMIMF(HF)$_{2.3}$ (**1**, 600 μl) were placed and stirred with magnetic stirrer vigorously. To this reaction mixture, *N*-halosuccinimide (2.0 mmol) was added in several portions at room temperature. When the reaction finished, hexane (1 ml) was added and the whole was stirred vigorously. After the stirring was stopped, the mixture had separated into two phases. The upper layer was collected by decantation. This extraction with hexane was repeated twice more. The combined hexane layers were concentrated in vacuo. The crude product was purified by short silica-gel column chromatography.

*5.1.1. 2-Fluoro-1-iodododecane (**3a**) [15]*

^{1}H NMR (300 MHz, $CDCl_3$): δ 4.41 (ddt, J = 48.0, 10.8, 1.5 Hz, 1H), 3.31 (ddd, J = 20.1, 5.7, 2.1 Hz, 2H), 1.80–1.65 (m, 2H), 1.45–1.20 (m, 14H), 0.88 (t, J = 6.9 Hz, 3H). ^{19}F NMR (282 MHz, $CDCl_3$): δ −170.6 (m).

*5.1.2. 2-Fluoro-1-iodo-2-methyldodecane (**3b**)*

^{1}H NMR (300 MHz, $CDCl_3$): δ 3.34 (d, J = 16.8 Hz, 2H), 1.83–1.72 (m, 2H), 1.49 (d, J = 21.0 Hz, 3H), 1.40–1.20 (m, 16H), 0.88 (t, J = 6.9 Hz, 3H). ^{13}C NMR (75 MHz, $CDCl_3$): δ 94.7 (d, J = 172.3 Hz), 39.3 (d, J = 22.0 Hz), 32.2, 30.0, 29.9, 29.8, 29.7, 29.6, 24.7 (d, J = 24.4 Hz), 23.9, 23.8, 22.9, 14.4, 13.8 (d, J = 27.3 Hz). ^{19}F NMR (282 MHz, $CDCl_3$): δ −140.0 (m). Anal. calcd. for $C_{13}H_{26}FI$: C, 47.57; H, 7.98. Found: C, 47.54; H, 7.70.

*5.1.3. 1-Fluoro-2-iodocyclohexane (**3c**) [15]*

^{1}H NMR (300 MHz, $CDCl_3$): δ 4.52 (ddt, J = 47.7, 8.7, 4.5 Hz, 1H), 4.16–4.06 (m, 1H), 2.44–2.30 (m, 1H), 2.28–2.13 (m, 1H), 2.02–1.78 (m, 2H), 1.66–1.54 (m, 2H), 1.50–1.24 (m, 2H). ^{19}F NMR (282 MHz, $CDCl_3$): δ −159.5 (m).

*5.1.4. 1-Fluoro-2-iodo-1-methylcyclohexane (**3d**) [15]*

^{1}H NMR (300 MHz, $CDCl_3$): δ 4.37 (dt, J = 8.1, 4.2 Hz, 1H), 2.30–2.08 (m, 2H), 2.00–1.87 (m, 1H), 1.82–1.62 (m, 3H), 1.56 (d, J = 22.2 Hz, 3H), 1.54–1.40 (m, 2H). ^{19}F NMR (282 MHz, $CDCl_3$): δ −132.4 (m).

*5.1.5. 1-Fluoro-2-iodo-1-phenylethane (**3e**) [15]*

^{1}H NMR (300 MHz, $CDCl_3$): δ 7.50–7.30 (m, 5H), 5.53 (ddd, J = 46.5, 7.2, 4.8 Hz, 1H), 3.55–3.41 (m, 2H). ^{19}F

NMR (282 MHz, $CDCl_3$): δ −166.4 (ddd, J = 46.5, 23.7, 17.8 Hz).

*5.1.6. 2-Fluoro-1-iodo-2-phenylpropane (**3f**) [15]*

^{1}H NMR (300 MHz, $CDCl_3$): δ 7.50–7.30 (m, 5H), 3.59 (d, J = 20.4 Hz, 2H), 1.86 (d, J = 21.6 Hz, 3H). ^{19}F NMR (282 MHz, $CDCl_3$): δ −142.4 (tq, J = 21.6, 20.4 Hz).

*5.1.7. 1-Fluoro-2-iodo-1-(4-methylphenyl)ethane (**3g**)*

^{1}H NMR (300 MHz, $CDCl_3$): δ 7.28–7.15 (m, 4H), 5.52 (ddd, J = 45.3, 18.6, 6.3 Hz, 1H), 3.55–3.40 (m, 2H), 2.37 (s, 3H). ^{13}C NMR (75 MHz, $CDCl_3$): δ 139.3, 135.1 (d, J = 20.5 Hz), 129.6, 125.8 (d, J = 6.2 Hz), 93.4 (d, J = 175.5 Hz), 21.7, 7.9 (d, J = 28.8 Hz). ^{19}F NMR (282 MHz, CDCl3): δ −164.6 (ddd, J = 45.4, 23.7, 15.8 Hz). Anal. calcd. for $C_9H_{10}FI$: C, 40.93; H, 3.82. Found: C, 40.66; H, 3.69.

*5.1.8. 1-Bromo-2-fluorododecane (**4a**) [16]*

^{1}H NMR (300 MHz, $CDCl_3$): δ 4.62 (dddt, J = 48.6, 7.5, 5.4, 5.4 Hz, 1H), 3.51 (ddd, J = 19.8, 10.8, 5.4 Hz, 2H), 1.77–1.64 (m, 2H), 1.49–1.26 (m, 16H), 0.88 (t, J = 6.8 Hz, 3H). ^{19}F NMR (282 MHz, $CDCl_3$): δ −178.0 (dddt, J = 48.6, 27.0, 19.8, 19.8 Hz).

*5.1.9. 1-Bromo-2-fluoro-2-methyldodecane (**4b**)*

^{1}H NMR (300 MHz, $CDCl_3$): δ 3.46 (d, J = 15.9 Hz, 2H), 1.80–1.71 (m, 2H), 1.46 (d, J = 21.3 Hz, 3H), 1.39–1.26 (m, 16H), 0.88 (t, J = 7.2 Hz, 3H). ^{13}C NMR (75 MHz, $CDCl_3$): δ 95.0 (d, J = 171.5 Hz), 38.6 (d, J = 29.3 Hz), 38.0 (d, J = 21.9 Hz), 32.0, 29.8, 29.7, 29.6, 29.5, 29.4, 23.6 (d, J = 23.9 Hz), 23.5, 23.4, 22.8, 14.2. ^{19}F NMR (282 MHz, $CDCl_3$): δ −144.9 (m). Anal. calcd. for $C_{13}H_{26}FBr$: C, 55.52; H, 9.32. Found: C, 55.59; H, 9.13.

*5.1.10. 1-Bromo-2-fluorocyclohexane (**4c**) [17]*

^{1}H NMR (300 MHz, $CDCl_3$): δ 4.48 (ddt, J = 48.0, 8.4, 4.5 Hz, 1H), 4.07–3.97 (m, 1H), 2.35–2.17 (m, 2H), 1.89–1.62 (m, 4H), 1.42–1.31 (m, 2H). ^{19}F NMR (282 MHz, $CDCl_3$): δ −167.4 (dm, J = 48.0 Hz).

*5.1.11. 2-Bromo-1-fluoro-1-methylcyclohexane (**4d**) [17]*

^{1}H NMR (300 MHz, $CDCl_3$): δ 4.20 (dt, J = 7.2, 3.9 Hz, 1H), 2.35–1.25 (m, 8H), 1.51 (d, J = 22.4, 3H). ^{19}F NMR (282 MHz, $CDCl_3$): δ −137.0 (m).

*5.1.12. 2-Bromo-1-fluoro-1-phenylethane (**4e**) [15]*

^{1}H NMR (300 MHz, $CDCl_3$): δ 7.51–7.35 (m, 5H), 5.50 (ddd, J = 46.8, 7.2, 4.2 Hz, 1H), 3.64–3.43 (m, 2H). ^{19}F NMR (282 MHz, $CDCl_3$): δ −174.1 (ddd, J = 46.8, 23.7, 16.5 Hz).

*5.1.13. 1-Bromo-2-fluoro-2-phenylpropane (**4f**) [17]*

^{1}H NMR (300 MHz, $CDCl_3$): δ 7.43–7.32 (m, 5H), 3.73–3.60 (m, 2H), 1.84 (d, J = 22.2 Hz, 3H). ^{19}F NMR (282 MHz, $CDCl_3$): δ −147.5 (ddq, J = 22.2, 22.2, 18.4 Hz).

*5.1.14. 2-Bromo-1-fluoro-1-(4-methylphenyl)ethane (**4g**) [18]*

^{1}H NMR (300 MHz, $CDCl_3$): δ 7.38–7.18 (m, 4H), 5.57 (ddd, J = 46.8, 8.1, 4.2 Hz, 1H), 3.75–3.53 (m, 2H), 2.37 (s, 3H). ^{19}F NMR (282 MHz, $CDCl_3$): δ −172.3 (ddd, J = 46.8, 25.9, 18.9 Hz).

*5.1.15. 2-Chloro-1-fluoro-1-phenylethane (**5b**) [19]*

^{1}H NMR (300 MHz, $CDCl_3$): δ 7.51–7.38 (m, 5H), 5.60 (ddd, J = 47.4, 8.1, 3.9 Hz, 1H), 3.86–3.69 (m, 2H). ^{19}F NMR (282 MHz, $CDCl_3$): δ −178.4 (ddd, J = 47.4, 23.7, 15.8 Hz).

*5.1.16. 1-Chloro-2-fluoroundecane (**5h**)*

^{1}H NMR (300 MHz, $CDCl_3$): δ 4.60 (dddt, J = 48.0, 8.4, 4.8, 4.8 Hz, 1H), 3.62 (ddd, J = 20.1, 5.4, 1.2 Hz, 2H), 1.79–1.61 (m, 2H), 1.48–1.26 (m, 14H), 0.88 (t, J = 6.9 Hz, 3H). ^{13}C NMR (75 MHz, $CDCl_3$): δ 92.7 (d, J = 173.8 Hz), 46.1 (d, J = 25.3 Hz), 32.7 (d, J = 20.0 Hz), 32.1, 29.8, 29.7, 29.6, 29.5, 29.4, 22.9, 14.4. ^{19}F NMR (282 MHz, $CDCl_3$): δ −181.6 (m). HRMS Found: m/z 208.1392. Calcd. for $C_{11}H_{22}ClF$: (M^+) 208.1394.

5.2. General procedure for ring opening fluorination of epoxides

In a 15 mm polypropylene tube, epoxide (**6**, 1.0 mmol), CH_2Cl_2 (500 μl), and methanol (4 μl) were placed. Ionic liquid $EMIMF(HF)_{2.3}$ (**1**, 600 μl) was added to the mixture at room temperature, and the mixture stirred. When the reaction finished, ethyl acetate (1 ml) was added and the whole was stirred vigorously. After the stirring was stopped, the mixture had separated into two phases. The upper layer was collected by decantation. This extraction with ethyl acetate was repeated twice more. The crude product was purified by short silica-gel column chromatography. The yield was determined by ^{19}F NMR in comparison with an internal standard.

*5.2.1. 2-Fluoro-2-phenylethanol (**7a**) [20]*

^{1}H NMR (300 MHz, $CDCl_3$): δ 7.41–7.34 (m, 5H), 5.57 (ddd, J = 3.0, 7.5, 48.3 Hz, 1H), 4.01–3.76 (m, 2H), 2.02 (bs, 1H). ^{19}F NMR (282 MHz, $CDCl_3$): δ −186.8 (ddd, J = 48.6, 29.6, 17.8 Hz).

*5.2.2. 2-Fluoro-2-phenylpropanol (**7b**) [21]*

^{1}H NMR (300 MHz, $CDCl_3$): δ 7.40–7.32 (m, 5H), 3.92–3.69 (m, 2H), 1.83 (bs, 1H), 1.75 (d, J = 22.5 Hz, 3H). ^{19}F NMR (282 MHz, $CDCl_3$): δ −157.2 (m).

*5.2.3. 2-Fluorocyclohexanol (**7c**) [4b]*

^{1}H NMR (300 MHz, $CDCl_3$): δ 4.21 (dm, J = 51.3 Hz, 1H), 3.67–3.57 (m, 1H), 2.45 (bs, 1H), 2.13–1.99 (m, 2H), 1.77–1.69 (m, 2H), 1.51–1.20 (m, 4H). ^{19}F NMR (282 MHz, $CDCl_3$): δ −181.4 (d, J = 51.3 Hz).

*5.2.4. 2-Fluoro-2-methylcyclohexanol (**7d**) [22]*

^{1}H NMR (300 MHz, $CDCl_3$): δ 3.76–3.67 (m, 1H), 2.17 (bs, 1H), 1.94–1.21 (m, 11H). ^{19}F NMR (282 MHz, $CDCl_3$): δ −142.0 (m).

*5.2.5. 2-Fluoro-2-methyl-3-decanol (**7e**)*

^{1}H NMR (300 MHz, $CDCl_3$): δ 3.55 (t, J = 7.5 Hz, 1H), 1.98 (s, 1H), 1.36 (d, J = 3.9 Hz, 6H), 1.35–1.24 (m, 14H), 0.88 (t, J = 6.9 Hz, 3H). ^{13}C NMR (75 MHz, $CDCl_3$): δ 98.5 (d, J = 163.4 Hz), 77.2 (d, J = 23.3 Hz), 32.2, 31.6, 31.5, 30.0, 29.9, 24.2, 23.0, 21.3 (d, J = 24.5 Hz, 2C), 14.5. ^{19}F NMR (282 MHz, $CDCl_3$): δ −144.7 (m). Anal. calcd. for $C_{12}H_{25}FO$: C, 70.54; H, 12.33. Found: C, 70.48; H, 12.28.

*5.2.6. 2-Fluoro-2-methyldecanol (**7f**)*

^{1}H NMR (300 MHz, $CDCl_3$): δ 3.67–3.47 (m, 2H), 1.76–1.56 (m, 2H), 1.36 (s, 3H), 1.34–1.22 (m, 12H), 0.88 (t, J = 6.9 Hz, 3H). ^{13}C NMR (75 MHz, $CDCl_3$): δ 98.0 (d, J = 165.3 Hz), 68.43 (d, J = 23.4 Hz), 36.6 (d, J = 22.2 Hz), 32.2, 30.4, 29.8, 29.6, 23.8 (d, J = 6.3 Hz), 23.0, 21.1 (d, J = 24.5 Hz), 14.5. ^{19}F NMR (282 MHz, $CDCl_3$): δ −154.8 (m). Anal. calcd. for $C_{11}H_{23}FO$: C, 69.43; H, 12.18. Found: C, 69.68; H, 11.88.

*5.2.7. 6-Fluoro-5-decanol (**7g**)*

^{1}H NMR (300 MHz, $CDCl_3$): δ 4.37 (ddt, J = 47.7, 9.3, 3.9 Hz, 1H), 3.77–3.69 (m, 1H), 1.77–1.25 (m, 12H), 0.92 (t, J = 7.2 Hz, 6H). ^{13}C NMR (75 MHz, $CDCl_3$): δ 96.6 (d, J = 167.9 Hz), 73.0 (d, J = 21.6 Hz), 31.4, 29.2 (d, J = 20.7 Hz), 28.0, 27.6, 22.7, 22.6, 14.1, 14.0. ^{19}F NMR (282 MHz, $CDCl_3$): δ −190.8 (m). Anal. calcd. for $C_{10}H_{21}FO$: C, 68.14; H, 12.01. Found: C, 68.21; H, 11.72.

5.3. General procedure for desilylation of silyl ether

In a 15 mm polypropylene tube, silylether (**8**, 1.0 mmol), CH_2Cl_2 (500 μl), and methanol (4 μl) were placed. Ionic liquid EMIMF(HF)$_{2.3}$ (**1**, 600 μl) was added to the mixture at room temperature, and the mixture was stirred. When the reaction finished, ethyl acetate (1 ml) was added and the whole was stirred vigorously. After the stirring was stopped, the mixture had separated into two phases. The upper layer was collected by decantation. This extraction with ethyl acetate was repeated twice more. The collected organic layers were evaporated in vacuo. The crude product was purified by short silica-gel column chromatography.

5.4. Preparation of silyl ethers

Silyl ethers **8a–8e** were prepared from corresponding alcohols by O-silylation with silylchloride and 1H-imidazole in DMF. **8f** was prepared from 1-trimethylsiloxy-9-decene by oxidation with 3-chloroperoxybenzoic acid.

*5.4.1. 6-(Trimethylsilyl)-5-hexyn-1-ol (**9d**) [23]*

^{1}H NMR (300 MHz, $CDCl_3$): δ 3.68 (t, J = 6.0, 2H), 2.27 (t, J = 6.6 Hz, 2H), 1.72–1.56 (m, 2H), 0.14 (s, 9H).

*5.4.2. 4O-(Tetrahydropyran-2-yl)-1-butanol (**9e**) [24]*

^{1}H NMR (300 MHz, $CDCl_3$): δ 4.61–4.56 (m, 1H), 3.89–3.72 (m, 2H), 3.66 (t, J = 6.3 Hz, 2H), 3.54–3.41 (m, 2H), 1.68–1.46 (m, 10H).

*5.4.3. 9,10-Epoxy-1-decanol (**9f**) [25]*

^{1}H NMR (300 MHz, $CDCl_3$): δ 3.64 (t, J = 6.6 Hz, 2H), 2.93–2.88 (m, 1H), 2.75 (dd, J = 5.1, 5.1 Hz, 1H), 2.45 (dd, J = 5.1, 5.1 Hz, 1H), 1.59–1.26 (m, 14H).

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