Electroytic Partial Fluorination of Organic Compounds. 52.[1] Regio- and Diastereoselective Anodic Fluorination of Thiazolidines

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Anodic fluorination of *N*-benzoyl, *N*-acethyl-, and *N*-formylthiazolidine derived from L-cysteine was carried out in dimethoxyethane (DME) and acetonitrile containing various supporting fluoride salts using an undivided cell. Highly regioselective fluorination proceeded to provide the corresponding 5-monofluorinated thiazolidine derivatives in good yields in DME, and the diastereoselectivitiy was moderate to high regardless of the supporting fluoride salts. The diastereoselectivitiy of the fluorination was greatly affected by the bulkyness of the subsitituent on the nitrogen atom, and *N*-benzoylthiazolidine gave much higher diastereoselectivity compared with *N*-formyl derivative. The fluorination of the thiazolidines was not achieved by commercially available fluorinating reagents such as *N*-fluoropyridinium salts.

Introduction

Organofluorine compounds are highly useful in material science and medicinal chemistry. It is well-known that the introduction of fluorine atom(s) into organic molecules greatly enhances or dramatically changes their biologial activities.[2] Although heterocyclic compounds have potentiality of unique biological activities, there have been only limited number of papers dealing with direct fluorination of heterocycles so far.[3] Therefore, electrochemical partial fluorination of various heterocycles such as 3-thiolanones, 2*H*-1,4-benzothiazinones, ethyl isonicotinate, *β*-lactams, thiazolidinones, 1,3-dithiolanones, 1,3-oxathiolanones, 3-oxindoles, flavones, and 2,3-dihydrochromanones was investigated in our group.[4]

On the other hand, asymmetric fluorination of organic compounds is of much importance, especially for medicinal and agrochemical applications. However, asymmetric anodic fluorination was very difficult in general, due to the smallness of a fluoride ion and necessity of use of polar solvents for electric conductivity. Therefore, only a few studies have been reported on asymmetric anodic fluorination.[5] Kabore et al. obtained up to 60% de in the anodic fluorination of α-phenylacetates having various chiral auxiliaries,[5a] while we obtained much lower de as 20% in the anodic fluorination of α-phenythioacetates having chiral auxiliaries.[5b]

Ando and co-workers reported unexpected diastereoselective hydroperoxylation of (4*R*)-benzoyl-2,2-dimethyl-4-carbomethoxythiazolidine (**1a**), easily derived from L-cysteine, by the photooxidation with singlet oxygen (Scheme 1).[6] They assumed a Pummerer type rearrangement of a hydroperoxysulfonium ylide intermediate for this reaction mechanism. On the other hand, we have already established that anodic fluorination of sulfides also proceeds in a manner of a Pummerer type reaction via a fluorosulfonium intermediate.[7] Therefore, it was expected that anodic fluorination of **1a** would also proceed highly diastereoselectively. Additionally, thiazolidines are well-known to be useful for the synthesis of natural products,[8] peptides,[9] and thiosugars.[10] Therefore, their optically active fluorinated derivatives are expected as useful precursors for biologically active compounds.[11]

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Scheme 1

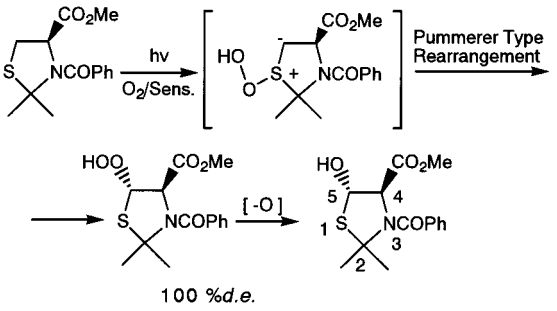
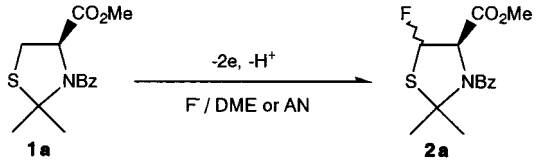


Table 1. Anodic Fluorination of Thiazolidine 1a

run	electrolyte	solvent	charge (F/mol)	yield (%)[a]	de (%)[b]
1	$Et_3N{\cdot}3HF$	AN	3.0	38	86
2	$Et_3N{\cdot}3HF$	DME	5.0	78	78
3	$Et_3N{\cdot}4HF$	AN	3.0	56	94
4	$Et_3N{\cdot}4HF$	DME	5.0	78 (50)	94
5	$Et_3N{\cdot}5HF$	AN	3.3	40	94
6	$Et_4NF{\cdot}3HF$	DME	5.0	73	78
7	$Et_4NF{\cdot}4HF$	DME	5.0	56	80
8	$Et_4NF{\cdot}5HF$	DME	5.0	53	99
9[c]	$Et_3N{\cdot}4HF$	DME	4.5	24	94

[a] Determined by ^{19}F-NMR. The figure in parentheses is isolated yield. [b] Determined by GC. [c] Carbon sheet anode.

Scheme 2



Results and Discussion

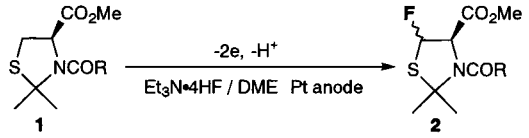
Anodic Fluorination of (4*R*)-3-Benzoyl-4-carbomethoxy-2,2-dimethylthiazolidine (1a) under Various Conditions. Anodic fluorination of **1a**[10] was carried out in an undivided cell using platinum electrodes under various conditions as shown in Table 1. Regardless of the electrolytic conditions, anodic fluorination proceeded and a fluorine atom was selectivly introduced into the position α to the sulfur atom (Scheme 2). In all cases, the diastereoselectivity was high. Regardless of the supporting fluoride salts, dimethoxyethane (DME) was more suitable for the fluorination than acetonitrile (AN).[12] In contrast to a platinum anode, the use of a carbon felt anode resulted in low product yield (run 9). Interestingly, the diastereoselectivity increased with an increase of HF content in the supporting fluoride salts and almost 100% de was obtained in DME containing $Et_4NF{\cdot}5HF$ (run 8). In these fluoride salts, fluoride ions are known to form a hydrogen bonding with hydrogen fluoride.[13] Therefore, with an increase of HF content in the electrolyte, the association of fluoride ions is changed. Due to this reason, the extremely high diastereoselectivity seems to be obtained particularly when $Et_4NF{\cdot}5HF$ was used. The same diastereomer was always formed as a major product in all cases. Since we have already established that anodic fluorination of organosulfur compounds proceeds in a Pummerer type reaction mechanism, the anodic fluorination of **1a** seems to proceed in a similar mechanism. Therefore, this successful fluorination of **1a** is notable because it is known that the Pummerer reaction acetoxylation of the sulfoxide derivative of **1a** does not proceed at all and only ring expansion takes place.[10]

Table 2. Anodic Fluorination of Thiazolidines 1a−d

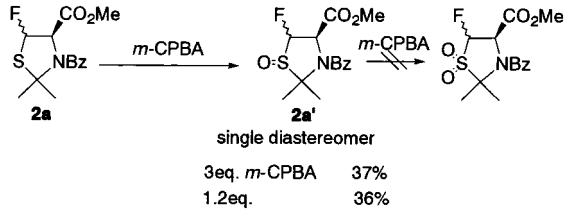
thiazolidine			product	
no.	R	electricity (F/mol)	yield (%) [a]	de (%)[c]
1a	Ph	5.0	**2a** 78 (50)[b]	94
1b	Me	5.5	**2b** (53)[b]	80
1c	H	5.5	**2c** 52 (40)[b]	59
1d	Tol	5.0	**2d** 91 (60)[b]	95

[a] Determined by ^{19}F-NMR. [b] Isolated yield. [c] Determined by ^{19}F-NMR or GC-MS.

Scheme 3



Scheme 4



Anodic Fluorination of 3-Acetoxy-, 3-Formyl-, and 3-*p*-Toluoylthiazolidine Derivatives 1b−d. Since a $Et_3N{\cdot}4HF$/DME solution gave the highest yield and high diastereoselectivity, anodic fluorination of other thiazolidine derivatives **1b−d** was also carried out similarly. The results are summarized in Table 2. The fluorination proceeded smoothly to give monofluorinated products **2b−d** (Scheme 3) in moderate to excellent yields. The *p*-toluoyl derivative **1d** gave high diastereoselectivity as observed in the case of **1a**, while **1b** and **1c** gave moderate diastereoselectivity. These results clearly indicate that the diastereoselectivity of the fluorinated product **2** decreased with a decrease of the bulkyness of the *N*-substituents.

Ando and co-workers determined the stereochemistry of the hydroxyl derivative, which was obtained by the reduction of hydroperoxylated product of **1a**, based on the zero coupling constant between the 4- and 5-methine protons in the ^{1}H NMR spectrum (Scheme 1).[6] In all the fluorinated products, however, the coupling between 4- and 5-methine protons was not observed in both diastereoisomers. Therefore, we tried to determine the stereochemistry by the X-ray analysis. To obtain a crystalline sample suitable for the X-ray analysis, we attempted to convert **2a** to the corresponding sulfone derivative. However, the corresponding sulfone was not obtained, but sulfoxide **2a′** was stereoselectively formed although a large excess amount of mCPBA (3 equiv) was used as shown in Scheme 4. Even when 1.2 equiv of *m*-CPBA was used, the yield was not changed. The structure **2a′** was found to be a trans form based on its X-ray analysis (see Supporting Information). The X-ray analysis of the

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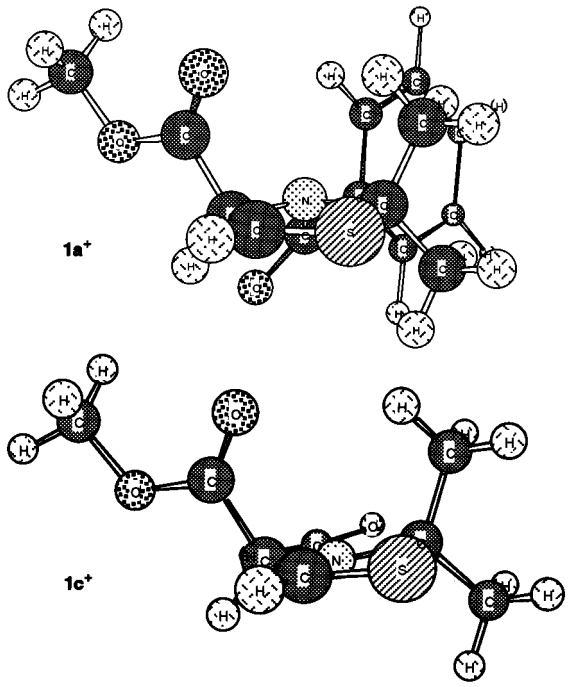


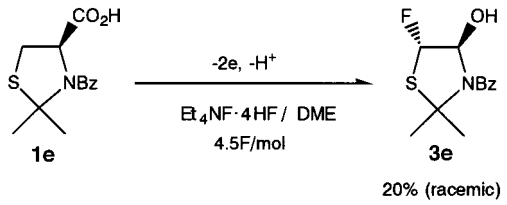
Figure 1.

crystalline of the major diastereomer of **2c** also showed a trans form.[14]

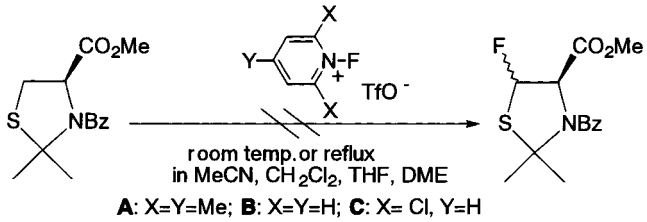
The diastereoselectivity seems to be controlled by the steric repulsion of the neighboring carbomethoxy group. However, as shown in Table 2, the acyl groups on the nitrogen atom greatly affected the diastereoselectivity. Namely, the diastereoselectivity increases with an increase of the bulkiness of the acyl group. To obtain more detailed information of the stereocontrol, PM3 calculation (MOPAC) was carried out for the cation intermediates of **1a** and **1c** to determine the minimum energy structures. As shown in Figure 1, the phenyl group is perpendicular to the thiazolidine ring in the case of $\mathbf{1a}^+$. Thus, one side of the thiazolidine was sterically blocked by both the carbomethoxy and phenyl groups. Therefore a fluoride ion should attack $\mathbf{1a}^+$ predominantly from the less hindered side. In sharp contrast, in the case of the $\mathbf{1c}^+$, the much smaller formyl group is coplanar to the heterocyclic ring. This seems to cause much lower diastereoselectivity. Therefore, the diastereoselectivity observed in the anodic fluorination of **1** is reasonable.

Anodic Fluorination of 3-Benzoyl-2,2-dimethyl-4-thiazolodinecarboxylic Acid (1e). Anodic fluorination of **1e** was also carried out in comparison with **1a.** Unexpectedly, fluorination and decarboxylation took place simultaneously to give only *trans*-3-benzoyl-2,2-dimethyl-5-fluoro-4-hydroxythiazolidine (**3e**) in low yield (Scheme 5). The stereochemistry was confirmed by the zero coupling between the fluorine and the hydroxyl proton in the ^{1}H and ^{19}F NMR spectra. Coupling between the 4- and 5-methine protons in the ^{1}H NMR spectrum was not also observed similar to **2a**. Although the starting carboxylic acid **1e**[10] was enantiomerically pure, the product **3e** was a racemic mixture. Therefore, it is more likely that the decarboxylation followed by hydroxylation with a trace amount of water in the electrolyte took place and subsequently the fluorination proceeded.

Scheme 5



Scheme 6



A: X=Y=Me; **B**: X=Y=H; **C**: X= Cl, Y=H

Attempt of Chemical Fluorination of 1a Using *N*-Fluoropyridinium Salts. *N*-Fluoropyridinium salts have been widely used for the selective fluorination of various organic compounds in recent years.[15] They are safe, easy to handle, and commercially available. It was expected that the fluorination would proceed similarly to the anodic fluorination since it was confirmed that the fluorination of sulfides proceeded via a fluorosulfonium ion intermediate.[15b] The reaction was performed under various conditions as shown in Scheme 5. However, the desired fluorinated product was not formed at all. When a strongly fluorinating reagent **C** was used, the substrate decomposed immediately. On the other hand, using weaker fluorinating reagents **A** and **B**, the reaction did not proceed even under reflux. Therefore, it was shown that this electrochemical method is much superior to the conventional chemical method.

Conclusion

We have achieved highly regio- and diastereoselective anodic fluorination of *N*-acylthiazolidines in good yields. The diastereoselectivity of the fluorination was affected mainly by *N*-acyl bulkyness. Electrolytic conditions such as a solvent and the type of supporting fluoride salt also affected the diastereoselectivity. In contrast, the anodic fluorination of a thiazolidine derivative having a carboxylic group gave a hydroxyfluorinated product accompanying decarboxylation. We also tried to carry out chemical fluorination of *N*-acylthiazolidines using *N*-fluoropyridinium salts. However, fluorinated product was not obtained in this case.

Experimental Section

General. Caution: $Et_3N{\cdot}nHF$ ($n = 3, 4, 5$) and $Et_4NF{\cdot}nHF$ ($n = 4, 5$) are toxic; if it comes in contact with skin, it cause a serious burn. Therefore, proper safety precautions should be taken at all times, and it is recommended that rubber gloves should be used.

(14) According to the ^{1}H and ^{19}F NMR data, it seemed that the stereoselectivity of **2a** was different from that of **2b** and **2c**. However, the X-ray analysis of both **2a′** and **2c** showed a trans structure, and we concluded that all the monofluorinated products were obtained as a trans form selectively.

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^{1}H NMR, ^{13}C NMR, and ^{19}F NMR spectra were recorded at 270, 68, and 254 MHz, respectively, in $CDCl_3$ as a solvent. The chemical shifts for ^{19}F are given in ppm downfield from external TFA. Preparative electrolysis experiments were carried out using a Potentiostat/Galvanostat HA-305 and Coulomb/Amperehour meter NOCM-1 (Hokuto Denko, Ltd., products). PM3 calculation was performed using the MOPAC[16] program on the Chem3D.

Materials. The supporting fluoride salts, $Et_3N{\cdot}nHF$ (n = 3, 4, 5) and $Et_4NF{\cdot}nHF$ (n = 4, 5) were kind gifts of Morita Chemical Industries Co., Ltd. (Japan) and used for the electrolysis without further purification. The optically pure starting materials, **1a** and **1e**, were prepared according to a literature.[10]

3-Acetyl-4-carbomethoxy-2,2-dimethylthiazolidine(1b). To a mixture of 4-carbomethoxy-2,2-dimethylthiazolidine hydrochloride (2 g, 9.5 mmol), prepared from cysteine according to a literature,[6] and acetyl chloride (0.4 g, 12.1 mmol) in toluene (80 mL) was added pyridine (1.8 g, 24.3 mmol) with a syringe. The mixture was stirred at room temperature for 1 h. After addition of ethyl acetate (25 mL), the mixture was cooled with a water−ice bath. The resulting precipitate was filtered off, and the filtrate was evaporated under vacuum. The residue was purified by column chromatography on silica gel using hexane/ethyl acetate (8/2) as an eluent to give 2.06 g (100%) of the product **1b** as a colorless oil. ^{1}H NMR δ 1.85 (3 H, s), 1.90 (3 H, s), 2.05 (3 H, s), 3.29−3.32 (2 H, m), 3.81 (3 H, s), 4.80−4.82 (1 H, m); ^{13}C NMR δ 25.20, 27.23. 29.56, 31.25, 52.83, 66.42, 73.21, 168.28, 170.49; MS m/z 217 (M^+), 202 ($M^+ - CH_3$); HRMS m/z: calcd for $C_9H_{15}NO_3S$ 217.0773, found: 217.0795

4-Carbomethoxy-2,2-dimethyl-3-formylthiazolidine(1c). To a mixture of 4-carbomethoxy-2,2-dimethylthiazolidine hydrochloride (2 g, 9.5 mmol) and sodium formate (1.56 g) in formic acid (34 mL) was slowly added acetic anhydride (11 mL) and stirred at room temperature for 24 h. After the reaction mixture was concentrated, water was added, and then the product was extracted with toluene (25 mL) and washed with water, saturated aqueous $NaHCO_3$, and brine. The extract was dried over $MgSO_4$ and concentrated. The residue was purified by column chromatography on silica gel using hexane to hexane/ethyl acetate (3/2) as an eluent to give 1.2 g (63%) of the product **1c** as a colorless oil. ^{1}H NMR δ 1.81 (3 H, s), 1.84 (3 H, s), 3.27−3.31 (2 H, m), 3.76 (3 H, m), 5.05−5.07 (1 H, m), 8.34 (1 H, s); ^{13}C NMR δ 30.98, 31.10, 32.04, 52.67, 62.23, 69.90, 159.10, 169.77; MS m/z 203 (M^+), 188 ($M^+ - CH_3$); HRMS m/z: calcd for $C_8H_{13}NO_3S$ 203.0616, found 203.0603.

4-Carbomethoxy-2,2-dimethyl-3-(*p*-toluoyl)thiazolidine (1d) was prepared by the similar procedure to **1a** using *p*-toluoyl chloride (66%). mp 71−72 °C; ^{1}H NMR δ 1.96 (s, 3H), 2.00 (s, 3H), 2.36 (s, 3H) 3.15−3.01 (m, 2H), 3.67 (s, 3H), 4.82 (m, 1H), 7.2−7.27 (m, 4H); ^{13}C NMR δ 21.43, 28.28, 29.66, 31.30, 52.73, 67.75, 73.11, 125.69, 129.01, 135.52, 139.30, 169.61, 170.72; MS m/z 293 (M^+), 278 ($M^+ - CH_3$). Anal. Calcd for $C_{15}H_{19}NO_3S$: C, 61.41; H, 6.53; N, 4.77. Found: C, 61.64; H, 6.63; N, 4.74

Electrolytic Procedures for Fluorination. Electrolysis was carried out at a platinum anode and cathode (2 × 2 cm^2, each) in solvent (15 mL) containing 15 mmol of fluoride salt and 1 mmol of **1** using an undivided glass cell. Constant current (20 mA/cm^2) was passed until the starting material was consumed. After the electrolysis, the resulting electrolytic solution was passed through a short column chromatography on silica gel using ethyl acetate to remove the fluoride salt. The eluent was evaporated under vacuum, and the residue was purified by column chromatography on silica gel using hexane to hexane/ethyl acetate (4/1) as an eluent.

(4*R*,5*S*)-3-Benzoyl-4-carbomethoxy-2,2-dimethyl-5-fluorothiazolidine (2a): mp 57−58 °C; $[\alpha]^{20}_D = -122$ (c = 0.59, $CHCl_3$); ^{1}H NMR δ 2.02 (3 H, s), 2.13 (3 H, s), 3.71 (3 H, s), 5.18 (1 H, d, J = 10 Hz), 6.26 (1 H, d, J = 54 Hz), 7.26−7.38 (m, 5H); ^{13}C NMR δ 28.57, 32.18, 53.14, 74.40(d, J = 28 Hz), 75.11, 96.70(d, J = 227 Hz), 125.89, 128.77, 129.68, 137.88, 167.51, 169.95; ^{19}F NMR δ −66.97 (brd, J = 54 Hz); MS m/z = 279 (M^+) ; HRMS m/e: calcd for $C_{14}H_{16}FNO_3S$ 297.0835, found 297.0836. Anal. Calcd for $C_{14}H_{18}FNO_3S$: C, 56.55; H, 5.42; N, 4.71. Found: C, 56.80; H, 5.14; N, 4.50.

3-Acetyl-4-carbomethoxy-2,2-dimethyl-5-fluorothiazolidine (2b): colorless oil; ^{1}H NMR (cis and trans mixture) δ 1.91 (3 H, s), 2.00 (3 H, s), 2.07 (3 H, s), 3.78 (3 H, s, cis isomer), 3.84 (3 H, s, trans isomer), 5.14 (1 H, d, J = 10 Hz, trans isomer), 5.64 (1 H, d, J = 13 Hz, cis isomer), 6.15 (1 H, d, J = 54 Hz, cis isomer), 6.32 (1H, d, J = 54 Hz, trans isomer); ^{13}C NMR(trans isomer) δ 25.12, 27.87, 32.26, 35.34, 73.80 (d, J = 27 Hz), 75.81, 96.96 (d, J = 230 Hz), 167.46, 168.54; ^{19}F NMR δ −62.80 (dd, J = 54 Hz, J = 13 Hz, cis isomer), −65.17 (dd, J = 54 Hz, J = 10 Hz trans isomer); MS m/z = 235 (M^+), 220 ($M^+ - CH_3$), 216 ($M^+ - F$); HRMS m/z: calcd for $C_9H_{14}FNO_3S$ 235.0678, found 235.0658.

4-Carbomethoxy-2,2-dimethyl-5-fluoro-3-formylthiazolidine (2c): mp 56−57 °C; ^{1}H NMR (cis and trans mixture) δ 1.90 (3 H, s), 1.96 (3 H, s), 3.80 (3 H, s, trans isomer), 3.84 (3 H, s, cis isomer), 5.08 (1H, d, J = 10 H cis isomer), 5.54 (1 H, d, J = 12 Hz, trans isomer), 6.33 (1 H, d, J = 54 Hz trans isomer), 6.41 (1 H, d, J = 54 Hz cis isomer), 8.31 (1 H, s cis isomer), 8.47 (1 H, s trans isomer); ^{19}F NMR (cis and trans mixture) δ −62.41 (dd, J = 54 Hz, J =12 trans isomer), −67.55 (dd, J = 54 Hz, J =10 cis isomer); MS m/z = 221 (M^+), 206 ($M^+ - 15$). Anal. Calcd for $C_8H_{12}FNO_3S$: C, 43.43; H, 5.47; N, 6.33. Found: C, 43.60; H, 5.31; N, 6.21.

***trans*-4-Carbomethoxy-2,2-dimethyl-5-fluoro-3-*p*-toluoylthiazolidine (2d):** colorless oil; ^{1}H NMR δ 2.01 (3H, s), 2.11 (3H, s), 2.35 (3H, s), 3.71 (3H, s), 5.22 (1H, d, J = 9 Hz), 6.23 (1H, d, J = 54 Hz), 7.16−7.27 (5H, m); ^{13}C NMR δ 21.41, 28.68, 28.75, 53.10, 74.38 (d, J = 27 Hz), 74.97, 96.64 (d, J = 227 Hz), 125.81, 129.20, 134.93, 139.61, 167.33 (d, J = 10 Hz), 169.92; ^{19}F NMR δ −66.48 (brd, J = 54 Hz); MS m/z 311 (M^+), 296 ($M^+ - CH_3$); HRMS m/z: calcd for $C_{15}H_{18}FNO_3S$: 311.0991, found: 311.0990.

***trans*-3-Benzoyl-2,2-dimethyl-5-fluoro-4-hydroxythiazolidine (3e)**: colorless oil; ^{1}H NMR δ 2.03 (3 H, s), 2.09 (3 H, s), 2.67 (1 H, d, J =11 Hz), 5.68 (1 H, dd, J =11 Hz, J = 4 Hz), 5.83 (1 H, d, J = 54 Hz), 7.26−7.47 (3 H, m), 7.55−7.59 (2 H, m); ^{13}C NMR δ 30.57, 31.82, 74.07, 89.70 (d, J = 34 Hz), 99.48 (d, J = 230 Hz), 126.77, 128.53, 130.15, 137.41, 170.11; ^{19}F NMR δ −70.50 (dd, J = 55 Hz, J = 4 Hz); IR (KBr) 3436, 1643 cm^{-1}; MS m/z 255 (M^+), 237 ($M^+ - H_2O$); HRMS m/z: calcd for $C_{12}H_{14}FNO_2S$: 255.0729, found: 255.0649.

(1*R*,4*R*,5*S*)-3-Benzoyl-4-carbomethoxy-2,2-dimethyl-5-fluoro-1-oxothiazolidine (2a′). To a solution of **2a** (89 mg, 0.3 mmol) in dry CH_2Cl_2 (5 mL) was added *m*-CPBA (0.9 mmol) at 0 °C and stirred 15 h at rt under a nitrogen atmosphere. After filtration, the filtrate was washed with saturated aqueous $Na_2S_2O_3$, aqueous $NaHCO_3$, and brine. The organic layer was separated and dried over $MgSO_4$ and then evaporated. The residue was purified by column chromatography on silica gel using hexane to hexane/ethyl acetate (7/3) as an eluent to give **2a′** (35 mg, 37%). mp 111−112 °C; $[\alpha]^{25}_D = -79$ (c = 0.62, $CHCl_3$); ^{1}H NMR δ 1.89 (3 H, s), 1.98 (3 H, s), 3.71 (3 H, s), 5.19 (1 H, d, J = 17 Hz), 5.90 (1 H, d, J = 48 Hz), 7.26−7.42 (5 H, m); ^{13}C NMR δ 19.23, 21.99, 53.24, 68.94 (d, J = 21 Hz), 83.38, 96.96 (d, J = 228 Hz), 125.73, 128.91, 129.94, 137.12, 165.96, 170.33. ^{19}F NMR δ −102.18 (dd, J = 48 Hz, J = 17 Hz). Anal. Calcd for $C_{14}H_{16}FNO_4S$: C, 53.66; H, 5.15; N, 4.47. Found: C, 53.56; H, 4.94; N, 4.47.

Chemical Fluorination Using *N*-Fluoropyridinium Salts. To a solution of **2a** (139.5 mg, 0.5 mmol) in dry solvent (5 mL) were added *N*-fluoropyridinium salts A−C and stirred at room temperature or under reflux in a nitrogen atmosphere for 12 h.

X-ray Crystallography. Single crsytals of **2a′** and **2c** suitable for X-ray diffraction determination were grown from hexane/CH_2Cl_2 The diffraction data for **2a′** and **2c** were measured on a Rigaku AFC 7S automated four-circle diffractometer with graphite-monochromated Mo Kα (λ = 0.71069 Å) radiation. The data were collected at 23 ± 1 °C using the $\omega-2\theta$ scan to a maximum 2θ value of 55.0°. The unit-cell

(16) Stewart, J. J. P. MOPAC97, Fujitsu, Ltd., Tokyo, Japan, 1998.

parameters of each crystal were obtained from a least-squares refinement based on 25 ($22 < 2\theta < 30°$) (2a′), 25 ($21 < 2\theta < 27°$) (3) reflections. The intensities of three representative reflections monitored every 150 reflections did not show any decay in each experiment. Therefore, no decay correction was applied. Azimuthal scans of several reflections for all complexes indicated no need for an absorption correction. All data were corrected for Lorentz and polarization effects. An empirical absorption correction based on azimuthal scans of several reflections was applied which resulted in transmission factors ranging from 0.93 to 1.00 (**2a′**) and from 0.86 to 1.00 (**2c**). The crystallographic data and collection details are summarized in Table S1. The structure was solved by direct methods (SAPI 91)[17] and expanded using Fourier techniques.[18] The non-hydrogen atoms were refined anisotropically. Hydrogen atoms were located on the calculated positions (C−H = 0.95 Å and $U = 1.3\ U(\mathrm{C})$). Refinements were carried out by a full-matrix least-squares method on F. The final discrepancy factors (R and Rw) are listed in Table S1. All calculations were performed using the teXsan[19] crystallographic software package of Molecular Structure Corporation.

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Supporting Information Available: Copies of ^{1}H NMR spectra of **1b**, **1c**, **2b**, **2e**, **3d** and ^{13}C NMR spectra of **1b**, **2d**, **3d.** Full numbering views, crystal data, data collection and refinement papameters, full tables of atomic coordinates, thermal displacement parameters, bond lengths and angles, and torsion agngles for X-ray crystal structures of **2a′** and **2c** (CIF file). This material is available free of charge via Internet at http://pubs.acs.org.

JO010472B

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