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Fluorochromate-catalyzed periodic acid oxidation of alcohols and aldehydes

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Abstract

Preparation of aldehydes and ketones from alcohols, and carboxylic acids from alcohols and aldehydes using pyridinium fluorochromate (PFC) as a catalyst and H_5IO_6 as the terminal oxidant is described here.

Keywords: Oxidation; Alcohols; Catalysis; Pyridinium fluorochromate (PFC); Carboxylic acids; Periodic acid; Aldehydes; Ketones

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1. Introduction

Oxidation, one the most fundamental reactions in synthetic organic chemistry, has been the subject of numerous studies [1,2]. Fluorochromates [3] and chlorochromates [4] are two of the most favored reagents for oxidation of organic substrates, particularly alcohols, under mild conditions. Unlike CrO_3, halochromates have a long shelf life and better solubility in organic solvents. However, the carcinogenicity of chromium in combination with the requirement of more than a stoichiometric amount of the above reagents to complete the reaction is a significant problem especially for large-scale industrial applications. In light of this, there is a need for environmentally friendlier oxidation reactions that retain the power of chromium oxidations. In addition to fluorochromates and chlorochromates, the Swern and co-workers [5] and Dess and Martin [6] oxidations are commonly used for preparation of aldehydes and ketones. Current methods for direct conversion of primary alcohols to carboxylic acids include $RuCl_3$/$NaIO_4$ [7], CrO_3/H_2SO_4 [8], TEMPO/NaClO [9], Na_2WO_4/H_2O_2 [10], and TEMPO/$NaClO_2$ in solution [11] and solid [12] phase.

Recently, several groups have reported chromium-catalyzed oxidations. Preparation of aldehydes and ketones in a chromium(III)-catalyzed periodic acid oxidation is reported [13a]. Oxidation of (homo-) allylic and (homo-) propargylic alcohols to ketones and carboxylic acids is achieved using $Na_2Cr_2O_7/NaIO_4$ [13b]. A CrO_3-catalyzed [14] periodic acid oxidation of primary alcohols to carboxylic acids that works very well for electron poor benzylic alcohols is also reported. However, the CrO_3-catalyzed oxidation gives complex mixtures when it comes to electron rich benzylic and homobenzylic alcohols. It also gives lower yields for benzylic alcohols and fails for allylic and propargylic alcohols. Our group have recently shown that pyridinium chlorochromate (PCC) can be used catalytically to oxidize alcohols to aldehydes and ketones using the recyclable periodic acid as the co-oxidant [15a]. We have also shown that carboxylic acids can be prepared in a PCC-catalyzed oxidation [15b].

Various fluorochromates [3] have been shown to be mild yet powerful oxidants. In an effort to show that fluorochromates can be used catalytically instead of stoichiometrically for mild oxidations and to further study the generality of halochromate-catalyzed oxidations using Periodic acid as the terminal oxidant, we have investigated pyridinium fluorochromate (PFC) catalyzed oxidations. We report herein a PFC-catalyzed oxidation of alcohols to aldehydes

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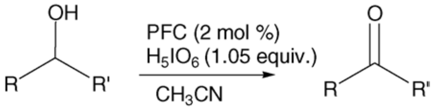
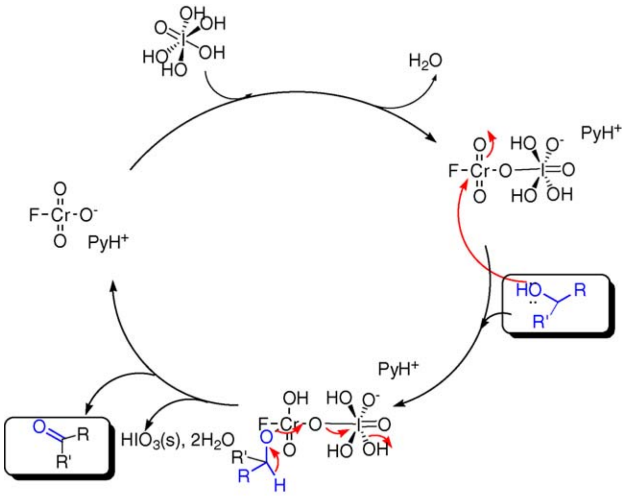


Scheme 1.

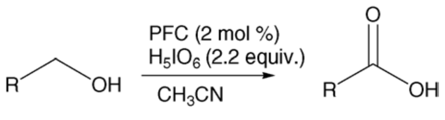


Scheme 2.

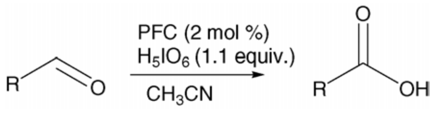
and ketones, and alcohols and aldehydes to carboxylic acids using only 2 mol% of pyridinium fluorochromate and stoichiometric amounts of the co-oxidant, H_5IO_6, in acetonitrile (Schemes 1–4).

2. Results and discussion

First, we investigated the preparation of aldehydes and ketones. Various alcohols were oxidized with PFC/H_5IO_6 to give the corresponding aldehydes and ketones mostly in quantitative yields and the results are shown in Table 1. Benzylic 2° alcohols (entries 3 and 4) were oxidized smoothly to give the ketones in a short amount of time. The aliphatic (entry 2) and homobenzylic (entry 1) 2° alcohols were also oxidized cleanly to the corresponding ketones with out any problems. Benzyl alcohols (entries 6–8) were oxidized effortlessly to give the corresponding aldehydes in moderate to excellent yields. An attempt to oxidize cinnamyl alcohol resulted in the formation of a mixture of products (data not shown). Oxidation of 1-naphthalenemethanol (entry 5) gave the aldehyde with out oxidation of the naphthalene ring unlike the CrO_3/H_5IO_6 oxidation [16].



Scheme 3.



Scheme 4.

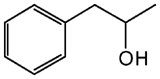
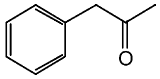
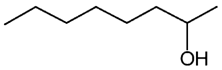
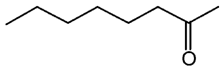
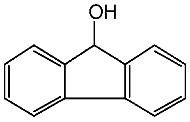
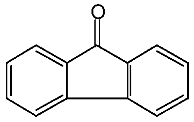
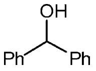
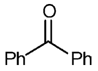
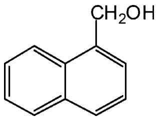
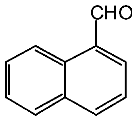
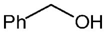
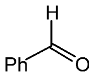
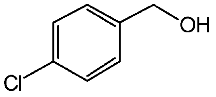
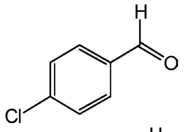
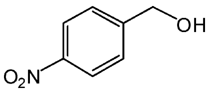
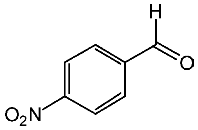
We hypothesize that the PFC/periodic acid combination may form fluorochromatoperiodate (FCP), [17] possibly a more powerful oxidizing agent than the fluorochromate (Scheme 2) that can accomplish oxidations not possible by PFC alone. We further hypothesize that the covalently attached fluoride ion may be facilitating the regeneration of the catalyst. No addition of water was required in contrast to the CrO_3/H_5IO_6 [14] oxidation.

Next, we investigated the preparation of carboxylic acids directly from primary alcohols using PFC/H_5IO_6. We used only a catalytic (2 mol%) amount of pyridinium fluorochromate and 2.2 equivalent of the co-oxidant, H_5IO_6, for a clean and quantitative conversion of primary alcohols to carboxylic acids (Scheme 3). As shown in Table 2, various primary alcohols were directly oxidized with PFC/H_5IO_6 to give the corresponding carboxylic acids in quantitative yields. Benzylic (entries 1, 4–6), aliphatic (entries 2, 9 and 10) as well as homobenzylic (entries 3 and 7) alcohols were oxidized smoothly in a short amount of time. Both electron poor (entries 5 and 6) as well as electron rich (entry 1) benzyl alcohols were also quantitatively oxidized with out any problem. The electron rich homobenzylic alcohol (entry 7) was also oxidized effortlessly. It is worth mentioning that unlike the CrO_3 catalyzed [14] oxidation, the PFC-catalyzed oxidation works very well for benzylic alcohols as well as for electron rich benzylic and homobenzylic alcohols. The naphthalene ring (entry 8) did not get oxidized under the above mentioned reaction conditions. It is noteworthy that in a control experiment where the reaction was repeated under the same conditions but in the absence of PFC, no oxidation of benzyl alcohol to benzaldehyde or benzoic acid was observed. We hypothesize that the mechanism may involve oxidation of the hydrates of the aldehydes that would form under the reaction condition (with the H_2O byproduct) to generate the carboxylic acids.

Lastly, we investigated the oxidation of aldehydes to carboxylic acids (Scheme 4). Aldehydes were oxidized in a shorter amount of time and the clean carboxylic acids were obtained quantitatively. The procedure for the oxidation of aldehydes to carboxylic acids was the same as the one for the direct conversion of primary alcohols to carboxylic acids except for the use of 1.1 equivalent of periodic acid and the shorter reaction time (90 min). As shown in Table 3, aliphatic aldehydes (entries 1 and 2) were oxidized cleanly. Benzaldehyde (entry 3) as well as electron rich (entries 4 and 7), and electron poor (entries 5, 6, 8, and 9) benzaldehydes were also oxidized effortlessly to deliver the corresponding carboxylic acids quantitatively.

In conclusion, we have shown for the first time that fluorochromates efficiently catalyze the oxidation of alcohols to aldehydes and ketones, and alcohols and

Table 1
Oxidation of alcohols to aldehydes and ketones with PFC/H_5IO_6[a]

Entry	Substrate	Product	Yield (%)[b]
1			99
2			95
3			96
4			97
5			98
6			67
7			90
8			53

[a] The reactions were conducted in acetonitrile using 1.05 equivalent of H_5IO_6 and 2 mol% PFC at 0 °C for 2 h. The products were characterized by comparing their NMR spectra with those reported by Aldrich and with authentic samples.

[b] Isolated yield.

aldehydes to directly to carboxylic acids using periodic acid as the terminal oxidant in moderate to excellent yields in a short amount of time. The protocols described in this work represent greener alternatives to the stoichiometric fluorochromate oxidations.

3. Experimental

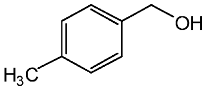
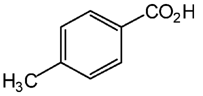
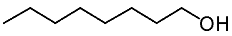
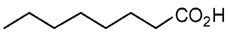
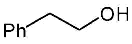
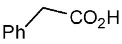
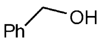
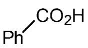
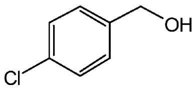
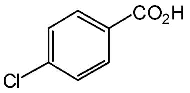
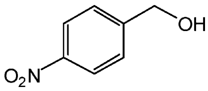
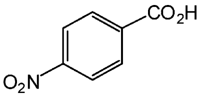
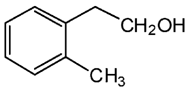
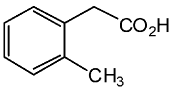
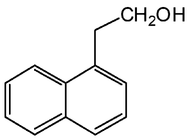
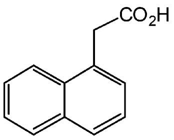
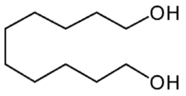
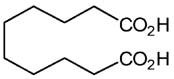
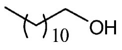
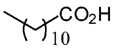
3.1. Representative procedure for preparation of aldehydes and ketones: synthesis of phenylacetone (Table 1, entry 1)

To 40 mL of acetonitrile was added 1.20 g (5.2 mmol) of H_5IO_6 and stirred vigorously at r.t. for 15 min. 3-Phenyl-2-propanol (0.69 g, 5 mmol) was then added (in ice-bath) followed by addition of 22 mg (2.0 mol%) PFC in 10 mL acetonitrile (in two portions) and the reaction mixture was stirred for 2 h. The reaction mixture was then diluted with 100 mL ethyl acetate and washed with 1:1 brine:water, saturated aq. Na_2SO_3 solution, and brine, respectively, dried over anhydrous Na_2SO_4 and concentrated to give the ketone. The crude product was purified by silica gel flash chromatography (hexanes:ethyl acetate, 8:1) to yield 0.67 g (99%) of phenyl acetone.

3.2. Representative procedure for preparation of carboxylic acids: synthesis of *p*-methyl benzoic acid (Table 2, entry 1)

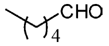
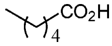
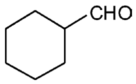
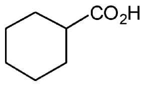
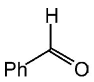
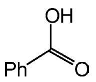
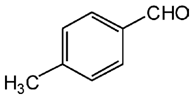
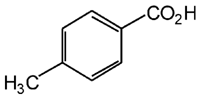
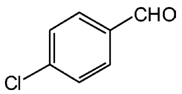
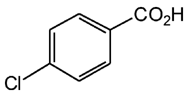
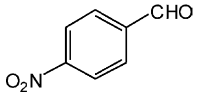
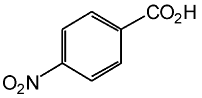
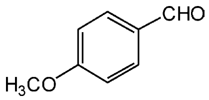
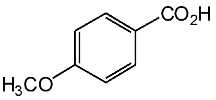
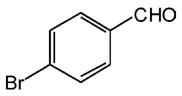
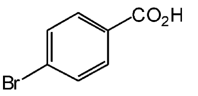
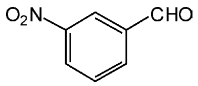
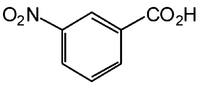
To 40 mL of acetonitrile was added 2.50 g (11 mmol) of H_5IO_6 and stirred vigorously at r.t. for 15 min. *p*-Methyl benzyl alcohol (0.61 g, 5 mmol) was then added (in ice-bath) followed by addition of 22 mg (2 mol%) PFC in 10 mL acetonitrile (in two portions) and the reaction mixture was stirred for 3 h. The reaction mixture was then diluted with 100 mL ethyl acetate and washed with 1:1 brine:water, saturated aq. $NaHSO_3$ solution, and brine, respectively, dried

Table 2
Direct oxidation of 1° alcohols to carboxylic acids with PFC/H_5IO_6[a]

Entry	Substrate	Product	Yield (%)
1			98
2			99
3			98
4			95
5			99
6			98
7			98
8			99
9			96
10			99

[a] The reactions were conducted in acetonitrile using 2.2 equivalent of H_5IO_6 and 2 mol% PFC at 0 °C. The products were characterized by comparing their NMR spectra with those reported by Aldrich and with authentic samples.

Table 3
Oxidation of aldehydes to carboxylic acids with PFC/H_5IO_6[a]

Entry	Substrate	Product	Yield (%)
1			96
2			95
3			98
4			100
5			92
6			98
7			99
8			92
9			98

[a] The reactions were conducted in acetonitrile using 1.1 equivalent of H_5IO_6 and 2 mol% PFC for 1.5 h at 0 °C. The products were characterized by comparing their NMR spectra with those reported by Aldrich and with authentic samples.

over anhydrous Na_2SO_4 and concentrated to give the carboxylic acid (0.65 g, 96% yield).

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