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Nucleophilic 5-endo-trig Cyclization of 3,3-Difluoroallylic Ketone Enolates: Synthesis of 5-Fluorinated 2-Alkylidene-2,3-dihydrofurans

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Abstract: 3,3-Difluoroallylic ketones readily undergo nucleophilic 5-endo-trig cyclization through their metal enolates to afford 5-fluorinated 2-alkylidene-2,3-dihydrofurans. O-Cyclization exclusively occurred via intramolecular substitution of the vinylic fluorines.

Key words: cyclization, fluorine, alkenes, furans, 5-endo-trig, ketone enolates, vinylic substitution

Gem-difluoroalkenes (1,1-difluoro-1-alkenes) have unique reactivities toward nucleophiles, which are based on their electron-deficient and highly polarized nature. They facilitate extraordinary substitution reactions, which hardly proceed in normal alkenes.1 Difluoroalkenes readily undergo vinylic nucleophilic substitution (SNV) via addition to electrophilic difluromethylene carbons and subsequent fluoride elimination. We have already reported syntheses of ring-fluorinated heterocycles by conducting the SNV reaction of difluoroalkenes in an intramolecular fashion. As well as sp3-heteroatom and carbon nucleophiles, sp2-nucleophiles have also participated in the 6-endo-trig cyclization to afford 6-membered heterocycles (eq 1). Furthermore, the high reactivity of 1,1-difluoro-1-alkenes has even allowed normally “disfavored” 5-endo-trig cyclization,5–9 which provides scaffolds for 2-fluoro-4,5-dihydroheteroles and 2-fluorobenzoheteroles (eq 2).10 Addressing the next challenge to the “disfavored” process, we herein demonstrate the 5-endo-trig cyclization with the metal enolates of 3,3-difluoroallylic ketones, which are sp2-atom-based ambident nucleophiles and rotationally-restricted around the anionic centers (eq 3). This process efficiently provides 2-alkylidene-2,3-dihydrofurans by (i) constructing the heterocyclic ring and (ii) introducing a fluorine substituent and an alkylidene group onto the prescribed ring carbon.

The starting 3,3-difluoroallylic ketones are readily accessible through the following chemoselective difluoromethylation protocol. 1,3-Ketoaldehydes 1, the precursors of 3,3-difluoroallylic ketones 2, were synthesized by the acylation of either morpholine enamines 3 or metal N-tert-butyl enamides prepared by deprotonation of imines 4, followed by hydrolysis (Scheme 1).12 Finally, difluoroalylketones 2 were obtained in moderate to high yield (27–86%) via difluoromethylation of ketoaldehydes 1 by a triminophosphonium difluoromethylide, generated in situ from dibromodifluoromethane and tris(dimethylamino)phosphine (Scheme 1).13 Success of the exclusively selective difluoromethylation of 1 was due to the much higher reactivity of formyl groups compared to ketone carbonyl groups.
Synthesis of 3,3-difluoroallylic ketones

First, we sought bases suitable for the enolate formation and the subsequent 5-endo-trig cyclization by using difluoroallylic ketone 2a as a model substrate (Table 1). Lithium diisopropylamide (LDA) afforded the O-cyclization product 5a as a single isomer, albeit in low yield, while the C-cyclization product 6a was not detected at all (Entry 1).14 Two-fold increase in the amount of LDA (2 equiv) turned out to be effective for the cyclization (Entry 2). Also, potassium hydride (1 equiv) exclusively gave 5a and drastically improved its yield up to 79% (Entry 3). As in the case of LDA, use of doubled amounts of potassium hydride (2 equiv) was highly effective, leading to a 91% yield of the desired dihydrofuran 5a (Entry 4). Thus, the nucleophilic 5-endo-trig cyclization successfully proceeded even with rotationally-restricted sp²-nucleophiles in 2a. This is likely due to the large polarization of the CF₂=CH moiety.10a

Table 1  Screening of Bases Suitable for 5-endo-trig Cyclization of 2a

<table>
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<th>Entry</th>
<th>Time</th>
<th>Product</th>
<th>Yield (%)</th>
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<tbody>
<tr>
<td>1</td>
<td>5 h</td>
<td>5a</td>
<td>91</td>
</tr>
<tr>
<td>2</td>
<td>4 h</td>
<td>5b</td>
<td>91</td>
</tr>
<tr>
<td>3</td>
<td>2 h</td>
<td>5c</td>
<td>91</td>
</tr>
<tr>
<td>4</td>
<td>2 h</td>
<td>5d</td>
<td>91</td>
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The optimized conditions obtained above for 2a were successfully applied to the cyclizations of a variety of difluoroallylic ketones 2 (Table 2).15,16 Ketones 2b–g, which are dimethylated at the allylic position, gave corresponding fluoride-containing dihydrofurans 5b–g in good to excellent yield. Difluoroallylic benzyl ketones 2e and 2f gave 2-benzylidene dihydrofurans 5e and 5f, respectively. Reactions of difluoroallylic ketones 2h–j, which possess a cyclohexane ring at the allylic position, constructed a spirocyclic structure in 5h–j. The reactions of α,α',α'-tetrasubstituted ketones 2g and 2j were sluggish under the same conditions. However, the longer reaction time or the use of pyridine as the solvent instead of THF improved the yields of 5g or 5j, respectively. Intriguingly, dihydrofuran derivatives 5a–f and 5i were obtained as single isomers about the exo-double bond, judging from ¹H and ¹³C NMR studies. The configurations of 5a–f and 5i were assigned as Z-isomers by a NOESY experiment of 5b.17 This Z-selectivity in the formation of dihydrofurans 5a–f and 5i is interpreted as follows: the Z-enolates seem to be generated predominantly by deprotonation of difluoroallylic ketones 2 because of steric repulsion between substituents at both of the α positions of the carbonyl groups in 2. The subsequent cyclization presumably proceeds through the Z-enolates with retention of stereochemistry.

Difluoroallylic ketones 2, as shown in Table 2, underwent 5-endo-trig O-cyclization via their enolate forms. The reaction afforded the corresponding 2-alkylidene-5-fluoro-2,3-dihydrofurans 5 without the formation of C-cyclization products, 3-fluorocyclopent-3-en-1-ones 6. Although 5-endo-trig cyclization is assigned as disfavored in Baldwin’s rules,5 the reactivity of 1,1-difluoro-1-alkenes allows the substrates to undergo such an extraordinary cyclization.
In summary, we have demonstrated that 3,3-difluoroallylic ketone enolates exclusively underwent intramolecular 3-exo-alkenylation to afford fluorinated 2,3-dihydrofurans 5 bearing a Z-exo-alkylidene unit. The cyclization proceeded in a 5-endotrig fashion, which is disfavored according to Baldwin’s rules. In this process, a fluorine substituent was introduced selectively onto the 5 position of the 2,3-dihydrofuran scaffold. Furthermore, since fluorinated 2-alkylidene-2,3-dihydrofurans are unprecedented and highly functionalized, it is expected that these compounds would serve as parts of bioactive molecules and versatile intermediates.18

Supporting Information for this article is available online at http://www.thieme-connect.com/ejournals/toc/synlett.

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(9) For recent reports on radical-initiated 5-endotrig cyclization, see: (a) Pattarozzi, M.; Ghelfi, F.; Roncaglia, F.; Pagnoni, U. M.; Parsons, A. F. Synlett 2009, 2172. (b) Yu, J.-D.; Ding, W.; Lian, G.-Y.; Song, K.-S.; Zhang, D.-W.; Gao X.; Yang, D. J. Org. Chem. 2010, 75, 3232.


(14) Baldwin noted that when endocyclic alkylation of ketone enolates constructs 5-membered rings, O-

a Pyridine was used as the solvent instead of THF.

(15) \((Z)-5\)-Fluoro-3,3-dimethyl-2-(2-phenylethylidene)-2,3-dihydropyrane (5b)

To a suspension of KH (oil free, 46 mg, 1.2 mmol) in THF (11 ml) was added 6,6-difluoro-4,4-dimethyl-1-phenylhex-5-en-3-one (2b, 138 mg, 0.58 mmol), and the mixture was heated to reflux for 2 h. After cooling to room temperature, the reaction was quenched with phosphate buffer (pH 7). Organic materials were extracted with Et₂O three times. The combined extracts were washed with brine and dried over MgSO₄. After removal of the solvent under reduced pressure, the residue was purified by thin layer chromatography on silica gel (AcOEt–hexane 1 : 5) to give 5b (122 mg, 97%) as a colorless oil. ¹H NMR (500 MHz, CDCl₃): δ 1.26 (d, JHF = 1.1 Hz, 6H), 3.45 (d, J = 7.5 Hz, 2H), 4.20 (d, JHF = 5.4 Hz, 1H), 4.73 (td, J = 7.5, JHF = 3.4 Hz, 1H), 7.18–7.22 (m, 3H), 7.27–7.30 (m, 2H). ¹³C NMR (126 MHz, CDCl₃): δ 30.1 (d, JCF = 2 Hz), 44.2 (d, JCF = 8 Hz), 79.7 (d, JCF = 8 Hz), 99.4 (d, JCF = 276 Hz), 128.0, 128.4, 141.0, 157.5 (d, JCF = 3 Hz), 160.6 (d, JCF = 3 Hz). ¹⁹F NMR (470 MHz, CDCl₃): δ 46.2 (s). IR (neat): 3028, 2970, 2931, 1801, 1726, 1703, 1454, 1279, 1219, 1126, 1088, 993, 976, 748, 698 cm⁻¹. Anal. Calcd. for C₁₄H₁₅FO: C, 77.04; H, 6.93. Found: C, 76.80; H, 7.16%.

(16) 3,3-Disubstituted 5-fluoro-2-alkylidene-2,3-dihydropyrans 5 are air- and thermally-stable.

(17) In the NOESY experiment of dihydropyrane 5b, substantial correlation between the methyl protons and the vinylic proton H² was observed. No NOE correlation was detected between the methyl protons and the allylic protons H⁶.

(18) For a review on bioactivities of fluorinated compounds, see: Müller, K.; Faeh, C.; Diederich, F. Science 2007, 317, 1881.
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