**Fluorine Chemistry**

**α-Fluorotricarbonyl Derivatives as Versatile Fluorinated Building Blocks: Synthesis of Fluoroacetophenone, Fluoroketo Ester and Fluoropyran-4-one Derivatives**

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**Abstract:** Fluorinated acyl-Meldrum’s acid derivatives were synthesized by electrophilic fluorination of appropriate phenacyl Meldrum’s acid substrates using Selectfluor. Reactions with water, ethanol, Grignard, and alkynyllithium reagents gave rise to the corresponding fluoro-acetophenone, –1,3-keto ester, –1,3-diketone and -pyran-4-one products respectively from the same selectively fluorinated scaffold in one-step procedures.

**Introduction**

The development of robust and scalable methods for the synthesis of polyfunctional aliphatic fluorinated building blocks continues to be of interest due, in part, to the increasing number of new chemical entities bearing fluorine atoms at sp³ carbon sites that are entering pharmaceutical, agrochemical and materials company product pipelines. Consequentially, methods for the fluorination at sp³ sites utilizing a variety of nucleophilic and electrophilic fluorinating agents continue to be developed to meet the needs for exploring new fluorinated chemical space. Alternatively, the construction of polyfunctional fluorinated aliphatic systems by early-stage fluorination and subsequent elaboration into more structurally complex systems offers a complementary approach. Consequently, many fluorine-containing building blocks have been assessed in a variety of reaction processes and, in particular, the chemistry of a range of fluorinated diesters, amides, ketones, and aldehydes, for example, has been established. However, the availability of a sufficiently wide range of fluorinated building blocks with established robust reactivity profiles can be a significant bottleneck in the synthesis of polyfunctional fluoroaliphatic systems. Thus, there remains a requirement for the development of synthetic routes to multi-functional fluorinated aliphatic building blocks for applications in diversity-oriented synthesis as part of drug discovery programs.

While the chemistry of synthetically versatile 2-fluoro-1,3-dicarbonyl derivatives continues to develop, reports on the preparation and synthetic utility of related α-fluorotricarbonyl compounds are very rare in the literature despite their potential utility as versatile fluorinated building blocks. Tricarbonyl systems can be accessed readily, for example, acylation of Meldrum’s acid gives corresponding α-tricarbonyl derivatives by either condensation with carboxylic acids using appropriate coupling reagents or from the corresponding mixed anhydride or acid chloride. However, despite the use of readily available acyl Meldrum’s acid derivatives in organic synthesis, there are very few reports in the literature concerning the synthesis and use of corresponding α-fluoro-derivatives. Formation of fluorotricarbonyl systems by double acylation of ethyl fluoroacetate and fluorination of tricarbonyl compounds using perchloryl fluoride have been reported previously. In addition, Kim and co-workers showed that triethyl 2-fluorophosphonoacetate can be acylated twice using an MgCl₂-Et₃N reagent system to afford 2-fluorodiketo ester derivatives.

![Scheme 1. Strategy for the synthesis and use of α-fluorotricarbonyl compounds derived from Meldrum’s acid.](image)

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In this paper, we report the synthesis of α-fluoro-acyl Meldrum’s acid derivatives using Selectfluor™ to gain access to potentially useful polyfunctional fluorinated tricarbonyl systems and, in proof-of-concept studies, show how these scaffolds may be used to provide access to fluoro-acetophenone, -keto ester and -pyran-4-one derivatives by reaction with appropriate nucleophiles following a synthetic strategy outlined in Scheme 1. Neither the synthesis nor reactivity of fluorinated acyl Meldrum’s acid derivatives have been described previously.

Results and Discussion

Syntheses of appropriate acyl Meldrum’s acid derivatives 3 were carried out by acylation of Meldrum’s acid 1 using a variety of aromatic acid chloride substrates 2 in acetonitrile in the presence of DMAP at ambient temperature by adapting a literature procedure.[10] After the reaction had reached completion, aqueous hydrochloric acid was added to dissolve the precipitated DMAP hydrochloride salt and acetonitrile was evaporated from the mixture under reduced pressure to precipitate the desired tricarbonyl product which was dried and recrystallized from acetone if required (Table 1). X-ray crystallography confirmed the structures of 3a and 3g showing that the systems exist as the enol forms in the solid state (Figure 1) with typical enol intramolecular OH···O(carbonyl) hydrogen bonds.

Table 1. Synthesis of acyl Meldrum’s acid derivatives 3.

| Acid Chloride 2 | Product 3, yield |
|-----------------|------------------|
| 2a              | 3a, 59 %         |
| 2b              | 3b, 65 %         |
| 2c              | 3c, 79 %         |
| 2d              | 3d, 59 %         |

Fluorinations of acyl Meldrum’s acid derivatives 3 were carried out using electrophilic fluorinating reagent Selectfluor™ in acetonitrile at ambient temperature over 16 h (Table 2) after which $^{19}$F NMR spectroscopic analysis of the reaction mixture confirmed full conversion to the desired product. Isolation of the desired α-fluoro-tricarbonyl products was achieved by selective dissolution of the crude residue into ethyl acetate and evaporation of the solvent after filtration from Selectfluor™ salt residues. When required, the crude product was further purified by dissolving in a small volume of dichloromethane/hexane, and, after cooling at 0–5 °C, the desired fluoro-tricarbonyl products precipitated in good yield as fine powders. Crystalline products for diffraction studies were obtained by further recrystallization from acetone.

Table 2. Fluorination of acyl Meldrum’s acid derivatives.

| Product 4, yield |
|------------------|
| 4a, 74 %         |
| 4b, 70 %         |
| 4c, 64 %         |
| 4d, 75 %         |
| 4e, 45 %         |
| 4f, 75 %         |
| 4g, 92 %         |
| 4h, 93 %         |
Under these reaction conditions, the competing electrophilic fluorination of the aromatic ring was not observed, even in the case of the electron-rich thiophene and furan derivatives and the products were found to be stable for a long time (over a month) in a refrigerator if moisture was excluded.

X-ray crystallographic analysis of fluorinated acyl Meldrum’s acid derivatives 4a,c,d (Figure 2) showed that the cyclohexane ring of these compounds adopts a distorted boat conformation where the torsion angle between the fluorine atom and the C=O oxygen atoms of the ring is approximately 30°. This conformation is further stabilized by short intramolecular CH···O (carbonyl) contacts (2.4–2.47Å) which can be regarded as weak hydrogen bonds. The difference between the two methyl groups can also be observed in the solution phase by 1H and 13C NMR spectroscopy where separate chemical shifts corresponding to the axial and equatorial environments are observed (for example, 3a: 1.92 ppm and 1.86 ppm).

Figure 2. Distorted boat conformation of fluorinated Meldrum’s acid derivatives 4a,c,d.

With a range of α-fluorotricarbonyl derivatives 4 in hand we began to explore reactions between these systems and some representative nucleophiles. Initially, a range of acid-catalyzed hydrolysis conditions was screened on 1 mmol scale to develop the hydrolysis reaction of 4a to form the corresponding fluoroacetophenone derivative 5a (see Supporting Information, Table SI1). The screening experiments (Table SI1) revealed that p-toluenesulfonic acid monohydrate was the most suitable reagent combination. Additional water improved the selectivity and conversion of the reaction, but more than 0.1 mL of water per mmol of starting material did not have any further benefit. After purification by column chromatography, 2-fluoroacetophenone 5a was isolated in 56 % yield. Attack by water at the more electrophilic ester functionality of the α-fluorotricarbonyl substrates leads to decarboxylation to the fluoroacetophenone system. Of course, fluoroacetophenones may be synthesised by a variety of methods including fluorination of appropriate enolate systems by Selectfluor[11] but, here, the concept of selective reactions of nucleophiles with α-fluorotricarbonyl derivatives was established.

Subsequently, the most effective hydrolysis reaction conditions were applied to a range of aromatic and heteroaromatic fluorinated Meldrum’s acid derivatives 4 to give fluoroacetophenone derivatives 5 in good yield after flash column chromatography (Table 3). The higher yield obtained in the synthesis of 5d suggests that an ortho substituent capable of further activating the system towards nucleophilic attack can improve the selectivity of the decarboxylation. The molecular structures of 5a and 5d were confirmed by X-ray crystallography (Figure 3). The presence of an ortho-nitro substituent results in almost perpendicular orientation of the carbonyl group relative to the aromatic ring in 5d.

Table 3. Synthesis of α-fluoroacetophenone derivatives 5.
tricarbonyl derivatives with ethoxide were carried out to access the corresponding α-fluoro-keto esters. Treating compound 4\textsubscript{a,g,h} in ethanol in basic conditions (Et\textsubscript{2}N) at 0 °C for 6 h afforded the desired products 6\textsubscript{a,g,h} in excellent yield without any further purification required (Table 4).

Table 4. Synthesis of α-fluoro-β-keto ester derivatives 6.

| 4 | 6a,6g,6h |
|---|---|
| 4a,4g,4h | 6a,6g,6h |

Thus, reactions of α-fluoro-tricarbonyl derivatives can lead to highly useful fluoroketo ester building blocks upon reaction with ethanol in basic conditions, providing alternative synthetic routes to fluorination of keto esters by fluorine gas\textsuperscript{[12]} and Selectfluor\textsuperscript{[13]} Fluorination of β-keto esters by fluorine gas is effective\textsuperscript{[12]} but can lead to difluorination at the enolic site and selective fluorination, particularly on electron-rich aromatic substituents such as the furan and thiophene moieties, in 6\textsubscript{g,h}. We next studied reactions of appropriate carbon-centered nucleophiles. Phenylmagnesium bromide 7 was formed in dry THF at r.t. from bromobenzene and magnesium turnings and added to 4a and the reaction mixture that was heated at reflux for 1 h. Numerous unidentified side products were formed during this reaction as observed by \textsuperscript{19}F NMR of the product mixture but purification via column chromatography and recrystallization gave the desired 2-fluoro-1,3-diphenylpropane-1,3-dione 8 albeit in low yield (Scheme 2).

Scheme 2. Reaction of 4a with Grignard reagent 7.

Analogous reactions of carbanions derived from terminal alkynes were next studied. Deprotonation of 1-hexyne 9a using nBuLi at –78 °C in THF under an argon atmosphere followed by addition of 4a and stirring of the reaction mixture overnight at room temperature gave a crude product which was purified by column chromatography and recrystallization to give the unexpected 3-fluoro-4H-pyran-4-one derivative 10a in moderate yield (22 %) from a mixture of unidentified products (Table 5). Analogous syntheses of pyran-4-one derivatives 10b-d were performed using ethynylbenzene 9b, ethynylcyclopropane 9c and ethynylcyclohexane 9d substrates to give the fluoropyran-
4-one products 10b–d respectively. The structures of pyranone products 10a–d were confirmed by X-ray crystallography (Figure 4).

Carbanions formed by deprotonation of the alkynes attack an ester group of the Meldrum’s acid moiety and, after elimination of acetone and decarboxylation, an enolate intermediate is formed. Intramolecular Michael-type addition forms the observed six-membered ring products (Scheme 3).

While well-known 4H-pyran-2-one sub-units are found in various natural products[14] and generally synthesized by γ-acylation of 1,3-diketones with carboxylic ester substrates,[15] corresponding 2-fluoro-4H-pyran-2-ones have not been reported in the literature, despite their relatively simple structures.

Conclusions

In this paper, the synthesis and reactivity of fluorinated acyl Meldrum’s acid derivatives with representative oxygen and carbon-centered nucleophiles were described. Meldrum’s acid was acylated and subsequent fluorination carried out using Selectfluor™ to provide access to the desired fluoro-tricarbonyl compounds in good yield. Reactions of the fluoro-tricarbonyl scaffolds with oxygen and carbon-centered nucleophiles led to appropriate fluoro-acetophenone, -keto ester, -diketone, and -pyran-4-one derivatives by simple processes. These proof-of-concept studies demonstrate that α-fluorotricarbonyl derivatives can be common substrates that allow access to a wide range of fluorinated aliphatic and heterocyclic building blocks.

Experimental Section

5-Benzoyl-2,2-dimethyl-1,3-dioxane-4,6-dione (3a): Meldrum’s acid 1 (14.4 g, 100 mmol) and DMAP (24.4 g, 200 mmol) were dissolved in acetonitrile (250 mL) and cooled in ice-water. Benzoyl chloride 2a (14.1 g, 100 mmol) was dissolved in acetonitrile (50 mL) and added dropwise over 40 min. The mixture was stirred for 16 h, then 1 M HCl (200 mL) was added, the mixture stirred for 5 min (clear solution) and was concentrated to approximately 150 mL under vacuum. The precipitated product was filtered, washed with water (15 mL) and dried (MgSO4) to give 5-benzoyl-2,2-dimethyl-1,3-dioxane-4,6-dione 3a (22.5 g, 90 %) as a yellow solid. Mp. 95–97 °C (with decomposition) (lit.[16] 103–104 °C, from acetone). IR (cm−1): ν ≈ 3066, 2998, 1736, 1652. 1H NMR (400 MHz, CDCl3) δ = 1.84 (s, 6H, CH3), 7.47 (t, JH-H 7.9, 2H, C3-H), 7.60 (tm, JH-H 7.5, 1H, C4-H), 7.66–7.69 (m, 2H, C2-H), 15.47 (bs, 1H, OH). 13C NMR (100 MHz, CDCl3) δ = 26.91 (CH3), 91.06 (C(CH3)2), 106.11 (C=COH), 128.17 (C3-H), 129.58 (C2-H), 132.82 (C1-C), 133.44 (C4-H), 159.90 (C=COH), 171.09 (C=O), 189.37 (C=O). m/z (ESI): 247 [M – H]+, 207 (100 %, [M – C3H7]+). HRMS (ESI) m/z calculated for [M]+: C13H11O5 requires: [M]+, 247.0605, found 247.0605.
5-Benzoyl-5-fluoro-2,2-dimethyl-1,3-dioxane-4,6-dione (4a): 5-Benzoyl-2,2-dimethyl-1,3-dioxane-4,6-dione 3a (2.48 g, 10.0 mmol) was dissolved in acetonitrile (50 mL) and Selectfluor (5.50 g, 15.5 mmol) was added to the mixture which was stirred at rt. for 16 h. The reaction mixture was evaporated to dryness under vacuum, the solids suspended in ethyl acetate (50 mL), filtered and washed with ethyl acetate (30 mL). The ethyl acetate solution was evaporated under reduced pressure, the residue dissolved in dichloromethane (20 mL), hexane (60 mL) was added and the solution was concentrated at atmospheric pressure until solids started to appear (approximately 30 mL). After cooling at 4 °C overnight the product was filtered and dried under vacuum to give 5-benzoyl-2,2-dimethyl-1,3-dioxane-4,6-dione 4a (1.07 g, 4.0 mmol) and p-toluene sulfonic acid monohydrate (0.76 g, 4.0 mmol) were dissolved in acetone (30 mL). The organic layer was washed with saturated NaHCO3 solution (2 × 20 mL), and brine (40 mL). After drying (Na2SO4), the solvent was removed under reduced pressure, the residue dissolved in DCM and reduced pressure and the product was purified by silica gel column chromatography (hexanes/EtOAc, 5:1) to afford 2-fluoroacetoephone 5a (0.31 g, 56 % yield) as a yellow oil. Rf 0.27 (hexanes/EtOAc, 5:1). IR (cm–1): ν = 3066, 2938, 1703, 1598. 1H NMR (400 MHz, CDCl3) δ = 5.53 (d, JCF 6.9 Hz, 2H, C2-F), 7.45–7.54 (m, 2H, C3-H, C4-H), 7.58–7.66 (m, 1H, C1-H), 8.73–7.92 (m, 2H, C2, C3-H). 2H (12, d, 3JCF 47.0 Hz, C). 13C NMR (101 MHz, CDCl3) δ = 83.64 (d, JCF 182.6 Hz, C15-H), 127.94 (d, JCF 2.6 Hz, C2-H), 129.03 (C3-H), 133.80 (C1-C), 134.24 (C4-H), 193.52 (d, JCF 14.4 Hz, C5-O). m/z (APSA): 139 (49 %, [M + H]+). HRMS (ESI) m/z calculated for [M + H]+: C15H12FO2. 2-Fluoroacetoephone 5a (0.31 g, 56 % yield) was used in the synthesis of 5-benzoyl-2,2-dimethyl-1,3-dioxane-4,6-dione 4a (1.07 g, 4.0 mmol) and p-toluene sulfonic acid monohydrate (0.76 g, 4.0 mmol) were dissolved in acetone (30 mL). The organic layer was washed with saturated NaHCO3 solution (2 × 20 mL), and brine (40 mL). After drying (Na2SO4), the solution was concentrated at reduced pressure and the product was purified by silica gel column chromatography (hexanes/EtOAc, 5:1) to afford 2-fluoroacetoephone 5a (0.31 g, 56 % yield) as a yellow oil. Rf 0.27 (hexanes/EtOAc, 5:1). IR (cm–1): ν = 3066, 2938, 1703, 1598. 1H NMR (400 MHz, CDCl3) δ = 5.53 (d, JCF 6.9 Hz, 2H, C2-F), 7.45–7.54 (m, 2H, C3-H, C4-H), 7.58–7.66 (m, 1H, C1-H), 8.73–7.92 (m, 2H, C2, C3-H). 2H (12, d, 3JCF 47.0 Hz, C). 13C NMR (101 MHz, CDCl3) δ = 83.64 (d, JCF 182.6 Hz, C15-H), 127.94 (d, JCF 2.6 Hz, C2-H), 129.03 (C3-H), 133.80 (C1-C), 134.24 (C4-H), 193.52 (d, JCF 14.4 Hz, C5-O). m/z (APSA): 139 (49 %, [M + H]+). HRMS (ESI) m/z calculated for [M + H]+: C15H12FO2.

Ethyl 2-Fluoro-3-oxo-3-phenylpropanoate (6a): 5-Benzoyl-5-fluoro-2,2-dimethyl-1,3-dioxane-4,6-dione 4a (1.00 g, 3.76 mmol) was dissolved in EtOH (10 mL) and the solution was cooled to 0 °C. Diethylamine (0.4 mL, 3.76 mmol) was added and the reaction was stirred at 0 °C for 15 min. After the mixture was cooled to −78 °C under an argon atmosphere, nBuLi (0.54 mL, 2.5 M in hexanes, 13.5 mmol) was added dropwise and the resulting solution stirred at −78 °C for 1 h. A solution of 5-benzoyl-5-fluoro-2,2-dimethyl-1,3-dioxane-4,6-dione 4a (300 mg, 1.13 mmol) in dry THF (2.5 mL) was added dropwise at 0 °C and the solution was slowly warmed to rt. while stirring overnight. After quenching with sat. aq. NH4Cl (3 mL) the solution was filtered and washed with water (5 mL) and the aqueous layer extracted with EtO. The combined organic layers were washed with brine (5 mL) and the aqueous layer extracted with EtO. The combined organic layers were washed with brine before being dried with MgSO4 and concentrated. The crude product was purified by column chromatography on silica gel (7:3 hexanes/EtOAc; Rf 0.2) and recrystallised from DCM and 3-hexane, to give 6-buty 2-fluoro-2-phenyl-4H-pyran-4-one 10a (62 mg, 22 %) as a white solid. M. p. 39–40 °C. IR (cm–1): ν = 3261, 2954, 2932, 1635. 1H NMR (700 MHz, CDCl3) δ = 7.88–7.82 (m, 2H, C11,15-H), 7.55–7.47 (m, 3H, C12,13,14-H), 6.31 (dd, JCF 6.6, 1.3 Hz, 1H, C14-H), 2.63 (t, 1H, C1-H, 2H, C6-H), 1.71 (p, 1H, C7-H, 2H, C7-H), 1.56–1.29 (m, 2H, C8-H). 1H NMR (700 MHz, CDCl3) δ = 1.56–1.29 (m, 2H, C8-H). 1H NMR (700 MHz, CDCl3) δ = 158.88 (d, JCF 6.6 Hz). 13C NMR (176 MHz, CDCl3) δ = 172.40 (d, JCF 16.4 Hz, C3-C), 168.73 (C5-C), 150.79 (d, JCF 24.2 Hz, C1-C), 149.28 (d, JCF 253.8 Hz, C2-CF3), 131.29 (d, JCF 1.4 Hz, C12-C, C14-C), 129.03 (C3-C), 128.65 (d, JCF 5.2 Hz, C10-C), 127.60 (d, JCF 7.6 Hz, C11-C), 104.21 (d, JCF 6.9 Hz, C4-C), 32.42(C6-C), 29.15(C7-C), 22.17(C8-C), 18.33(C9-C). HRMS (APSA) m/z calculated for [M + H]+: C15H14FO2. 247.1129, found 247.1123.

Deposition Numbers 1953837–1953848 contain the supplementary crystallographic data for this paper. These data are provided free of charge by the joint Cambridge Crystallographic Data Centre and Fachinformationszentrum Karlsruhe Access Structures service www.ccdc.cam.ac.uk/structures.

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