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Hydrogen peroxide oxidation of aldehydes to carboxylic acids: an organic solvent-, halide- and metal-free procedure

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Abstract

Aqueous hydrogen peroxide oxidizes aldehydes to carboxylic acids under aqueous/organic biphasic conditions without affecting olefinic or alcoholic functions © 2000 Elsevier Science Ltd. All rights reserved.

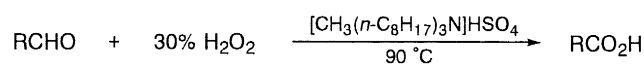
Keywords: aldehydes; Baeyer–Villiger reaction; carboxylic acids; hydrogen peroxide; oxidation; quaternary ammonium salts.

Despite the growing awareness of the need for ‘green chemistry’, many chemists still use environmentally unacceptable reagents or unnecessarily sophisticated conditions for the oxidation of aldehydes.^{1–3} Certain aldehydes can be oxidized to carboxylic acids with 3–60% aqueous H₂O₂ *without organic solvents or metallic catalysts*. Here we propose a very simple procedure which is suitable for medium and large scale reactions.

Ignoring the ability of aqueous H₂O₂ to oxidize aldehydes, tremendous efforts have been made to develop metal-based catalysts⁴ and inorganic⁵ or organic promoters⁶ for the oxidation of aldehydes. In 1941, Späth found that H₂O₂ reacts with dodecanal to form a perhydrate, which decomposes slowly at 120°C to give dodecanoic acid.⁷ Since then aqueous H₂O₂ has been considered to have a weak ability to oxidize aldehydes. Some benzaldehyde derivatives can be converted to methyl benzoates with 31% H₂O₂ in methanol containing 38 mol% H₂SO₄,⁸ and a patent claimed that 35% H₂O₂ in dioxane containing HBr oxidizes aldehydes to carboxylic acids.⁹ However, the general capability of H₂O₂ to oxidize aldehydes to carboxylic acids has not yet been reported explicitly in academic literature. During our recent study of the alcohol dehydrogenation reaction,¹⁰ we found that the oxidation of some aliphatic and aromatic aldehydes with H₂O₂ proceeds under aqueous/organic biphasic conditions without organic solvents, halides, or metal catalysts (Scheme 1). The reaction is catalyzed simply by an acid. Thus, when a mixture of octanal, 30% H₂O₂, and [CH₃(*n*-C₈H₁₇)₃N]HSO₄ (QHSO₄) in a 200:220:1 molar ratio was heated at 90°C for 2 h with magnetic stirring at 1000 rpm, octanoic acid was obtained with a yield of 82%. Without stirring under otherwise identical conditions, the yield was lowered to 73%. The reaction at 70°C gave the carboxylic acid with a yield of only 4%. When a biphasic mixture of octanal and 30% H₂O₂ was stirred at 1000 rpm at 90°C without the acidic quaternary ammonium salt, octanoic acid was produced in a yield

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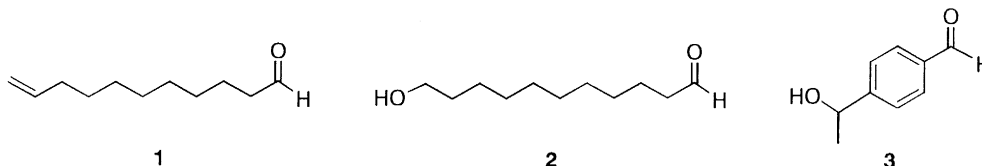
of only 30%.¹¹ Decreased lipophilicity of the catalysts tends to lower the reaction rate. The reaction of octanal and 30% H₂O₂ at 90°C for 2 h in the presence of other acids (aldehyde:H₂O₂:acid=200:220:1) gave yields of 47% with [(*n*-C₄H₉)₄N]HSO₄, 36% with H₂SO₄, 55% with HBr, 39% with HCl, 41% with *n*-C₁₂H₂₅SO₃H, and 34% with Nafion-H. Thus, the use of a lipophilic, acidic Q salt as catalyst¹² is the key to efficient biphasic oxidation. As oxidant, 3% H₂O₂ can also be used. Reaction with 60% H₂O₂ at 90°C takes place faster, but such conditions are not recommended because of the production of some peroxy acids.



Scheme 1.

Examples of the simple oxidation are given in Table 1. Although the reaction was performed normally in a 5–75 mmol range with substrate/catalyst ratios of 100 to 1000, no technical problems in scaling-up are foreseen. The reaction of 100 g of octanal (aldehyde:H₂O₂:QHSO₄=200:300:1, 90°C, 2 h, 1000 rpm) gave octanoic acid in a yield of 81% after distillation (85% by ¹H NMR).¹³ α -Branched aldehydes were converted to acids with lower yields. Benzaldehyde derivatives with an electron-withdrawing group produced the benzoic acids in reasonable yields. The reaction of melted *p*-nitrobenzaldehyde (m.p. 105°C) under the standard conditions gave *p*-nitrobenzoic acid with a yield of 93%. If necessary, toluene can be employed as a solvent. Unfortunately, *p*-methoxybenzaldehyde afforded the carboxylic acid with a yield of only 9%.

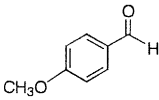
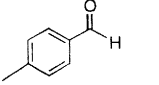
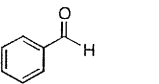
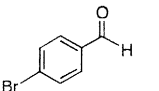
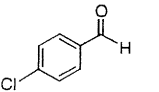
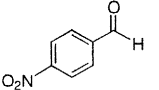
Because of the absence of metallic catalysts, olefinic and alcoholic (primary and secondary) functions survive the oxidation conditions (Table 1). 10-Undecenal (**1**) was converted to 10-undecenoic acid with a yield of 85% with 30% H₂O₂ and QHSO₄ (substrate:H₂O₂:Q salt=200:220:1, 90°C, 2 h, 1000 rpm).¹⁴ Under the same conditions, 11-hydroxyundecanal (**2**) selectively gave 11-hydroxyundecanoic acid with a yield of 75%. Even *p*-(1-hydroxyethyl)benzaldehyde (**3**) which has a highly reactive alcoholic moiety was oxidized solely at the aldehyde group to give the hydroxy carboxylic acid with a yield of 79%.



We consider that the oxidations proceed via perhydrate intermediates. The acidic Q salt facilitates the addition of H₂O₂ to aldehydes in the organic layer and, more importantly, the elimination of water from the tetrahedral intermediate via a Baeyer–Villiger type fragmentation. This view is consistent with the structure-dependent efficiency of the reaction. Straight-chain aliphatic aldehydes are cleanly converted to carboxylic acids, because the perhydrates eliminate water by selective hydride migration. Whereas, secondary and tertiary *R* groups tend to migrate competitively with hydride, resulting in the formation of formate products (Scheme 2). In fact, oxidation of 2-ethylhexanal with 30% H₂O₂ and QHSO₄ under the standard conditions gave 3-heptanol and 3-heptanone with a total yield of 11% together with the desired 2-ethylhexanoic acid with a yield of 65%. The efficiency observed with *para*-substituted benzaldehydes also agrees with this mechanism.

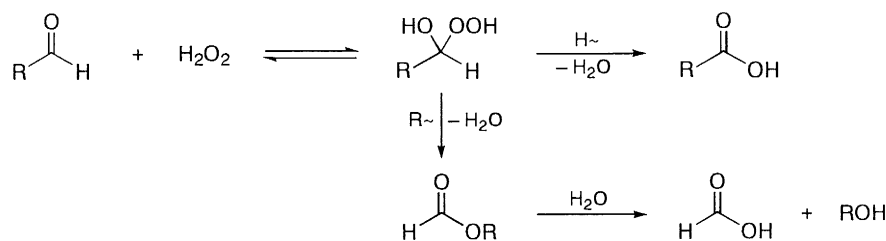
Aqueous H₂O₂ is a cheap, safe oxidant which produces only water as a coproduct. Although its ability to oxidize aldehydes has been ignored, it is very useful for this purpose. Changing current practices to a process using this environmentally friendly oxidant is highly desirable.

Table 1
Hydrogen peroxide oxidation of aldehydes to carboxylic acids^a

aldehyde		H ₂ O ₂	[CH ₃ (<i>n</i> -C ₈ H ₁₇) ₃ N]HSO ₄	time	% yield of
structure	mmol	mmol (equiv)	mmol (S/C) ^b	h	carboxylic acid ^c
C ₆ H ₅ (CH ₂) ₂ CHO	745	820 (1.1)	3.7 (200)	2	73 ^d
	74.5	82 (1.1)	0.37 (200)	2	78 ^d
	74.5	82 (1.1)	0.075 (1000)	4	77 ^d
<i>n</i> -C ₇ H ₁₅ CHO	780	1170 (1.5)	3.9 (200)	2	81, ^d 85 ^e
	10	11 (1.1)	0.05 (200)	2	82 ^e
	10	11 (1.1) ^f	0.05 (200)	1	73 ^{e,g}
<i>n</i> -C ₄ H ₉ CH(C ₂ H ₅)CHO	10	11 (1.1)	0.05 (200)	2	65
(CH ₃) ₃ CCHO	10	11 (1.1)	0.05 (200)	2	40 ^e
C ₆ H ₅ CH(CH ₃)CHO	10	11 (1.1)	0.05 (200)	2	17
	5	12.5 (2.5)	0.05 (100)	3	9
	5	12.5 (2.5)	0.05 (100)	3	41
	5	12.5 (2.5)	0.05 (100)	3	85
	5	12.5 (2.5)	0.05 (100)	3	78
	5	12.5 (2.5)	0.05 (100)	3	76
	5	12.5 (2.5)	0.05 (100)	3	93 ^h
	5	12.5 (2.5)	0.05 (100)	3	88 ^{i,j}
CH ₂ =CH(CH ₂) ₈ CHO (1)	10	11 (1.1)	0.05 (200)	2	85 ^e
HO(CH ₂) ₁₀ CHO (2)	5	5.5 (1.1)	0.025 (200)	2	75 ^e
<i>p</i> -[CH ₃ CH(OH)]C ₆ H ₄ CHO (3)	5	12.5 (2.5)	0.05 (100)	3	79 ^k

^a Unless otherwise stated, reactions were run using 30% H₂O₂ at 90 °C. ^b Substrate/catalyst molar ratio.

^c Determined by GC analysis. Carboxylic acids were analyzed after conversion to their methyl esters with trimethylsilyldiazomethane. Conversion of aldehydes was >90%. ^d Isolated by distillation. ^e Determined by ¹H NMR. ^f Reaction with 60% H₂O₂. ^g Contaminated with 6% of the peroxy acid. ^h Determined by HPLC analysis. ⁱ Toluene (2 mL) was used as solvent. ^j Isolated by recrystallization from ethanol. ^k Isolated by silica-gel column chromatography.



Scheme 2.

Acknowledgements

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- Venturello reported that heating a mixture of octanal and 40% H₂O₂ (1:1.2 mol ratio) at 90°C for 1 h gave octanoic acid with a yield of 34%, while the presence of 0.5% [CH₃(n-C₈H₁₇)₃N]₃PO₄[W(O)(O₂)₂]₄ increased the yield to 87%.^{4a}
- When a mixture of [CH₃(n-C₈H₁₇)₃N]HSO₄ (0.3 mmol), toluene (10 mL), and water (10 mL) in a 20 mm diameter test tube was mechanically stirred at 1000 rpm for 2 h at room temperature and then allowed to stand for 1 h, the acid was partitioned in toluene and water in a ratio of about 7:3. No concentration gradient was seen in both organic and aqueous phases. ¹H NMR analysis showed that 1 mL of D₂O dissolves 0.068 mmol of [CH₃(n-C₈H₁₇)₃N]HSO₄ at 25°C.
- Typical procedure: A 500 mL, round-bottomed flask equipped with a magnetic stirring bar and a reflux condenser was charged with 1.82 g (3.90 mmol) of [CH₃(n-C₈H₁₇)₃N]HSO₄ and 133 g (1.17 mol) of aqueous 30% H₂O₂. The mixture was vigorously stirred at room temperature for 10 min, and then 100 g (780 mmol) of octanal was added. The biphasic mixture was heated at 90°C with stirring at 1000 rpm for 2 h and then cooled to room temperature. The organic phase was separated, washed with 100 mL of saturated aqueous Na₂S₂O₃, and distilled through a short column to give 91.5 g (81%) of octanoic acid as a colorless liquid, b.p. 114.0–116.0°C/3 mmHg.
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