squares refinement, anisotropic for the C, O, and N atoms and isotropic for the H atoms. The calculations were carried out with XRAY76 and scattering factors from Cromer and Mann.[17]

**5-(*p*-Nitrophenyl)-2-pent-4-yn-1-ylpyrimidine (1).** Crystals of 1 are orthorhombic, space group *Pbca* with 8 molecules in the unit cell with dimensions $a$ = 10.066 (2) Å, $b$ = 34.428 (6) Å, $c$ = 7.647(3) Å, $V$ = 2650 (1) Å$^3$, $\mu$ = 0.86 cm$^{-1}$, and $d_{calc}$ = 1.34 g cm$^{-3}$. Crystal dimensions are 0.18 × 0.20 × 0.50 mm. A total of 2437 intensities were measured, from which 1466 were below the 2.5$\sigma(I)$ level. The final $R$ value was 0.052 ($R_w$ = 0.062, using a weighing scheme $w = (85 + F_o + 0.003F_o^2)^{-1}$).

**2-(1,1-Dicyanopent-4-yn-1-yl)-5-nitropyrimidine (2).** Crystals of 2 are monoclinic, space group $P2_1/n$, with 8 molecules in the unit cell with dimensions $a$ = 22.604 (2) Å, $b$ = 10.271 (2) Å, $c$ = 10.146 (2) Å, $\beta$ = 98.75 (2)°, $V$ = 2328.1 (7) Å$^3$, $\mu$ = 0.73 cm$^{-1}$, and $d_{calc}$ = 1.32 g cm$^{-3}$. Crystal dimensions are 0.15 × 0.25 × 0.30 mm. A total or 4051 intensities were measured, from which 2286 were below the 2.5$\sigma(I)$ level. The final $R$ value was 0.054 ($R_w$ = 0.094, using a weighing scheme $w = (3.98 + F_o + 0.0216F_o^2)^{-1}$).

**Computations.** All molecular mechanics calculations were performed on the VAX cluster of the CAOS/CAMM Centre, University of Nijmegen, The Netherlands, with the MM force field of the CHEMX program.[7a] The MNDO calculations were carried out on a CONVEX C120 computer, with use of the VAMP program.[11]

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**Supplementary Material Available:** Tables of atomic coordinates, thermal parameters, bond distances, and bond angles (12 pages). Ordering information is given on any current masthead page.

(17) Cromer, D. T.; Mann, J. B. *Acta Crystallogr.* **1968**, *A24*, 321.

# Indirect Electrooxidation of Alcohols by a Double Mediatory System with Two Redox Couples of $[R_2N^+{=}O]/R_2NO^\bullet$ and $[Br^\bullet$ or $Br^+]/Br^-$ in an Organic–Aqueous Two-Phase Solution

Tsutomu Inokuchi, Sigeaki Matsumoto, and Sigeru Torii*

*Department of Applied Chemistry, Faculty of Engineering, Okayama University, Okayama, Japan 700*

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An indirect electrooxidation method for alcohol to aldehyde or ketone conversion has been developed. This method, applicable to chemoselective oxidation, employs two redox couples, consisting of 2,2,6,6-tetramethylpiperidine-1-oxyl derivatives **6** and active bromine species. The former is required for the chemical process and recycled, whereas the latter is to be involved in the electrochemical process. Three chemical events play an important role in this system: (1) the formation of [Br$^\bullet$ or Br$^+$] from bromide ion by discharge on the anode in an aqueous solution, (2) the reaction of *N*-oxyl compounds **6** with active bromine species to generate *N*-oxoammonium ion **7**, and (3) the oxidation of alcohols with **7** in an organic phase. Optimum conditions were established as follows: an aqueous 25% NaBr solution buffered at pH 8.6 in a binary system, the use of 1–10 mol % of 4-(benzoyloxy)piperidine derivatives **6**, and adjustment of an electric current at 10–100 mA/cm$^2$. The successful applications of the present method to the oxidation of a variety of primary and secondary alcohols including 1,*n*-diols, giving the corresponding carbonyl compounds, have delineated its synthetic utility. The chemoselective oxidation of a primary hydroxy group in the presence of secondary one has been achieved with a high selectivity by the present procedure.

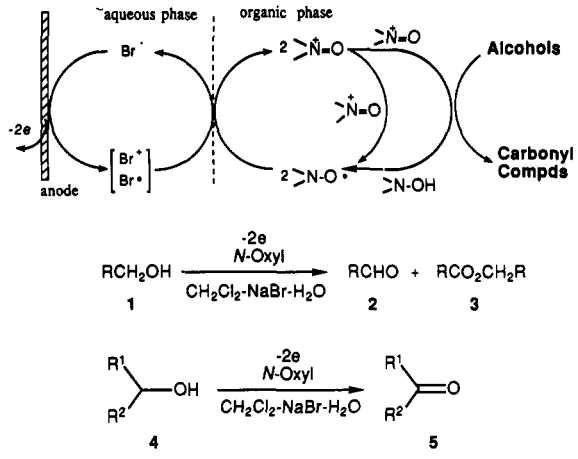
The development of practical electrooxidation methods for alcohols is one of desirable goals in synthetic chemistry.[1] In this context, a double mediatory system which features two redox couples consisted of Ru(VIII)/Ru(IV) and [Cl$^+$]/Cl$^-$ has been developed in our laboratory prior to the present work. This idea provided a considerable advantage that the chemical and the electrochemical processes took place separatedly in an organic and aqueous phase, respectively, by use of a two-phase solution.[2] Indeed, this procedure bears a practical aspect that it is capable of oxidizing secondary alcohols in a large-scale work.[2b] However, it is still desirable to find a more efficient system for selective aldehyde synthesis, which motivated us to examine the role of a nonmetallic redox reagent such as *N*-oxoammonium salts **7** as a mediator[3,4] for the chemical process to circumvent the problems imposed by the high-valency ruthenium compounds.

*N*-Oxoammonium salts **7** are highly useful for the oxidation of primary and secondary alcohols to the corresponding aldehydes and ketones, respectively. For this purpose, aprotic media are usually employed, probably because they are labile in water.[5] However, it became feasible to manipulate this reagent in an aqueous–organic two-phase system because **7** can be revived, after oxidizing alcohols, by being oxidized with reagents such as NaOCl–KBr,[6] $NaBrO_2$,[7] $Ca(OCl)_2$,[7] and $R_4NBr_3$,[8] which occurs

(1) Torii, S. *Electroorganic Syntheses*; Kodansha + VCH: Tokyo + Weinheim, 1985; Part I, Chapter 11.
(2) (a) Torii, S.; Inokuchi, T.; Sugiura, T. *J. Org. Chem.* **1986**, *51*, 155. (b) Torii, S.; Inokuchi, T.; Matsumoto, S.; Saeki, T.; Oki, T. *Bull. Chem. Soc. Jpn.* **1990**, *63*, 852.
(3) Semmelhack, M. F.; Chou, C. S.; Cortes, D. A. *J. Am. Chem. Soc.* **1983**, *105*, 4492.
(4) Preliminary results have been reported: Inokuchi, T.; Matsumoto, S.; Nisiyama, T.; Torii, S. *Synlett* **1990**, 57.
(5) Yamaguchi, M.; Takata, T.; Endo, T. *J. Org. Chem.* **1990**, *55*, 1490.

0022-3263/91/1956-2416$02.50/0 

**Scheme I**




at the boundary face of the two-phase system. In this paper, we describe a new method for the indirect electrooxidation of alcohols by using the combination of two redoxes, $[R_2N^+{=}O]/R_2NO^\bullet$ and $[Br^\bullet$ or $Br^+]/Br^-$, in an organic–aqueous two phase solution (Scheme I).[9]

Investigated are the following factors, which are essential for optimizing the reaction conditions: (1) the effect of halide salt types and its concentration in an aqueous phase, (2) the ensemble of *N*-oxyl compound types, their concentration, and pH values, and (3) the effect of electrolysis conditions such as current density and the kind of electrode. Eventually, the oxidation of various alcohols were examined by using the method developed here. These results would highlight the potential of the method together with our previous method employing Ru(VIII)/Ru(IV)–$[Cl^+]/Cl^-$ redox couples.[2]

## Results and Discussion

The effect of halide salts in a two-phase solution such as $CH_2Cl_2$–$H_2O$ or AcOEt–$H_2O$ system was firstly investigated by using 4-(benzoyloxy)-2,2,6,6-tetramethylpiperidine-1-oxyl (**6a**) as a mediator. The electrolysis of undecanol **1a** (R = $n$-$C_{10}H_{21}$, 1.0 mmol) in a $CH_2Cl_2$ (5 mL)–aqueous 25% NaBr (buffered at pH 8.6 with $NaHCO_3$, 10 mL) system in the presence of **6a** (0.01 mmol) at a current density of 20 mA/cm$^2$ (applied voltage: 1.5–2.5 V) afforded the desired undecanal (**2a**) in 97% yield by passing 2.0 F/mol of electricity for 60 min. Similar results were obtained with respect to other bromide salts such as potassium bromide (93% yield) and lithium bromide (93% yield). In contrast to these, ammonium bromide did not work well (19% yield of **2a**), which may be ascribed to the formation of a 1:1 complex of molecular bromine and ammonia generated during the electrolysis.[10] Chloride salts such as LiCl and NaCl were less satisfactory (13–33% yields of **2a**) and the iodide was not effective at all.

As a result of our effort to clarify the concentration effect of sodium bromide in an aqueous layer, it was found that the yield of **2a** reached a plateau at about 15 wt % of NaBr. Hereafter, a 25% NaBr solution was utilized as the standard conditions.

**Table I. Indirect Electrooxidation of Undecanol (1a) under Various Conditions**[a]

| entry | *N*-oxyl (mol %)[b] | pH[c] | electricity, F/mol | product yield, %[d] 2a | 3a | 1a |
|---|---|---|---|---|---|---|
| 1 | **6a** (0.2) | 8.6 | 2.0 | 10 | 75 | 12 |
| 2 | **6a** (0.5) | 8.6 | 2.0 | 77 | 14 | 2 |
| 3 | **6a** (1.0) | 8.6 | 2.0 | 92 | 0 | 6 |
| 4[e] | **6a** (1.0) | 8.6 | 2.0 | 88 | 0 | 1 |
| 5 | **6a** (10.0) | 8.6 | 2.0 | 92 | 0 | 4 |
| 6 | **6b** (1.0) | 8.6 | 2.0 | 93 | 0 | 5 |
| 7 | **6c** (1.0) | 8.6 | 2.0 | 91 | 0 | 8 |
| 8 | **6d** (1.0) | 8.6 | 2.0 | 93 | 0 | 6 |
| 9 | **6e** (1.0) | 8.6 | 2.0 | 90 | 0 | 9 |
| 10 | **8a** (1.0) | 8.6 | 2.0 | 76 | 0 | 15 |
| 11 | **8b** (1.0) | 8.6 | 2.0 | 57 | 0 | 33 |
| 12 | **6a** (1.0) | 11 | 2.0 | 87 | 0 | 6 |
| 13 | **6a** (1.0) | 7 | 2.0 | 88 | 0 | 3 |
| 14 | **6a** (1.0) | 4 | 2.0 | 69 | 10 | 20 |
| 15 | **6a** (1.0) | 8.6 | 2.2 | 97 | 0 | 0 |
| 16 | **6c** (1.0) | 8.6 | 2.6 | 97 | 0 | 0 |
| 17 | **6f** (1.0) | 8.6 | 2.4 | 99 | 0 | 0 |

[a] Carried out by using **1a** (1.0 mmol) in $CH_2Cl_2$ (5 mL)–25% NaBr (10 mL) at room temperature. [b] Mol % based on **1a**. [c] The pH of aqueous 25% NaBr solution was adjusted as follows: pH 11 = 0.2 M $Na_2B_4O_7$–0.1 M NaOH, pH 8.6 = saturated with $NaHCO_3$, pH 7 = 0.1 M $Na_2HPO_4$–0.1 M $KH_2PO_4$, pH 4 = 0.2 M $Na_2PO_4$. [d] Determined by GC analyses with $\alpha$-methoxynaphthalene as a standard. [e] Carried out in AcOEt (5 mL)–25% NaBr (10 mL).

Effect of the *N*-oxyl compounds was investigated in an ordinary way to determine the minimum amount of the reagent capable of effecting a smooth conversion. As shown in entries 1–5 (Table I), the reactions are satisfactory even with 1–10 mol % of *N*-oxyl compound **6a** (based on **1a**) in a $CH_2Cl_2$–$H_2O$ or an AcOEt–$H_2O$ system; the turnover number of the reagent **6a** was about 100 when 1 mmol of the substrate was employed. The formation of ester **3a** (R = $n$-$C_{10}H_{21}$) of homocoupling type increased as the amount of **6a** was decreased to 0.2 mol % (entry 1). The run in the absence of **6a** resulted in the substantial recovery of **1a**.[11]

Various *N*-oxyl derivatives of both piperidine and pyrrolidine skeletons were employed to gain further insight into their role in the mediatory system. Data in entries 6–14 were obtained at the stage when 2 F/mol of electricity had been passed for the oxidation of **1a** to **2a**. Piperidine derivatives **6a–d**, bearing a benzoyloxy, (4-*tert*-butylbenzoyl)oxy, cyano, and methoxy group at the C-4 positions, respectively, provided high yields of **2a** (entries 3 and 6–9), although a small amount of **1a** remained unchanged. It appears that hydrophobic appendages to the C-4 of piperidine favor the yield of **2a**.[12] It is noteworthy, however, that the oxidations were completed with 2.2–2.6 F/mol of electricities (entries 15–17).

The unsatisfactory results obtained with the pyrrolidine derivatives **8a** and **8b** as a mediator (entries 10 and 11, 76 and 57% yields) may be ascribed to the structural characteristic of themselves. Inspection of a molecular model of **8a** and its 3D space-filling model assessed as the most stable conformer by computer calculations suggests that the 2,2,6,6-tetramethyl groups make **9a** less congested than **7** around the N=O bond. It has been proposed that the addition of alcohols to the N=O bond is reversible, and

(6) (a) Anelli, P. L.; Biffi, C.; Montanari, F.; Quici, S. *J. Org. Chem.* **1987**, *52*, 2559. (b) Siedlecka, R.; Skarzewski, J.; Mlochowski, J. *Tetrahedron Lett.* **1990**, *31*, 2177.

(7) Inokuchi, T.; Matsumoto, S; Nisiyama, T.; Torii, S. *J. Org. Chem.* **1990**, *55*, 462.

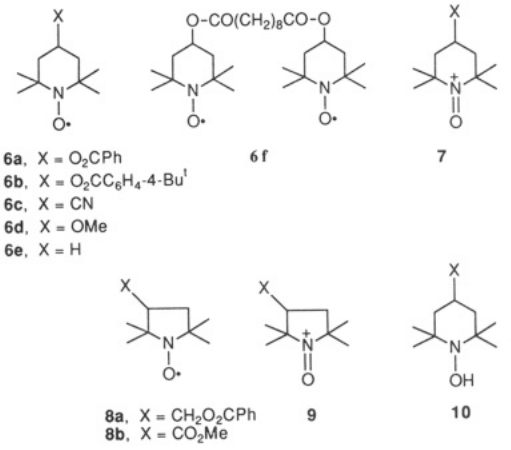
(8) Inokuchi, T.; Matsumoto, S.; Fukushima, M.; Torii, S. *Bull. Chem. Soc. Jpn.*, in press.

(9) It has been proposed that oxoammonium salts **7** react with alcohols to form hydroxylamine **10**, which leads to two molecules of *N*-oxyl **6** by comproportionation with **7** (see ref 3).

(10) Bellucci, G.; Berti, G.; Bianchini, R.; Orsini, L. *Tetrahedron Lett.* **1982**, *23*, 3635.

(11) The reaction was partially accompanied by bromination at the C-4 and C-5 positions of **1a**.

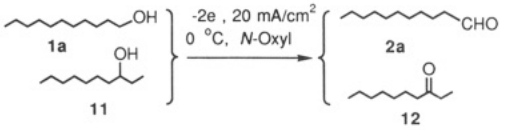
(12) Our attempts with di-*tert*-butylnitroxyl and 3,3-dimethyl-1-oxa-4-azaspiro[4.5]decane-4-oxyl (DOXYL-cyclohexane) as a mediator were unsuccessful.




this process quickly reaches a state of equilibrium, and the $\beta$-elimination of A to give the carbonyl compound (**2** or **5**) and *N*-hydroxy compound **10** becomes a rate-determining step accordingly (Scheme II).[5] A five-membered cyclic transition state required for the $\beta$-elimination may be achieved more readily in the piperidine than in the pyrrolidine derivatives because the former is conformationally immobilized around the C–O–$N^+$ bond in A for steric reason as mentioned above.

Furthermore, the yields of **2a** turned out to be sensitive to the pH in the aqueous phase. Neutral to weakly basic media were highly favorable over acidic ones for the aldehyde synthesis as indicated in entries 12–14, Table I.

The competitive oxidations of a 1:1 mixture of undecanol (**1a**) and 3-decanol (**11**) have been examined at 0 °C with different kinds of *N*-oxyl compounds **6a**, **6d**, **6e**, and **8a** (entries 1–4, Table II) under pH-controlled conditions. In general, the electrolyses mediated by the piperidine derivatives **6a**, **6d**, and **6e** gave higher selectivities (**2a**:**12** = 10–18/1) compared with the pyrrolidine derivative **8a** (**2a**:**12** = 6/1). The highest product ratio (**2a**:**12** = 73/1) among the entries was attained when 2 F/mol of electricity was passed with the *N*-oxyl compound **6a** at pH 12 (ca. 60% conversion, entry 6).

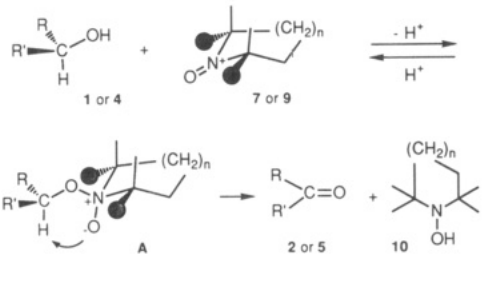



Correlations between the yield of **2a** and the current density are illustrated in Figure 1, which indicate that high efficiency is available over the range of 10–140 mA/$cm^2$ with a platinum electrode or over 10–80 mA/$cm^2$ with a glassy carbon electrode. These delightful results suggest that the *N*-oxoammonium salts are efficiently recycled as a mediator, reacting quickly with the substrate **1a** through an aqueous–organic two phase system. More importantly, this implies high processability and promising applicability of the present method to a practical process.

Semmelhack et al. reported the indirect electrooxidation of alcohols with *N*-oxoammonium salts **7** generated directly from 2,2,6,6-tetramethylpiperidine-1-oxyl (**6e**, TEMPO) by potential-controlled electrooxidation at +0.4 V (Ag/Ag(I)) in an MeCN–$LiClO_4$ system with lutidine as a base.[3] Osa, Bobbit, and their co-workers have recently devised a similar reaction system with a TEMPO-derived modified electrode on carbon felt, which is operated in an in-cell manner with lutidine as a base.[13a] However, these single

(13) (a) Osa, T.; Akiba, U.; Segawa, I.; Bobbitt, J. M. *Chem. Lett.* **1988**, 1423. (b) MacCorquodale, F.; Crayston, J. A.; Walton, J. C.; Worsfold, D. J. *Tetrahedron Lett.* **1990**, *31*, 771.

**Scheme II**



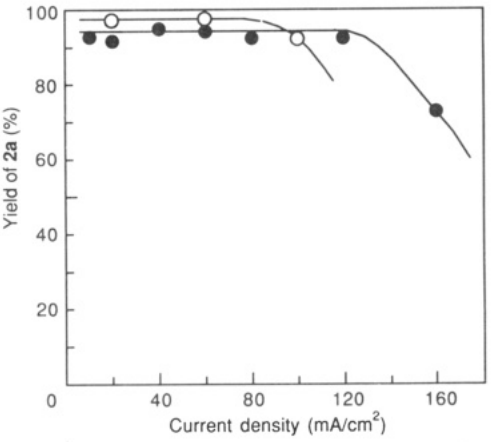




**Figure 1.** Relationships between the yield of **2a** and current density. Symbols are as follows: Pt electrode (shaded circles). Glassy carbon electrode (open circles).

mediatory methods with an *N*-oxoammonium/*N*-oxyl redox couple are successful only under anhydrous conditions in a divided cell. On the other hand, the present double mediatory system is obviously featured by an aqueous–organic two-phase system. The electrolysis plays a role of generating reactive bromine species in the aqueous solution (in an undivided cell) and the generation of *N*-oxoammonium salts **7** from **6** by the action of this active bromine species and the oxidation of the substrates with **7** proceed in the organic phase. The reaction, therefore, can be carried out under a wide range of current densities (10–120 mA/$cm^2$) with continuous generation of these recyclable reagents. As shown in Table I, the use of the buffer solution (pH 8.6) favors the oxidation of both primary and secondary alcohols, which is in marked contrast with the case of lutidine in anhydrous acetonitrile.

Application of the present procedure to a variety of primary and secondary alcohols was tested to ensure its feasibility. A number of examples compiled in Table III were carried out under the conditions indicated in entry 3 (Table II). Aldehydes were produced efficiently from primary alcohols without any overoxidation to homocoupling type esters or carboxylic acids (entries 1–6). Oxidations of aromatic alcohols proceeded smoothly, but there emerged an undesired case in which the bromination of the aromatic nucleus occurred in addition to the formation of the carbonyl group (entry 4). While the bromination was predominant in the oxidation of *m*-methoxybenzyl alcohol, *m*-phenoxybenzyl alcohol was oxidized to *m*-phenoxybenzaldehyde without any concomitant bromination of the aromatic ring (entry 5). These phenomena may be ascribed to the difference in steric circumstances between the two compounds. Such a drawback observed for *m*-methoxybenzyl alcohol can be eliminated by use of electrosynthesized tetraalkylammonium tribromide as a cooxidant.[8]

The present method turned out to effect the selective oxidation of a variety of diols. 1,3-Diols led to the corre-

Table II. Effect of *N*-Oxyl Compounds on the Competitive Oxidation of 1a or 11[a]

| entry | *N*-oxyl compd | aqueous phase (pH) | electricity,[b] F/mol | product yield, %[c] 2a | 12 | ratio 2a/12 |
|---|---|---|---|---|---|---|
| 1 | 6a | sat. $NaHCO_3$–25% NaBr (8.6) | 2.0 | 88 | 5 | 18/1 |
| 2 | 6d | sat. $NaHCO_3$–25% NaBr (8.6) | 2.0 | 63 | 6 | 10/1 |
| 3 | 6e | sat. $NaHCO_3$–25% NaBr (8.6) | 2.0 | 78 | 6 | 13/1 |
| 4 | 8a | sat. $NaHCO_3$–25% NaBr (8.6) | 2.0 | 64 | 10 | 6/1 |
| 5 | 6a | 5% NaOAc–25% NaBr (8.0) | 2.0 | 84 | 4 | 28/1 |
| 6 | 6a | 5% $Na_2CO_3$–25% NaBr (12.0) | 2.0 | 58 | 0.8 | 73/1 |
| 7 | 6a | 5% $Na_2CO_3$–25% NaBr (12.0) | 3.5 | 89 | 1.7 | 52/1 |

[a] Carried out at 0 °C by using a 1:1 mixture of 1a (1 mmol) and 11 (1 mmol) in an aqueous (5 mL)–organic ($CH_2Cl_2$, 10 mL)–(Pt) system. [b] Faradays/mol based on 1a at a current density of 20 mA/cm$^2$. [c] Based on isolated products.

sponding β-hydroxy aldehydes (aldols, entries 7 and 8), selectively, without any dehydration and epimerization at the α-position.[7] Oxidative cyclizations of 1,4- and 1,5-diols to γ- and δ-lactones, respectively, proceeded nicely (entries 9 and 10). Primary–primary or primary–secondary 1,*n*-diols ($n > 5$) gave 1,*n*-dialdehyde with more than 4 F/mol of electricity (entry 11) or *n*-hydroxyalkanals with 2 F/mol of electricity, predominantly (entries 12 and 13).[6b] The oxidation of secondary alcohols also proceeded smoothly without any bromination at the α-position of carbonyl groups (entries 14–17). It is noteworthy that the oxidation of 1,2-diol produced 1,2-diketone in good yield without any cleavage of a carbon–carbon bond (entry 18). Similarly, α-acetoxy alcohol and 2-hydroxy alcohol were converted to the corresponding acetoxy ketone and vicinal diketone, respectively (entries 19 and 20).

In conclusion, we have explored that the combination of an organic and a halogen redox couples is effective for the selective oxidation of alcohols, especially primary ones, and the turnover of oxoammonium salt is almost 100 in a 1–100-mmol-scale work. This electrolysis system is expected to be extended in a large-scale preparation (example of 100-mmol-scale operation was noted in the Experimental Section) since no deterioration of the mediator, most of which was recoverable by the chromatographic separation or distillation under reduced pressure, was observed in the run with 6a under high current densities. High selectivity observed for the competitive oxidation of primary and secondary hydroxy groups with 2,2,6,6-tetramethylpiperidine-1-oxyl 6a under the basic conditions (pH 12) is of significant synthetic value.

## Experimental Section[14]

**Electrolysis Apparatus.** Unless otherwise noted, an undivided cell [2.5-cm diameter and 10-cm height (30-mL volume) or 8.0-cm diameter and 12-cm height (300-mL volume)] fitted with a gas inlet pipe, a stirring bar, and a thermometer was used. Two platinum foil electrodes (3 cm$^2$) or glassy carbon electrodes (3 cm$^2$) were placed parallel to each other 10 mm apart. The vessel was immersed in a water bath maintained to 15–25 °C by external cooling.

**Electrooxidation of Primary Alcohols to Aldehydes: Typical Procedure.** Undecanol (1a, 172 mg, 1.0 mmol) and 4-(benzoyloxy)-2,2,6,6-tetramethylpiperidine-1-oxyl (6a, 2.8 mg, 0.01 mmol) were dissolved in $CH_2Cl_2$ (5 mL) in an electrolysis vessel, and to this solution was added an aqueous 25% NaBr solution (10 mL) saturated with $NaHCO_3$, thereby being buffered at pH 8.6. Into the upper layer of the resulting biphase solution were immersed two platinum or glassy carbon electrodes, and the mixture was electrolyzed under a constant current of 20 mA/cm$^2$ with a moderate stirring (applied voltage: 1.5–2.5 V). The electrolysis was continued until the organic phase showed a color change from slightly yellow to brown (it required about 2.2 F/mol of electricity based on the alcohol 1a). The mixture was then treated with ethanol (0.1 mL) to destroy the excess of oxoammonium salt. The $CH_2Cl_2$ layer was separated, and the aqueous layer was extracted with $CH_2Cl_2$ (5 mL × 3). The combined extracts were washed with brine, dried ($Na_2SO_4$), and concentrated under reduced pressure. The crude product was purified by column chromatography ($SiO_2$, 20 g, hexane–AcOEt, 10:1, 150 mL) to give 165 mg (97%) of undecanal (2a) as an oil and the *N*-oxyl 6a (ca. 2 mg). 2a: bp 113 °C (9 mm); IR (neat) 2716, 1729 (C=O), 1466 cm$^{-1}$; $^1$H NMR (500 MHz) δ 0.88 (t, $J$ = 7.0 Hz, 3, $CH_3$), 1.26 (br s, 14, $CH_2$), 1.62 (m, 2, $CH_2$), 2.41 (dt, $J$ = 7.3, 2.0 Hz, 2, $CH_2CO$), 9.76 (t, $J$ = 2.0 Hz, 1, CHO); $^{13}$C NMR (126 MHz) δ 14.1, 22.1, 22.7, 19.2, 29.29, 29.34, 29.4, 29.5, 31.9, 43.9, 203.0.

**A Large-Scale Operation.** A mixture of 1a (17.23 g, 100 mmol) and 6a (0.28 g, 1.0 mmol) in $CH_2Cl_2$ (200 mL)–aqueous 25% NaBr (pH 8.6, 400 mL) was electrolyzed in a beaker-type flask (1500-mL volume) with two graphite plate electrodes (3 × 6 cm$^2$) under a constant current of 900 mA (current density: 50 mA/cm$^2$). After passage of 2.8 F/mol of electricity (reaction time: 8.5 h), the reaction was quenched with ethanol (2 mL), and the mixture was extracted with $CH_2Cl_2$ (50 mL × 2). The combined organic layers were dried ($Na_2SO_4$) and concentrated. Crude product was purified by distillation to give 15.1 g (88%) of 2a as an oil: bp 95–98 °C (6 mm).

**Oxidation of Secondary Alcohols to Ketones: A Typical Procedure.** 4-*tert*-Butylcyclohexanol (4a, 4.69 g, 30 mmol) and 4-(benzoyloxy)-2,2,6,6-tetramethylpiperidine-1-oxyl (6a, 83 mg, 0.3 mmol) were dissolved in $CH_2Cl_2$ (50 mL) placed in an electrolysis vessel [6.0-cm diameter and 13-cm height (250-mL volume)], and to this solution was added aqueous 25% NaBr buffered at pH 8.6 with saturated $NaHCO_3$ (75 mL). Into the upper aqueous layer were immersed two graphite plate electrodes (2.5 × 4.0 cm$^2$), and the mixture was electrolyzed under a constant current of 200 mA with a moderate stirring (applied voltage: 1.5–2.5 V). During the electrolysis, the mixture was maintained at 20–25 °C. The electrolysis was continued until 2.2 F/mol of electricity had been passed. The mixture was then treated with ethanol (1 mL). The organic layer was separated, and aqueous layer was extracted with $CH_2Cl_2$ (20 mL × 3). The combined extracts were dried ($Na_2SO_4$) and concentrated to give 4.30 g of the crude products. Distillation at 80–82 °C (12 mm) gave 3.86 g (83%) of 4-*tert*-butylcyclohexanone (5a): mp 48–49 °C (from hexane) (lit.[16] mp 47.5–48.5 °C).

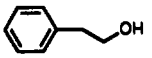
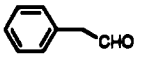
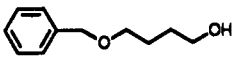
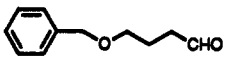
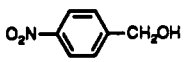
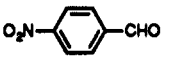
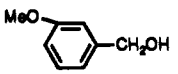
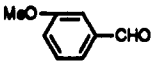
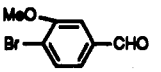
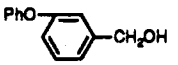
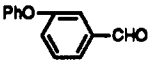
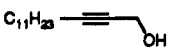
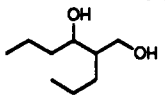
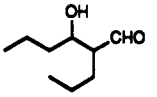
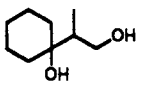
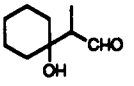
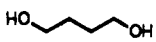
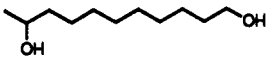
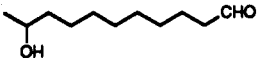
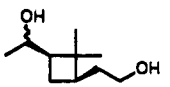
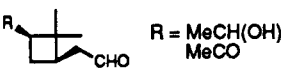
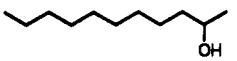
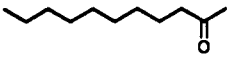
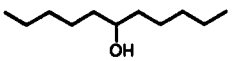
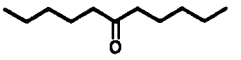
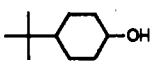
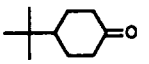
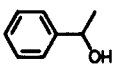
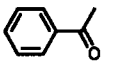
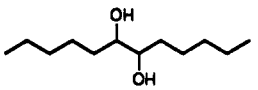
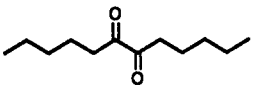
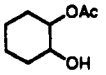
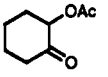
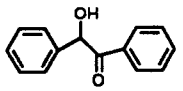
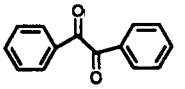
**Competitive Oxidation of 1a or 3-Decanol (11).** A mixture of 1a (172 mg, 1.0 mmol), 11 (158 mg, 1.0 mmol), and 6a (2.8 mg, 0.01 mmol) was electrolyzed in a two-phase solution of $CH_2Cl_2$ (5 mL) and aqueous 25% NaBr buffered at pH 12 with 5% $Na_2CO_3$ in the presence of octyl acetate (172 mg, 1.0 mmol) as an internal standard for GC analyses. After 2 F/mol of electricity had been passed at a current of 20 mA/cm$^2$, the mixture was

(14) 2,2,6,6-Tetramethylpiperidine-1-oxyl (6a–f) and their pyrrolidine analogues (8a,b) were prepared according to the method reported[15] and purified by recrystallizations or column chromatography. Starting alcohols were purified by distillation or column chromatography ($SiO_2$) prior to use. Boiling points indicated by an air-bath temperature and melting points are uncorrected. $^1$H NMR and $^{13}$C NMR spectra were recorded in $CDCl_3$. GC analyses were carried out on a "Quadrex" Bond-Fused silica capillary column (methyl silicone 20M: 0.25 μm film thickness, 25 m × 0.25 mm i.d.) at programmed temperature (from 80 to 250 °C, 10 °C/min) after 10-min isothermal analysis.

(15) (a) Rozantzev, E. G.; Neiman, M. B. *Tetrahedron* **1964**, *20*, 131. (b) Rozantsev, E. G.; Sholle, V. D. *Synthesis* **1971**, 401.

(16) Winstein, S.; Holness, N. J. *J. Am. Chem. Soc.* **1955**, *77*, 5562.

**Table III. Oxidation of Primary and Secondary Alcohols by an *N*-Oxyl (6a) or [$Br^+$ or $Br^•$]/$Br^-$ System[a]**

| entry | substrate | electricity,[b] F/mol | product | (yield, %)[c] |
|---|---|---|---|---|
| 1 |  | 3.0 |  | (96) |
| 2 |  | 2.2 |  | (92) |
| 3 |  | 3.0 |  | (98) |
| 4 |  | 4.0 |  | (14) |
| | | |  | (81) |
| 5 |  | 3.0 |  | (97) |
| 6 |  | 2.5 |  | (90) |
| 7 |  | 3.7 |  | (97) |
| 8 |  | 2.0 |  | (87) |
| 9 |  | 4.5 |  | (97) |
| 10 |  | 4.5 |  | (97) |
| 11 | $HOCH_2(CH_2)_{10}CH_2OH$ | 4.5 | $OHC(CH_2)_{10}CHO$ | (85) |
| 12 |  | 2.0 |  | (72) |
| 13 |  | 2.0 |  R = MeCH(OH) MeCO | (86) (5) |
| 14 |  | 2.5 |  | (95) |
| 15 |  | 2.2 |  | (91) |
| 16 |  | 3.0 |  | (93) |
| 17 |  | 2.5 |  | (90) |
| 18 |  | 6.0 |  | (85) |
| 19 |  | 8.0 |  | (94) |
| 20 |  | 2.2 |  | (97) |

[a] Substrates (1 mmol) were oxidized in the presence of **6a** (0.01 mmol) in $CH_2Cl_2$ (5 mL)–25% NaBr (pH 8.6 buffered with $NaHCO_3$, 10 mL). [b] Electricity based on the substrate. [c] Yields based on isolated products.

worked up in the usual manner and the crude products were analyzed by GC to be 58% of **2a** and 0.8% of **12**.

Selected physical and spectral data for compounds listed in Table III are as follows.

**Phenylacetaldehyde**: bp 76–78 °C (10 mm) (lit.[17] bp 63–64 °C (5 mm)).

**4-(Benzyloxy)butanal**: bp 154–156 °C (24 mm) (lit.[18] bp 143 °C (10 mm)); IR (neat) 3032, 2862, 2728, 1725 (C=O), 1456, 1363, 1100, 739, 698 $cm^{-1}$; $^1H$ NMR (60 MHz) δ 2.00 (m, 2, $CH_2$), 2.57 (m, 2, $CH_2$), 2.55 (t, $J$ = 6.5 Hz, 2, $CH_2$), 4.55 (s, 2, $CH_2$), 7.42 (s, 5, PhH), 9.89 (m, 1, CHO); $^{13}C$ NMR (126 MHz) δ 22.5, 40.9, 69.1, 72.9, 127.6 (3 C), 128.4 (2 C), 138.2, 202.3.

(17) Gilsdorf, R. T.; Nord, F. F. *J. Am. Chem. Soc.* **1952**, *74*, 1837.

(18) Paul, R.; Tchelitcheff, S. *Bull. Soc. Chim. Fr.* **1948**, 197.

**4-Nitrobenzaldehyde**: mp 103–104 °C (lit.[19] mp 104–105 °C).

**4-Bromo-3-methoxybenzaldehyde**: mp 71.3–73.2 °C (from hexane) (lit.[20] mp 74 °C); IR (KBr) 1601 (C=O), 1572, 1475, 1286, 934, 822, 648, 598 $cm^{-1}$; $^1H$ NMR (500 MHz) $\delta$ 3.828, 3.834 (s, 3, MeO), 7.01 (m, 1, PhH), 7.40 (m, 1, PhH), 7.45 (m, 1, PhH), 10.29 (d, $J$ = 4 Hz, 1, CHO); $^{13}C$ NMR (126 MHz) $\delta$ 55.7, 112.6, 117.9, 123.1, 133.9, 134.5, 159.2, 191.7

**3-Phenoxybenzaldehyde**: bp 180–184 °C (14 mm) (lit.[21] bp 175–176 °C (11 mm)); IR (neat) 3066, 2818, 2734, 1694 (C=O), 1582, 1483, 1452, 1390, 1164, 1131, 944 $cm^{-1}$; $^1H$ NMR (500 MHz) $\delta$ 7.04 (d, $J$ = 7.4 Hz, 2), 7.17 (t, $J$ = 7.4 Hz, 1), 7.29 (d,d, $J$ = 7.8, 2.2 Hz, 1), 7.38 (t, $J$ = 7.8 Hz, 2), 7.46 (m, 1), 7.50 (t, $J$ = 7.8 Hz, 1), 7.60 (d, $J$ = 7.4 Hz, 1), 9.96 (s, 1, CHO); $^{13}C$ NMR (126 MHz) $\delta$ 118.1, 119.5, 124.2, 124.6, 124.7, 130.0, 130.4, 138.0, 156.2, 158.4, 191.6.

**2-Tetradecynal**: bp 98–100 °C (0.2 mm) (lit.[22] bp 94–98 °C (0.3 mm)).

**2-Ethyl-3-hydroxyhexanal**: bp 100–102 °C (9 mm) (lit.[23] bp 107–110 °C (16 mm)).

**2-(1-Hydroxycyclohexyl)propanal**:[7] IR (neat) 3426 (OH), 2738, 1719 (C=O) $cm^{-1}$; $^1H$ NMR (500 MHz) $\delta$ 1.13 (d, $J$ = 7.0 Hz, 3, $CH_3$), 1.24 (m, 1, $CH_2$), 1.42 (m, 1, $CH_2$), 1.50–1.66 (m, 8, $CH_2$), 2.04 (s, 1, OH), 2.43 (m, 1, CHCO), 9.83 (d, $J$ = 2 Hz, 1, CHO).

**Dodecanedial**: mp 47–50 °C (lit.[24] bp 128–30 °C (4 mm)); IR (neat) 2918, 2852, 1715 (C=O), 1473, 1410, 1394 $cm^{-1}$; $^1H$ NMR (500 MHz) $\delta$ 1.28 (br s, 8, $CH_2$), 1.59–1.64 (m, 4, $CH_2$), 2.42 (m, 8, $CH_2$), 9.76 (t, $J$ = 1.8 Hz, 1, CHO); $^{13}C$ NMR (126 MHz) $\delta$ 22.0 (2 C), 29.1 (2 C), 29.3 (4 C), 43.9 (2 C), 202.9 (2 C).

**10-Hydroxyundecanal**:[25] IR (neat) 3330 (OH), 2930, 2853, 2720, 1725 (C=O) $cm^{-1}$; $^1H$ NMR (200 MHz) $\delta$ 1.16, 1.17 (d, $J$ = 6.2 Hz, 3, $CH_3$), 1.29 (br s, 12, $CH_2$), 1.40 (br, 1, OH), 1.61 (m, 2, $CH_2$), 2.40 (m, 2, $CH_2$), 3.76 (m, 1, OCH), 9.74 (m, 1, CHO); $^{13}C$ NMR (50 MHz) $\delta$ 22.0, 23.5, 25.7, 29.1, 29.2, 29.3, 29.5, 39.3, 43.9, 68.1, 203.0.

**3-(1-Hydroxyethyl)-2,2-dimethylcyclobutylacetaldehyde**:[6b] IR (neat) 3330 (OH), 2726, 1721 (C=O) $cm^{-1}$; $^1H$ NMR (500 MHz) $\delta$ 0.99, 1.13 (s, 6, $CH_3$), 1.03 (d,d, $J$ = 7.3, 1.3 Hz, 3, $CH_3$), 1.13–1.19 (m, 1), 1.76–1.82 (m, 1), 1.95–2.03 (m, 1), 2.16–2.34 (m, 2), 2.42–2.48 (m, 1), 3.69 (m, 1), 9.70 (t, $J$ = 1.9 Hz, 1, CHO); $^{13}C$ NMR (126 MHz) (major isomer) $\delta$ 17.0, 21.2, 26.4, 31.0, 35.7, 40.0, 45.1, 50.5, 69.1, 202.1.

**6-Undecanone**: bp 93–95 °C (5 mm) (lit.[26] bp 124–125 °C (35 mm)).

**Dodecane-6,7-dione**: bp 110–113 °C (13 mm) (lit.[27] bp 90–92 °C (3 mm)); IR (neat) 3414, 1715 (C=O), 1678, 1653, 1466, 1404, 1122 $cm^{-1}$; $^1H$ NMR (200 MHz) $\delta$ 0.88 (m, 6, $CH_3$), 1.22–1.32 (m, 8, $CH_2$), 1.57 (m, 4, $CH_2$), 2.72 (t, $J$ = 7.6 Hz, 2, $CH_2$); $^{13}C$ NMR (50 MHz) $\delta$ 13.9, 22.4, 22.7, 31.3, 36.0, 200.2.

**2-Acetoxycyclohexanone**: bp 114–116 °C (9 mm) (lit.[28] bp 120–123 °C (12 mm)).

**Benzil**: mp 94–95 °C (lit.[29] mp 95 °C).

**Registry No.** **1a**, 112-42-5; **1j**, 10596-05-1; **2a**, 112-44-7; **2j**, 38199-58-5; **3a**, 42231-61-8; **4a**, 98-52-2; **5a**, 98-53-3; **6a**, 3225-26-1; **6b**, 132207-24-0; **6c**, 38078-71-6; **6d**, 95407-69-5; **6e**, 2564-83-2; **6f**, 2516-92-9; **8a**, 132207-25-1; **8b**, 2154-33-8; **11**, 1565-81-7; **12**, 928-80-3; $CH_2Cl_2$, 75-09-2; NaBr, 7647-15-6; KBr, 7758-02-3; $NH_4Br$, 12124-97-9; LiCl, 7447-41-8; NaCl, 7647-14-5; $Br_2$, 7726-95-6; $Br^+$, 22541-56-6; C, 7440-44-0; 2-phenylethanol, 60-12-8; 4-(benzyloxy)butanol, 4541-14-4; 4-nitrobenzyl alcohol, 619-73-8; 3-methoxybenzyl alcohol, 6971-51-3; 3-phenoxybenzyl alcohol, 13826-35-2; 2-tetradecynol, 51309-22-9; 2-ethyl-3-hydroxyhexanol, 94-96-2; 2-(1-hydroxycyclohexyl)propanol, 90676-81-6; 1,4-butanediol, 110-63-4; 1,5-pentanediol, 111-29-5; phenylacetaldehyde, 122-78-1; 4-(benzyloxy)butanal, 5470-84-8; 4-nitrobenzaldehyde, 555-16-8; 3-methoxybenzaldehyde, 591-31-1; 4-bromo-3-methoxybenzaldehyde, 43192-34-3; 3-phenoxybenzaldehyde, 39515-51-0; 2-tetradecynal, 101098-99-1; 2-ethyl-3-hydroxyhexanal, 496-03-7; 2-(1-hydroxycyclohexyl)propanal, 123903-25-3; 2*H*-2-oxotetrahydrofuran, 96-48-0; 2*H*-2-oxo-tetrahydropyran, 542-28-9; 1,12-dodecanediol, 5675-51-4; 1-(2-hydroxyethyl)-3-(1-hydroxyethyl)-2,2-dimethylcyclobutane, 22630-96-2; 2-undecanol, 1653-30-1; 6-undecanol, 23708-56-7; 1-phenylethanol, 98-85-1; 6,7-dodecanediol, 91635-53-9; 2-acetoxycyclohexanol, 22241-34-5; 2-hydroxy-1,2-diphenylethanone, 119-53-9; 1,12-dodecanedial, 38279-34-4; 3-(1-hydroxyethyl)-2,2-dimethylcyclobutanal, 72257-92-2; *cis*-3-acetyl-2,2-dimethylcyclobutanal, 58558-22-8; 2-undecanone, 112-12-9; 6-undecanone, 927-49-1; 1-phenylethanone, 98-86-2; 6,7-dodecanedione, 13757-90-9; 2-acetoxycyclohexanone, 17472-04-7; benzil, 134-81-6.

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