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Synthesis of perfluorinated carboxylic acid membrane monomers by utilizing liquid-phase direct fluorination

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Dedicated to Professor Richard D. Chambers on the occasion of his 70th birthday.

Abstract

A new synthetic procedure for the preparation of perfluorinated carboxylic acid membrane monomers from non-fluorinated compounds has been developed. A key step in the synthetic route is liquid-phase direct fluorination reaction with elemental fluorine. Direct fluorination of a partially fluorinated diester, which was prepared from a hydrocarbon diol and a perfluorinated acyl fluoride, followed by thermal elimination, gave a perfluorinated diacyl fluoride, which is a precursor of a perfluorinated carboxylic acid membrane monomer.

Keywords: Acyl fluorides; Direct fluorination; Fluorine; Membrane; Synthesis

1. Introduction

The ion exchange membrane Flemion®, which was developed by Asahi Glass, is used as a membrane in the energy-saving and pollution-free chlor-alkali production process. Nafion® (DuPont) is also used for the same purpose. They surpass the conventional mercury cell or diaphragm processes [1,2]. Recently, a sulfonate–carboxylate laminated polymer membrane has been used to obtain an higher concentration of caustic soda. A perfluorinated carboxylic acid membrane is an important component there [3].

Flemion® carboxylic acid is a copolymer of tetrafluoroethylene (TFE) and perfluorinated vinyl ether, which has a carboxylic acid group in the side chain. The conventional manufacturing process of the Flemion® comonomer is shown in Scheme 1 [4].

Diiodide **1** obtained from TFE and iodine, is oxidized with oleum to give diacyl fluoride **2**. Cesium alkoxide from the diacyl fluoride **2** is added to hexafluoropropylene oxide (HFPO) to give diacyl fluoride **3**. Pyrolysis followed by methanolysis affords the Flemion® comonomer **5**. Although this chemistry is well-established, it is costly, uses hazardous reagents, such as oleum and has an iodine-containing waste problem. Moreover, there are restrictions in the monomer structure because of the poor variety of raw materials available.

The Exfluor–Lagow elemental fluorine process is effective under mild conditions [5–7]. Lagow et al. reported liquid-phase direct fluorination of non-fluorinated compounds with relatively simple structure, such as octyl octanoate, and the methodology is a powerful tool for the synthesis of perfluorinated compounds. Our new synthetic methodology, the PERFECT (PERFluorination of an Esterified Compound then Thermal elimination) process, starts from non-fluorinated compounds and utilizes liquid-phase direct fluorination as a key step (Scheme 2) [8,9].

A small hydrocarbon component with the backbone structure of the desired compound in the alcohol form **6** is made by conventional organic synthesis. Then, **6** is coupled with a perfluorinated moiety, the desired perfluoroacyl

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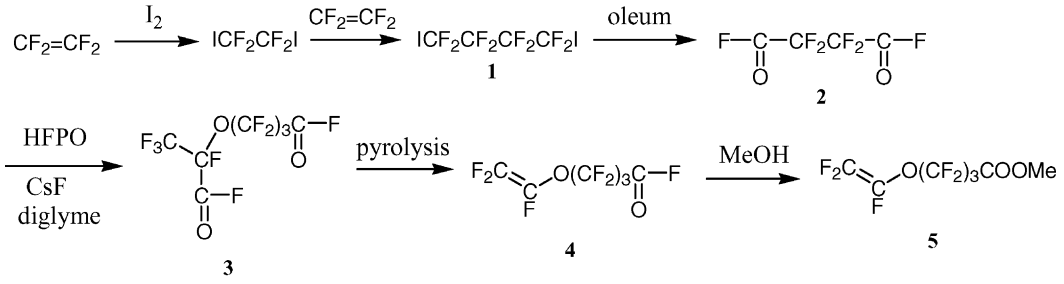


Scheme 1.

fluoride **7** in a typical case, to form a larger partially fluorinated molecule **8**. Perfluorination is achieved by direct fluorination of the partially fluorinated ester compound **8**. Thus, a vapor-phase reaction is avoided since the substrate **8** has low vapor pressure. In addition, the solubility of the substrate **8** in perfluorinated solvent significantly increases, and this is an advantage because we can use various perfluorinated solvents other than CFCs. Finally, thermal elimination followed by the separation of the mixture of acyl fluorides gives the desired perfluorinated compound **10** and recovered **7**.

As an example, we have reported the synthesis of perfluoro(propyl vinyl ether), PPVE [8,9], perfluorinated butenyl vinyl ether, BVE, which is the monomer of transparent perfluorinated cyclic polymer, CYTOP® [10]. We have also reported the synthesis of perfluoroalkanesulfonyl fluorides [11], and perfluoroketones [12].

Herein, we present a new synthesis of the perfluorinated carboxylic acid membrane monomer using the PERFECT process. It also serves to provide monomer candidates other than conventional structures.

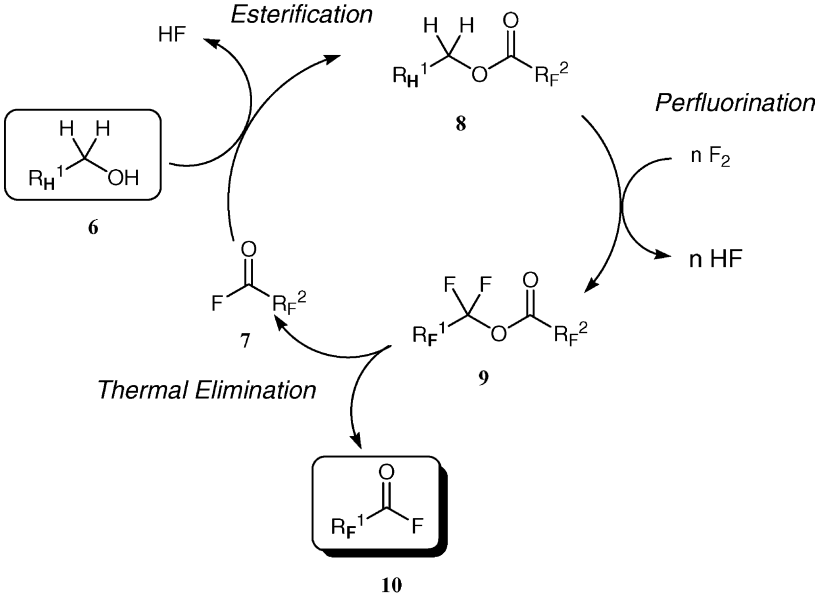
2. Results and discussion

2.1. Preparation of substrates for the PERFECT process

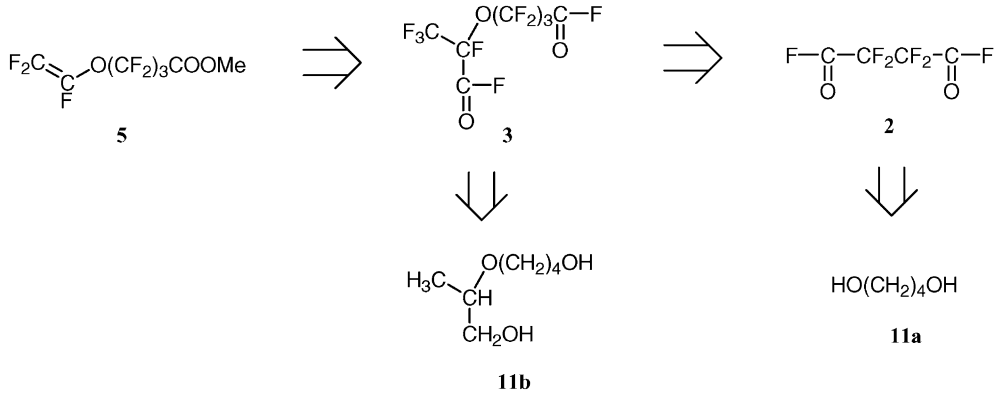
Flemion® monomer **5** is made from diacyl fluoride **2** through diacyl fluoride **3**. Therefore, it was postulated that these perfluorinated diacyl fluorides would be synthesized by the PERFECT methodology. In the PERFECT methodology, the counterpart of a perfluoroacyl fluoride is the corresponding alcohol. Therefore, diols **11a** and **11b** are the candidates to be starting materials for the PERFECT process (Scheme 3).

One of the starting non-fluorinated diols, 1,4-butanediol (**11a**), is commercially available and inexpensive. On the other hand, diol **11b** must be synthesized, because it is not commercially available. The synthesis is shown in Scheme 4.

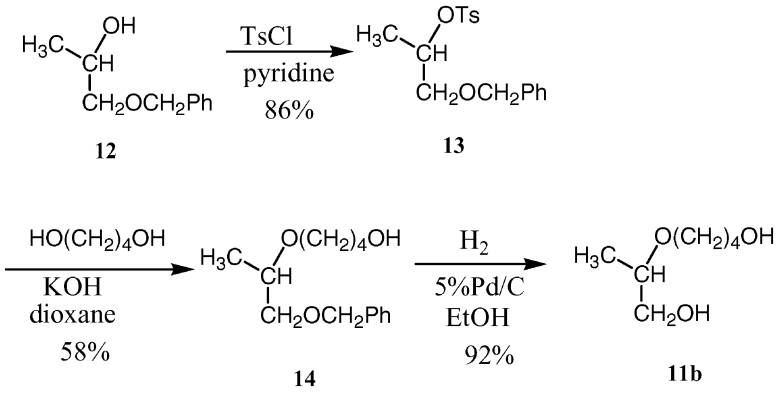
The starting material was 1-benzyloxy-2-propanol (**12**) and was treated with tosyl chloride in pyridine to give tosylate **13** in 86% yield. Then, reaction of tosylate **13** with 1,4-butanediol gave mono-substituted alcohol **14** in 58%



Scheme 2. The "PERFECT" cycle.



Scheme 3. Retrosynthetic analysis.



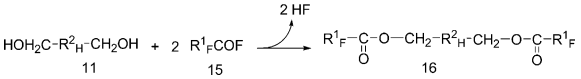
Scheme 4.

yield. Elimination of the benzyl group from **14** by catalytic hydrogenation gave the desired diol **11b** in 92% yield.

*2.2. The PERFECT process for the synthesis of diacyl fluorides **2** and **3***

Esterification of **11** was carried out simply by mixing the non-fluorinated diol and perfluoropropanoyl fluoride with removal of HF formed during the reaction from the reaction system by a stream of nitrogen (Table 1). In the case of the esterification of **11b**, the yield was not high, probably due to C–O bond cleavage by HF in the reaction mixture.

Table 1
Esterification



Substrate	R^2_H	R^1_F	Product	Yield (%)
11a	$-(CH_2)_2-$	CF_3CF_2-	**16a**	97[a]
11b	$-CHO(CH_2)_3-$ (CH$_3$)	CF_3CF_2-	**16b**	46

[a] Crude yield.

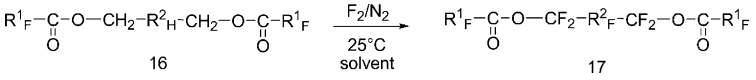
The next liquid-phase direct fluorination of partially fluorinated esters was carried out basically in a manner similar to the Exfluor–Lagow method. In order to control the reaction, heat removal, use of an inert solvent, appropriate dilution of both fluorine and the substrate, and an excess amount of fluorine to replace all of the hydrogen atoms in the substrate at all times were essential as in the case of non-fluorinated substrates.

In our method, however, dangerous vapor-phase reactions were avoided by employing a higher-molecular weight partially fluorinated ester as the substrate. Thus, the reaction was carried out with 1.5–3.0 equivalents of fluorine diluted to 20–50% in nitrogen to give the desired perfluoroester in high yield (Table 2).

To increase conversion, addition of benzene was effective in generating a higher concentration of fluorine radicals [13].

R113 (1,1,2-trichlorotrifluoroethane) was used as a typical solvent on the laboratory scale, but other perfluorinated compounds, such as perfluorohexane can also be used. Ideally, this reaction should be carried out in the

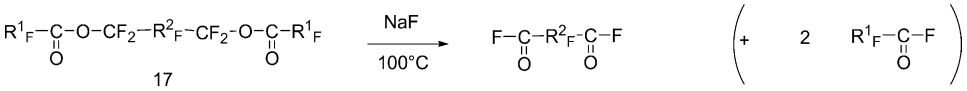
Table 2
Direct fluorination



Substrate	R^1_F	R^2_H	R^2_F	Solvent	F_2/N_2 (%)	Yield (%)[a]
16a	CF_3CF_2–	–$(CH_2)_2$–	–$(CF_2)_2$–	R113	20	92
				R113	50	89
				Perfluorohexane	20	78
16b	CF_3CF_2–	-CH(CH_3)$(CH_2)_3$-	-CF(CF_3)$(CF_2)_3$-	R113	20	94

[a]Determined by ^{19}F NMR.

Table 3
Thermal elimination



Substrate	R^1_F	R^2_F	Amount of NaF (eq)	Product	Yield (%)
17a	CF_3CF_2–	–$(CF_2)_2$–	1	**2**	52
17b	CF_3CF_2–	-CF(CF_3)$(CF_2)_3$-	0.22	**3**	77

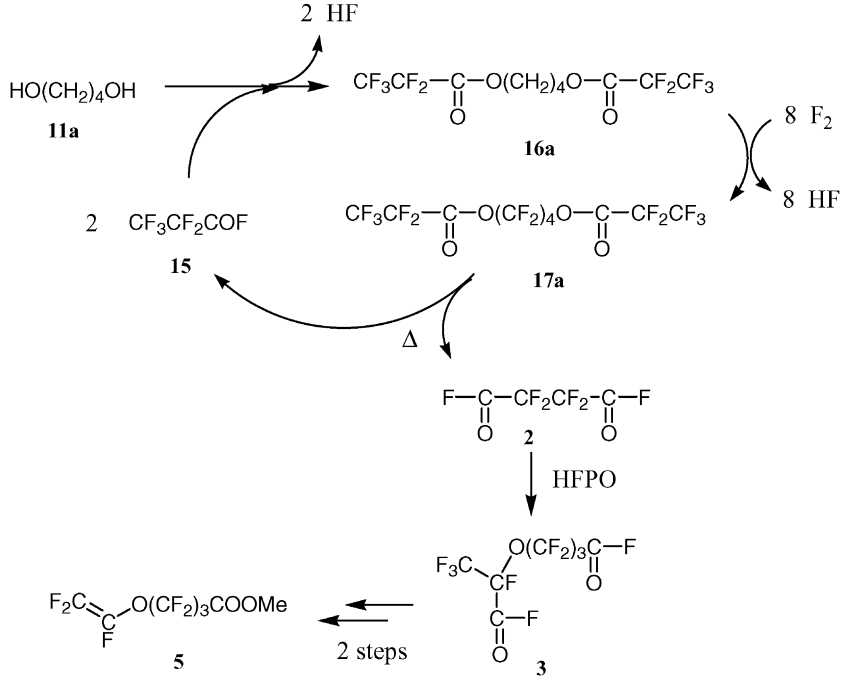
product itself as the solvent. However, when sufficient quantity of the product is not readily available, any available perfluorinated solvents can be employed.

The thermal elimination was carried out with sodium fluoride as a catalyst at 100 °C to give the desired perfluorinated diacyl fluorides after separation of the starting perfluoropropanoyl fluoride (Table 3).

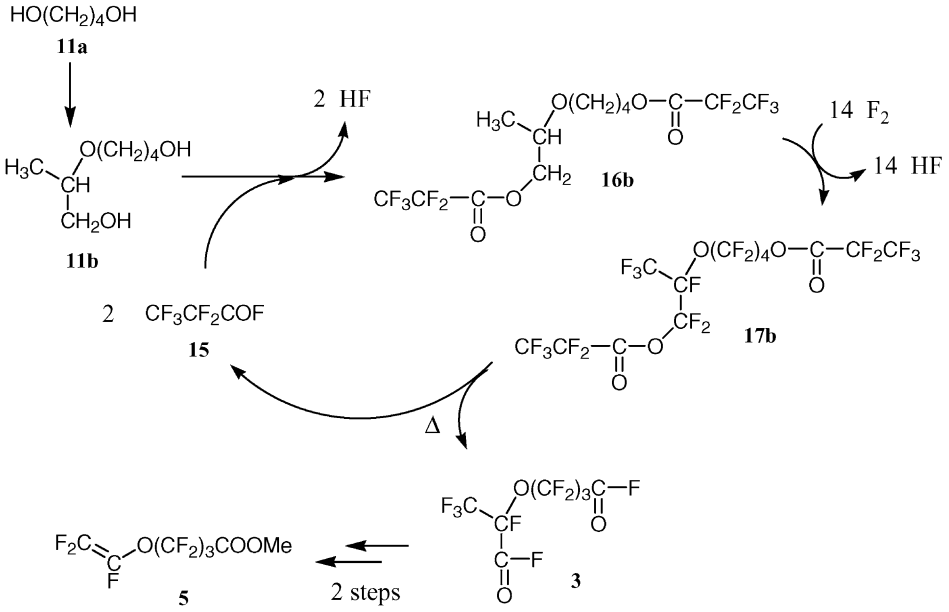
2.3. Total synthesis for the Flemion® monomer by using the PERFECT process

The total synthetic processes for the preparation of the monomer are shown in Schemes 5 and 6.

As for diacyl fluoride **2** production, 1,4-butanediol (**11a**) was employed as the starting material (Scheme 5).



Scheme 5.



Scheme 6.

It was esterified with 2 mol of perfluoropropanoyl fluoride (**15**) to obtain the partially fluorinated ester **16a**. It was then perfluorinated with elemental fluorine in the liquid-phase to give perfluorinated ester **17a**. Thermal elimination afforded the desired perfluorodiacyl fluoride **2** and perfluoropropanoyl fluoride **15** was recovered. This can be recycled.

By repeating the cycle, the quantity of perfluorodiacyl fluoride **2** will increase. Perfluorodiacyl fluoride **2** once obtained is reacted with HFPO to give perfluoroacyl fluoride **3**, and the following reactions give Flemion® monomer **5** by a known process [4].

In the synthesis of perfluorodiacyl fluoride **3** by the PERFECT process, HFPO is not required (Scheme 6), because hydrocarbon backbone structure was synthesized before fluorination. Thus, diol **11b** was esterified with 2 mol of perfluoropropanoyl fluoride (**15**), perfluorinated with elemental fluorine, and dissociated to give the desired perfluorodiacyl fluoride **3**. It is converted to Flemion® monomer **5** in further two steps.

This methodology is applicable to the synthesis of other diacyl fluorides as well as Flemion® precursor **5**, and it can be expected to be useful for various perfluorinated diacyl fluorides.

3. Conclusions

Diacyl fluorides, which are precursors of Flemion® carboxylic acid membrane monomer, were synthesized by the PERFECT process from non-fluorinated diols by utilizing direct fluorination with elemental fluorine as a key step.

The PERFECT methodology does not require oleum, and has no iodine-containing waste problem.

It does not require an additional solvent when the product itself is used for the solvent in the direct fluorina tion step, and HF is the only by-product in the PERFECT cycle.

By using the PERFECT process, various new perfluorodiacyl fluorides, which are transformed into new Flemion®-type monomer, can be created.

4. Experimental

4.1. General

NMR spectra were obtained on a JEOL EX-400 (tetramethylsilane as internal standard for ^{1}H, and trichlorofluoromethane for ^{19}F). High resolution mass spectra were obtained on JEOL SX-102A coupled to HP-5890 with a 60 m capillary column J&W DB-1 or DB-1301. Elemental fluorine was generated by Fluorodec™ 30, Fluoro Gas (UK). Elemental fluorine is highly toxic and corrosive gas, and may cause explosion when it meets organics in the vapor-phase. Extreme care must be taken when handling it! Both the liquid and vapor of hydrogen fluoride (bp 19.5 °C) evolved during the reaction are also highly corrosive and cause severe burns when in contact. Care must be taken! Prior to use, all hydrocarbon greases must be removed and the apparatus must be gradually passivated with elemental fluorine. Although the use of 1,1,2-trichlorotrifluoroethane (R113) is regulated, we give experimental examples with it for convenience, because it is still much more cheaply available (Aldrich) than compound **2** or **3** for use as solvent.

Care must be taken in order not to emit it to the environment by using, for example, a rotary evaporator with PTFE diaphragm-type vacuum pump and cooling trap. Once enough of the compound **2** or **3** is obtained in the cycle, it should be used instead of R113. Other reagents were obtained from Kanto Chemicals (Japan) and used without purification.

4.2. Typical procedure

4.2.1. Preparation of $CF_3CF_2COO(CH_2)_4OCOCF_2CF_3$ (16a)

While bubbling nitrogen gas, 1,4-butanediol (**11a**, 200 g, 2.22 mol) was stirred, perfluoropropanoyl fluoride **15** (800 g, 4.82 mol) was introduced at 25–30 °C over a period of 2.5 h. After completion of the addition, stirring was continued at room temperature for 15 h. The crude liquid was washed twice with saturated $NaHCO_3$ aqueous solution (500 ml) at 20 °C. The organic-phase was washed three times with water (1 L), and dried over magnesium sulfate. After filtration, the crude liquid (825 g) was purified by silica gel column chromatography with R225 (mixture of $CF_3CF_2CHCl_2$ and $CClF_2CF_2CHClF$) as an eluent and following distillation (91–93 °C/1.0–1.3 kPa) afforded the partially fluorinated ester **16a** (255 g, 0.667 mol, 30.0%). The GC purity was 99%; ^{1}H NMR (300.4 MHz, $CDCl_3$) δ: 1.85–1.89 (m, 4H, CH_2), 4.41–4.45 (m, 4H, OCH_2); ^{19}F NMR (282.65 MHz, $CDCl_3$) δ: −83.0 (6F, CF_3), −121.4 (4F, CF_2). High resolution mass spectrum (CI^+) 383.0367 ($[M+H]^+$, calculated for $C_{10}H_9F_{10}O_4$: 383.0341).

4.2.2. Synthesis of $CF_3CF_2COO(CF_2)_4OCOCF_2CF_3$ (17a)

Into a 3000 ml autoclave made of nickel, R113 (3232 g) was charged, stirred and maintained at 25 °C. At the gas outlet of the autoclave, a cooler maintained at −10 °C was installed. After supplying nitrogen gas for 1 h, 20% F_2/N_2 was supplied for 1 h at a flow rate of 8.49 L/h for 2.3 h. Then, while supplying 20% fluorine gas at the same flow rate, a solution of compound **16a** (80 g, 0.209 mol) in R113 (800 g), was injected over a period of 45.7 h. Further, 20% fluorine gas was supplied at the same flow rate for 0.5 h, and then nitrogen gas was supplied for 3.0 h to remove volatile materials.

The yield of the perfluorinated ester **17a** determined by ^{19}F NMR spectroscopy was 92%; ^{19}F NMR (376.0 MHz, $CDCl_3$) δ: −83.8 (6F, CF_3), −87.3 (4F, OCF_2), −122.6 (4F, CF_3CF_2), −126.6 (4F, OCF_2CF_2). High resolution mass spectrum (EI^+) 506.9536 ($[M-F]^+$, calculated for $C_{10}F_{17}O_4$: 506.9525).

4.2.3. Synthesis of $FCO(CF_2)_2COF$ (2)

Perfluorinated diester **17a** (5.00 g, 9.51 mmol) was charged together with 0.4 g of NaF powder into a flask and heated at 100 °C for 0.25 h in an oil bath while vigorously stirring. A gaseous sample (3.46 g) was recovered. By the NMR spectrum, it was confirmed that acyl fluoride **15** and diacyl fluoride **2** [4] were the main components. The yield of **2** was 52%.

4.2.4. Preparation of $CF_3CF_2COO\ CH_2CH(CH_3)O(CH_2)_4OCOCF_2CF_3$ (16b)

p-Toluenesulfonyl chloride (63.1 g, 0.331 mol) was added gradually to $HOCH(CH_3)CH_2OCH_2Ph$ (**12**, 50.0 g, 0.301 mol) in pyridine (150 ml) with stirring at 5 °C over a period of 1 h. Then the mixture was added to water (165 ml), and extracted with dichloromethane (165 ml). The organic layer was washed with $NaHCO_3$ (165 ml), further washed three times with water (130 ml), dried over magnesium sulfate, filtered and then concentrated by an evaporator. The precipitated white crystals were collected by filtration and washed with hexane to obtain tosylate **13** (83.2 g, 0.260 mol, 86%); ^{1}H NMR (300.4 MHz, $CDCl_3$) δ: 1.31 (d, ^3J = 6.3 Hz, 3H, CH_3), 2.40 (s, 3H, $CH_3C_6H_4$), 3.46 (m, 2H, OCH_2CH), 4.41 (m, 2H, OCH_2Ph), 4.73 (m, 1H, CH), 7.19–7.34 (m, 7H, C_6H_5 and 2H of C_6H_4), 7.75–7.89 (m, 2H of C_6H_4). Diol **11a** (37 g, 0.41 mol), potassium hydroxide (23 g, 0.41 mol) and dioxane (200 ml) were heated to an internal temperature of 102 °C to dissolve potassium hydroxide. A solution of tosylate **13** (63.7 g, 0.199 mol) obtained above in dioxane (65 ml) was added dropwise over a period of 1 h and stirred for 4 h. The reaction mixture was added to water (350 ml) and extracted three times with dichloromethane (100 ml). The organic layer was washed with water (20 ml), dried over magnesium sulfate, filtered, concentrated and purified by silica gel column chromatography to obtain compound **14** (27.6 g, 0.116 mol, 58%); ^{1}H NMR (300.4 MHz, $CDCl_3$) δ: 1.15 (d, ^3J = 6. 2 Hz, 3H, CH_3), 1.64 (m, 4H, CH_2), 2.98 (bs, 1H, OH), 3.62–3.68 (m, 7H, OCH_2 and CH), 4.53 (m, 2H, OCH_2Ph), 7.23–7.29 (m, 5H, C_6H_5).

Under an argon atmosphere, 5% palladium–carbon powder (1.5 g) was charged. Compound **14** (15.2 g, 63.8 mmol) in ethanol (100 ml) was added. The mixture was stirred at room temperature for 17 h and then filtered through celite. The filtrate was concentrated to obtain compound **11b** (8.65 g, 58.4 mmol, 92%); ^{1}H NMR (300.4 MHz, $CDCl_3$) δ: 1.11 (q, ^3J = 6.2 Hz, 3H, CH_3), 1.68 (m, 4H, CH_2), 2.48 (bs, 2H, OH), 3.41–3.68 (m, 7H, OCH_2 and CH). Diol **11b** (18.8 g, 0.127 mol) was stirred at 30 °C, then perfluoropropanoyl fluoride (**15**, 276 g, 1.66 mol) was supplied together with nitrogen over 6 h while maintaining the internal temperature at 30 °C. After completion of the addition, stirring was continued for 2 h at 30 °C while supplying nitrogen gas. A 5% $NaHCO_3$ aqueous solution (300 ml) was added at 15 °C. The organic layer was separated, washed twice with water (100 ml), dried over anhydrous magnesium sulfate and then filtered to obtain a crude liquid. The crude liquid was purified by silica gel column chromatography (eluent: R225)

to obtain **16b** (25.9 g, 58.8 mmol, 46%); ^{1}H NMR (300.4 MHz, $CDCl_3$) δ: 1.20 (d, $^{3}J = 6.3$ Hz, 3H, CH_3), 1.56–1.68 (m, 2H, CH_2), 1.78–1.87 (m, 2H, CH_2CH_2OCO), 3.42–3.60 (m, 2H, OCH_2), 3.66–3.76 (m, 1H, OCH), 4.26–4.42 (m, 4H, $COOCH_2$); ^{19}F NMR (282.7 MHz, $CDCl_3$) δ: −83.0 (6F, CF_3), −121.4 (2F, CF_2), −121.5 (2F, CF_2). High resolution mass spectrum (CI^+) 441.0768 ($[M + H]^+$, calculated for $C_{13}H_{15}F_{10}O_5$: 441.0760).

4.2.5. Synthesis of $CF_3CF_2COO\ CF_2CF(CF_3)O(CF_2)_4OCOCF_2CF_3$ (17b)

The direct fluorination of **16b** was carried out in a manner similar to the procedure for the direct fluorination of **16a**, where the flow rate of 20% F_2/N_2 was 10.1 L/h, and a solution of **16b** (4.95 g, 11.2 mmol) in R113 (100 g) was supplied over a period of 5.5 h. Then, a solution of benzene in R113 (0.01 g/mL, 9 mL) was supplied intermittently at 0.20 MPa, and this operation was repeated four times. Nitrogen gas was supplied to remove solvent and volatile materials to give the crude perfluorinated product. The structure of the desired product **17b** was confirmed by ^{19}F NMR and the yield determined by the ^{19}F NMR was 94%; ^{19}F NMR (376.0 MHz, $CDCl_3$) δ: −80.4 (3F, $CF(CF_3)$), −81.0 (2F, $CF(CF_3)OCF_2$), −83.3 (3F, CF_2CF_3), −83.4 (3F, CF_2CF_3), −86.8 (2F, $COOCF_2$), −86.9 (2F, $COOCF_2$), −122.1 (4F, CF_2CF_3), −125.9 (2F, OCF_2CF_2), −126.2 (2F, OCF_2CF_2), −145.6 (1F, CF). High resolution mass spectrum (EI^+) 672.9378 ($[M - F]^+$, calculated for $C_{13}F_{23}O_5$: 672.9378).

4.2.6. Synthesis of $FCOCF(CF_3)O(CF_2)_3COF$ (3)

The thermal elimination of **17b** was carried out in a manner similar to the procedure for the thermal elimination of **17a**. The yield of the desired product **3** [4] determined by the ^{19}F NMR was 77%.

Acknowledgement

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