DOI: 10.1002/cctc.201600491

Ionic TEMPO in Ionic Liquids: Specific Promotion of the Aerobic Oxidation of Alcohols

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The main objective of this study was to design a recyclable TEMPO (2,2,6,6-tetramethylpiperidinyl-*N*-oxyl) derivative that could be used as a catalyst in an ionic liquid solvent for the aerobic oxidation of alcohols by using $NaNO_2$ and HCl as co-catalysts. To this end, a TEMPO derivative bearing a quaternary ammonium group, [4-Bu_2MeN-TEMPO][PF_6] (**1**), was prepared. It was subsequently shown that this ionic TEMPO derivative is an efficient catalyst for the aerobic oxidation of a variety of primary and secondary alcohols. It exhibits a synergistic effect with ionic liquid solvents and readily outperforms analogous oxidations in methylene chloride. Moreover, the ionic TEMPO could be recycled five times with no loss of activity.

Introduction

The selective oxidation of alcohols is one of the most important reactions in organic synthesis.[1] There is a growing concern to develop greener oxidation processes that eliminate the need for a stoichiometric amount of toxic heavy metals. The 2,2,6,6-tetramethylpiperidinyl-*N*-oxyl[2] (TEMPO)-catalysed oxidation of alcohols has emerged as a clean and economical oxidation process using bleach or dioxygen as terminal oxidizing agents.[3] In general, TEMPO-catalysed oxidations proceed with high chemoselectivity; the over-oxidation of aldehydes to carboxylic acids is very slow because TEMPO prevents auto-oxidation under aerobic conditions.[4]

Because of its high atom efficiency, oxygen (air) is usually the oxidant of choice and aerobic oxidations are considered one of the greenest oxidation processes; however, they are usually performed with the aid of a catalytic amount of transition-metal compounds. Metal contamination of products causes serious issues in the field of fine chemicals and pharmaceuticals manufacture. The best way to avoid this contamination is to eliminate the need for metal catalysts for oxidative processes. Recently, an appealing aerobic oxidation of alcohols catalysed by TEMPO and nitrite or its precursor has been introduced in this field.[5] However, these reactions are normally performed in aqueous biphasic systems using methylene dichloride as the organic phase.[4e] Hence, from the point of view of green chemistry, the design of a greener protocol for this oxidation is necessary.

Ionic liquids have been used as alternative to organic solvents owing to their low vapour pressure; safety issues associated with the flammability of mixtures of oxygen and volatile organic solvents in the gas phase can thus be circumvented. Moreover, ionic liquids have the potential to immobilise catalysts and recycle them for further reaction.[6] The metal-free aerobic oxidation of alcohols with recyclable catalysts immobilised in ionic liquids is a desirable method for the preparation of aldehydes and ketones. The TEMPO-catalysed oxidation in ionic liquids and the recyclability of the ionic liquids in the process have been successfully examined in the literature.[7] Because TEMPO is a rather expensive material, a technique that facilitates its separation from the products and its reuse should be considered. However, extraction of the reaction products from the ionic liquid with an organic solvent results in leaching of TEMPO, which prevents its recycling. To overcome this difficulty, TEMPO derivatives containing polar functionalities have been tested.[8] Besides their recyclability, the use of ionic liquids as media for the aerobic oxidation of alcohols catalysed by a stable *N*-oxy radical, has not been systematically investigated.[7e, 8a, 9] Herein, we report an expeditious aerobic oxidation of alcohols catalysed by $NaNO_2$/HCl by using a suitable ionic liquid and a TEMPO derivative bearing an ammonium moiety. The recyclability of the ionic liquid and catalyst is also discussed.

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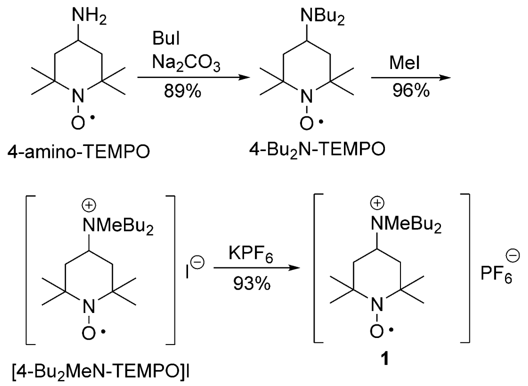
Supporting information for this article can be found under:
http://dx.doi.org/10.1002/cctc.201600491.

Results and Discussion

Synthesis of [4-Bu_2MeN-TEMPO][PF_6] (1)

To recycle the catalyst in the ionic liquid, an ammonium tag was introduced into TEMPO (Scheme 1). The ionic TEMPO **1** was prepared by alkylation of 4-amino-TEMPO with *n*-butyl iodide, followed by quaternisation with MeI. Ion exchange with KPF_6 gave [Bu_2MeN-TEMPO][PF_6] as a pale-orange solid in good yield.[10]



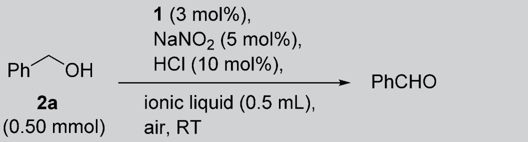
Scheme 1. Synthesis of [4-Bu_2MeN-TEMPO][PF_6] (**1**).

Catalytic activity of 1 in aerobic oxidation

We first examined the oxidation of benzyl alcohol (**2a**) using 3 mol% of ionic TEMPO **1**, 5 mol% of $NaNO_2$ and 10 mol% of HCl in [bmim][PF_6] (bmim = 1-butyl-3-methylimidazolium). Benzaldehyde was obtained in 99% yield in 1 h (Table 1, entry 1).

In [bmim][NTf_2], a slower oxidation rate was observed than in [bmim][PF_6] (entry 2), and a high yield can be obtained by simply prolonging the reaction time (entry 3). The reaction in [bmpy][PF_6] showed a lower oxidation rate, with a trend similar to that of the reaction performed in [bmim][NTf_2] (entries 4 and 5). In a blank experiment in [bmim][PF_6], benzaldehyde was not detected, instead benzoic acid was formed in 4% yield and **2a** was recovered almost quantitatively. These results demonstrate the importance of the proper choice of ionic liquid in promoting the oxidation reaction.

Table 1. Oxidation of **2a** with **1**.[a]



Entry	Solvent[b]	Time [h]	Yield of Aldehyde[b] [%]	Recovery of **2a**[c] [%]
1	[bmim][PF_6]	1	99	0
2	[bmim][NTf_2]	1	53	43
3	[bmim][NTf_2]	16	99	0
4	[bmpy][PF_6]	1	52	40
5	[bmpy][PF_6]	16	99	0
6[d]	[bmim][PF_6]	1	0[e]	83

[a] Reaction conditions: **2a** (0.50 mmol), **1** (0.015 mmol), $NaNO_2$ (0.025 mmol), HCl (0.050 mmol) in ionic liquid (0.5 mL), air, RT. [b] bmim = 1-butyl-3-methylimidazolium; bmpy = 1-butyl-4-methylpyridinium. [c] GC yield. [d] Without **1**. [e] Benzoic acid was obtained in 4% yield.

Effect of ammonium tag and solvent

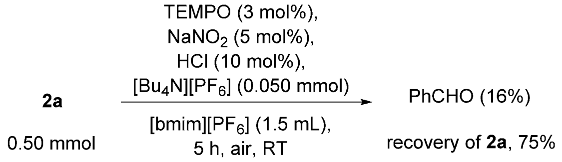
To clarify the conditions for a faster oxidation, a set of reactions was performed in [bmim][PF_6] and CH_2Cl_2 (Table 2). Compared with the reaction using TEMPO **1** in [bmim][PF_6], oxidation in CH_2Cl_2 was found to be sluggish, affording benzaldehyde in only 49% yield in 10 h (entry 2). In contrast, if TEMPO was used, better results were obtained in CH_2Cl_2 (entry 3). Under the conditions reported in reference [5e], the corresponding aldehyde was obtained in 77% yield, although a longer reaction time (13 h) was needed (entry 4).

Table 2. Solvent and catalyst effect on the oxidation of **2a**.[a]

Entry	Catalyst	Solvent	Time [h]	Yield [%][b]	TOF [h^{-1}]
1	**1**	[bmim][PF_6]	1	99	33
2	**1**	CH_2Cl_2	10	49 (51)	1.6
3	TEMPO	[bmim][PF_6]	10	27 (64)	0.9
4	TEMPO	CH_2Cl_2	13	77 (23)	2.0

[a] Reaction conditions: **2a** (0.50 mmol), TEMPO or **1** (0.015 mmol), $NaNO_2$ (0.025 mmol), 1 M HCl (0.050 mmol), solvent (ionic liquid: 1.5 mL or CH_2Cl_2: 5 mL), air, RT. [b] GC yield. Values in parentheses show the recovery of **2a**.

To confirm the importance of the ammonium group bound to TEMPO, the reaction was performed in the presence of the individual components: the oxidation of **2a** in the presence of TEMPO and tetrabutylammonium hexafluorophosphate gave benzaldehyde in a lower yield compared with that obtained by using catalyst **1** (Scheme 2).



Scheme 2. Oxidation of **2a** with TEMPO in the presence of [Bu_4N][PF_6].

These results clearly indicate that the use of ionic TEMPO **1** in the ionic liquid is crucial for increasing the oxidation rate.

Aerobic oxidation of alcohols with 1

Having established the optimum conditions, the scope and limitations were examined by using a series of alcohols (Figure 1). The results are summarised in Table 3. Benzylic

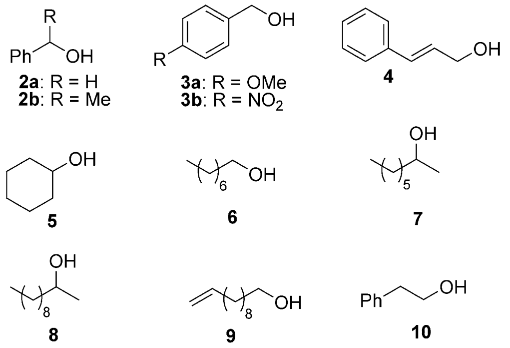
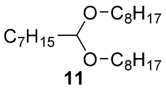


Figure 1. Selected alcohol substrates.

Table 3. Oxidation of various alcohols.[a]

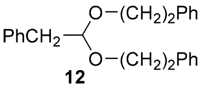
Entry	Alcohol	Conditions[b]	Time [h]	Yield [%][c]
1[d]	**2a**	3:5:10	1	99
2	**2b**	3:5:10	1	99
3	**3a**	5:10:10	1	98
4	**3b**	5:10:10	16	90 (2)
5	**4**	5:10:20	2	99
6	**5**	5:10:20	5	79 (12)
7	**5**	5:10:20	16	92
8	**6**	5:8:16	5	36 (13), **11**: 51
9[e]	**6**	5:8:16	5	68 (22)
10	**7**	5:8:16	5	91
11	**8**	5:10:20	3	99
12	**9**	5:8:16	5	50 (19)
13	**10**	5:8:16	5	18 (21), **12**: 56
14[e,f]	**10**	5:8:16	5	59 (13)

[a] Reaction conditions: alcohol (0.50 mmol) in [bmim][PF_6] (1.5 mL) under air at RT. [b] **1**/$NaNO_2$/HCl (mol %). [c] Determined by GC. Values in parentheses show the recovery of the starting alcohol. [d] Entry 1 in Table 1. [e] In [bmim][NTf_2]. [f] Performed under O_2 (balloon pressure) at 60 °C.



$C_7H_{15}CH(O{-}C_8H_{17})_2$

11



$PhCH_2CH(O{-}(CH_2)_2Ph)_2$

12

alcohols **2a**, **2b** and **3a** were easily oxidised to the corresponding aldehydes in high yields (entries 1–3), whereas benzylic alcohol **3b** with an electron-withdrawing group was significantly less reactive (entry 4). Allylic alcohol **4** was converted to cinnamaldehyde in good yield (entry 5). Normally, cyclic secondary alcohol **5** resists oxidation because of steric factors: for instance, the TEMPO-catalysed reaction in CH_2Cl_2 generates cyclohexanone only with 37 % conversion and with 91 % selectivity after 24 h.[5e] In contrast, the present method afforded cyclohexanone in high yields, although a longer reaction time was required (entries 6 and 7). In [bmim][PF_6], aliphatic alcohol **6** was mainly converted into acetal **11**, originating from the reaction of the formed aldehyde with **6** (entry 8). The formation of acetal in a protic ionic liquid has been previously reported;[11] however, this side reaction can be suppressed by switching the ionic liquid to [bmim][NTf_2], which affords the corresponding aldehyde in moderate yield (entry 9). Secondary aliphatic alcohols **7** and **8** were converted into the corresponding ketones in excellent yields (entries 10 and 11). Moreover, the oxidation of unsaturated aliphatic alcohol **9** afforded the corresponding aldehyde in moderate yield (entry 12). β-Phenethyl alcohol (**10**) gave predominantly the corresponding acetal **12** (entry 13). Using oxygen instead of air in [bmim][NTf_2] under heating was found to accelerate the reaction: phenylacetaldehyde was obtained in moderate yield and formation of acetal **12** was suppressed, presumably by the faster oxidative process (entry 14).

Thus, the optimum ionic liquid for this reaction depends on the alcohol employed. Whereas [bmim][PF_6] was preferable for the oxidation of **2a** as shown in Table 1, the use of [bmim][NTf_2] resulted in the selective oxidation of a primary aliphatic alcohol (Table 3, entry 9).

Aerobic oxidation of octan-2-ol with 1

We next tested the oxidation of **7**, as a representative aliphatic secondary alcohol, in a series of ionic liquids with different anionic counterparts (Table 4). In contrast to the case of primary alcohols, [bmim][PF_6] was superior to [bmim][NTf_2] (entries 1 and 2) and to [bmim][BF_4], which resulted in slow oxidation (entry 3). Ionic liquid [bmim][OTf] was also suitable for the oxidation of **7** (entry 4).

Table 4. Oxidation of **7** with **1** in ionic liquids.[a]

Entry	Solvent	Yield of 2-octanone [%][b]	Recovery of **7**[b]
1	[bmim][PF_6]	91	0
2	[bmim][NTf_2]	78	0
3	[bmim][BF_4]	69	24
4	[bmim][OTf]	91	0

[a] Reaction conditions: **7** (0.50 mmol), **1** (0.015 mmol), $NaNO_2$ (0.025 mmol), HCl (0.050 mmol), ionic liquid (1.5 mL) under air atmosphere at RT for 5 h. [b] GC yield.

Recyclability of 1

Next, the recyclability of the catalytic system was examined in the oxidation of **2a**. After the first run, the product was separated from the ionic liquid layer by extraction with diethyl ether. The ionic liquid containing ionic TEMPO **1** was directly reused for the next oxidation. Although addition of new $NaNO_2$ and HCl was required, no decrease in yield was observed up to five recycles (Table 5).

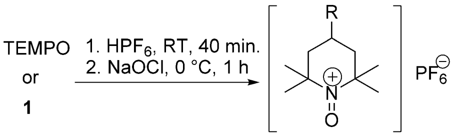
Stoichiometric oxidation

To gain insight into the catalytic role of **1**, oxidation of **2a** using a stoichiometric amount of oxoammonium $\mathbf{1}^+$ was tested. Oxoammonium $\mathbf{1}^+$ was prepared according to the literature procedure described for [$TEMPO^+$][BF_4].[12] After exposure of **1** to HPF_6,[13] the reaction mixture was treated with NaOCl. The purity of the resulting oxoammonium salt was estimated by oxidation of an excess amount of benzyl alcohol. $TEMPO^+$ obtained by this procedure showed good purity (98 %), whereas the oxoammonium derived from **1** was only 46 % pure

Table 5. Recycling of ionic TEMPO **1** and [bmim][PF_6] for the oxidation of **2a**.[a]

Run	Yield [%][b]	Recovery of **2a** [%][b]
1	99	0
2	99	0
3	99	0
4	98	0
5	95	0
6	92	0

[a] Reaction conditions: **2a** (0.50 mmol), **1** (0.015 mmol), $NaNO_2$ (0.025 mmol), HCl (0.050 mmol), [bmim][PF_6] (1.5 mL), air, RT for 1 h. The ionic phase recovered from the previous reaction was used. $NaNO_2$ (0.025 mmol) and HCl (0.050 mmol) were added. [b] GC yield.



$TEMPO^+$ (R = H)
1^+ (R = $NMeBu_2$•PF_6)

HPF_6 (mol%)	NaOCl (mol%)	Purity
100	50	$TEMPO^+$: 98%
100	50	1^+: 46%
200	100	1^+: 88%

Scheme 3. Preparation of oxoammonium salts.

(Scheme 3). However, a satisfactory result was obtained by using a double amount of reagents (88 % purity of 1^+).

Stoichiometric oxidation of **2a** with $TEMPO^+$ or 1^+ was performed in CH_2Cl_2, CH_3CN and [bmim][PF_6], and the results are summarised in Table 6.

Table 6. Stoichiometric oxidation of **2a** with $TEMPO^+$ or 1^+.[a]

Entry	Oxidant	Solvent	Time [h]	Yield of aldehyde [%][b]	Recovery of **2a** [%][b]
1	1^+	[bmim][PF_6]	0.25	96	0
2	1^+	CH_3CN	0.25	100	0
3	1^+	CH_2Cl_2	1.5	64	36
4	$TEMPO^+$	[bmim][PF_6]	1.5	23	66
5	$TEMPO^+$	CH_3CN	1.5	70	24
6	$TEMPO^+$	CH_2Cl_2	1.5	92	6

[a] Reaction conditions: **2a** (0.09 mmol), $TEMPO^+$ or 1^+ (0.10 mmol) in solvent (1.0 mL) at RT. [b] Determined by GC.

Comparison of the results in Tables 2 and 6 reveals a similar tendency in the stoichiometric and catalytic oxidations. The reaction with 1^+ in CH_3CN and [bmim][PF_6] proceeded faster than that in CH_2Cl_2 (entries 1–3), whereas $TEMPO^+$ was most efficient in CH_2Cl_2 (entries 4–6). Notably, 1^+ was not completely dissolved in CH_2Cl_2, and therefore the above results may not accurately reflect the reaction rate of 1^+ in CH_2Cl_2.

Comparison of TEMPO and ionic TEMPO (1) in ionic liquids

For the catalytic and stoichiometric oxidations, CH_2Cl_2, which is typically used for TEMPO-catalysed reactions, was a superior solvent to [bmim][PF_6]. The oxidation in acetonitrile also yielded better results than those obtained in [bmim][PF_6]. This is in good agreement with the literature reports,[9a] which ascribe this tendency to the different viscosities of molecular solvents and ionic liquids. In contrast, $TEMPO^+$-mediated oxidations in an alternative ionic liquid, *N*-butyl-*N*-methyl pyrrolidinium bis(trifluoromethylsulfonyl)imide, proceeded faster those in acetonitrile,[9b] suggesting that the reaction rate of the $TEMPO^+$-mediated oxidation is strongly dependent on the ionic liquid employed. On the other hand, the results related to the use of **1** were found to be quite different. The reactions in [bmim][PF_6] proceeded at a clearly faster rate than those performed in CH_2Cl_2, and approximately the same results were obtained in acetonitrile. This trend can be rationalized by assuming that more polar solvents preferably promote the formation and reaction of the highly active oxoammonium 1^+ containing both oxoammonium and ammonium groups,[14] thus compensating for the high viscosity of the ionic liquid. Compared with the ionic liquid, acetonitrile served as a good solvent, giving the same level of conversion. However, [bmim][PF_6] is superior to acetonitrile in separating the products from the reaction mixture while keeping the catalyst in the solvent to be reused in the next reaction.

Conclusions

TEMPO derivative **1** proved to be an effective mediator for the aerobic oxidation of alcohols in ionic liquids. This study clearly demonstrates the importance of careful screening of ionic liquids with respect to the selectivity as well as the acceleration. In addition, a strong synergistic effect between ionic TEMPO **1** and ionic liquids became apparent. The use of **1** and an ionic liquid plays a key role in increasing the oxidation rate. The ammonium tag on **1** is responsible not only for recycling the *N*-oxy radical in the ionic liquid phase but also for enhancing the oxidation rate.

Experimental Section

General methods

IR spectra were recorded with a JASCO IRA-102 spectrophotometer. ^1H NMR spectra were obtained in $CDCl_3$ or CD_3CN by using a Varian Mercury 300 spectrometer (300 MHz) with Me_4Si as internal standard; *J* values are given in Hz. GC analyses were performed with a SHIMADZU GC-14B and GC-2014 fitted with a capillary column and a flame ionization detector. Elemental analyses were performed with a PerkinElmer 2400II analyser. Melting points were measured with a Yanaco MP 50533 and are uncorrected. Ionic liquids were purchased from Kanto Chemical and were used as received. All alcohols were commercially available and distilled before use.

Experimental procedures

Preparation of 4-Bu_2N-TEMPO

A mixture of 4-amino-TEMPO (1.62 g, 9.45 mmol), *n*-butyl iodide (4.5 mL, 39.6 mmol) and K_2CO_3 (8.23 g, 59.5 mmol) in acetonitrile (50 mL) was heated at reflux for 23 h. The product was diluted with diethyl ether (150 mL), washed with water (40 mL × 3) and brine and dried over Na_2SO_4. The solvent was removed under reduced pressure to give 4-Bu_2N-TEMPO (2.38 g, 89%). $R_f = 0.82$ (SiO_2/EtOH); ^{1}H NMR spectra were recorded after addition of phenylhydrazine (one drop) to the NMR sample tube. ^{1}H NMR (300 MHz, $CDCl_3$): $\delta = 0.94$ (t, $J = 7.1$ Hz, 6H), 1.16 (s, 6H), 1.22 (s, 6H), 1.30–1.42 (m, 4H), 1.46–1.71 (br s, 6H), 1.79–1.83 (m, 2H), 2.65 (br s, 4H), 3.17–3.22 ppm (m, 1H); ^{13}C NMR (75 MHz, $CDCl_3$): $\delta = 14.144$, 19.925, 20.694, 31.234, 32.796, 41.227, 50.323, 50.371, 59.253 ppm; IR (neat): $\tilde{\nu} = 3448$, 2955, 2871, 2809, 1639, 1464, 1376, 1362, 1328, 1287, 1243, 1217, 1195, 1089, 1074, 1035, 937, 903, 867, 735, 680 cm^{-1}.

Preparation of [4-Bu_2MeN-TEMPO]I

4-Bu_2N-TEMPO (2.24 g, 7.92 mmol) was treated with MeI (2.5 mL, 40 mmol) in acetonitrile (40 mL) and heated at reflux for 3 h. After complete consumption of 4-Bu_2N-TEMPO, as monitored by TLC, the solvent was removed under reduced pressure affording [4-Bu_2MeN-TEMPO]I (3.23 g, 96%). $R_f = 0.78$ (Al_2O_3/EtOH). ^{1}H NMR spectra were recorded after addition of phenylhydrazine (one drop) to the NMR sample tube. ^{1}H NMR (300 MHz, $CDCl_3$): $\delta = 1.03$ (t, $J = 7.4$ Hz, 6H), 1.23 (s, 6H), 1.32 (s, 6H), 1.44–1.60 (m, 4H), 1.68–1.84 (m, 4H), 1.88 (d, $J = 12$ Hz, 2H), 2.02 (d, $J = 9.6$ Hz, 2H), 3.22 (s, 3H), 3.30–3.62 ppm (m, 5H); ^{13}C NMR (75 MHz, $CDCl_3$): $\delta = 13.714$, 19.678, 24.419, 32.479, 37.916, 46.840, 59.186, 59.597, 64.477 ppm; IR (KBr): $\tilde{\nu} = 3434$, 2962, 2867, 1633, 1463, 1362, 1245, 1195 cm^{-1}.

Preparation of ionic TEMPO 1

[4-Bu_2MeN-TEMPO]I (2.15 g, 5.06 mmol) and KPF_6 (1.06 g, 5.74 mmol) were mixed in distilled water (40 mL) and acetone (40 mL) at room temperature for 3 h. The product was extracted with methylene chloride, washed with water and brine and dried over Na_2SO_4 to give [4-Bu_2MeN-TEMPO][PF_6] (**1**, 2.08 g, 93%). $R_f = 0.80$ (Al_2O_3/EtOH); m.p.: 167–169 °C; ^{1}H NMR and ^{13}C NMR spectra were recorded after addition of phenylhydrazine (one drop) to the NMR sample tube. ^{1}H NMR (300 MHz, CD_3CN): $\delta = 0.97$ (t, $J = 7.2$ Hz, 6H), 1.14 (s, 6H), 1.18 (s, 6H), 1.32–1.40 (m, 4H), 1.64–1.72 (m, 6H), 1.92–1.95 (m, 2H), 2.83 (s, 3H), 3.13–3.19 (m, 4H), 3.43–3.51 ppm (m, 1H); ^{13}C NMR (75 MHz, CD_3CN): $\delta = 13.80$, 19.56, 20.29, 24.77, 32.87, 38.31, 46.09, 59.69, 60.02, 65.18 ppm; IR (KBr): $\tilde{\nu} = 2970$, 2879, 1637, 1469, 1384, 1368, 1243, 1198, 1105, 843, 741, 679 cm^{-1}; HRMS (ESI$^+$): *m/z* calcd for $C_{18}H_{38}N_2O$ (cation): 298.2984; found: 298.3002; HRMS (ESI$^-$): *m/z* calcd for PF_6 (anion): 144.9642; found: 144.9636; elemental analysis calcd (%) for $C_{18}H_{38}F_6N_2OP$ (443.47): C 48.75, H 8.64, N 6.3; found: C 49.08, H 8.82, N 6.23.

$NaNO_2$/HCl-mediated oxidation of alcohols catalysed by ammonium TEMPO 1 (Table 1, entry 1)

A mixture of benzyl alcohol (52 μL, 0.50 mmol), $NaNO_2$ (1.7 mg, 25 μmol), 1 M HCl (50 μL) and ionic TEMPO **1** (6.7 mg, 3 mol%) in [bmim][PF_6] (1.5 mL) was stirred at room temperature for 1 h. The product was extracted with ether (5 mL × 5). The yield was determined by GC by using hexadecane as an internal standard.

Octanal dioctyl acetal

^{1}H NMR (300 MHz, $CDCl_3$): $\delta = 0.86$–0.90 (m, 9H), 1.2–1.4 (m, 30H), 1.54–1.59 (m, 6H), 3.39–3.44 (m, 2H), 3.53–3.57 (m, 2H), 4.46 ppm (t, $J = 5.7$ Hz, 1H); ^{13}C NMR (75 MHz, CD_3CN): $\delta = 14.23$, 22.81, 23.13, 24.95, 26.43, 29.40, 29.44, 29.59, 30.05, 30.46, 31.94, 31.99, 33.56, 65.50, 103.23 ppm.

Phenylacetaldehyde diphenetyl acetal

^{1}H NMR (300 MHz, $CDCl_3$): $\delta = 2.77$–2.90 (m, 4H), 2.89 (d, $J = 5.7$ Hz, 2H), 3.49–3.60 (m, 2H), 3.69–3.77 (m, 2H), 4.62 (t, $J = 5.7$ Hz, 1H), 7.10–7.30 ppm (m, 15H); ^{13}C NMR (75 MHz, CD_3CN): $\delta = 36.44$, 40.68, 67.20, 104.10, 126.30, 126.42, 128.36, 128.42, 129.08, 129.70, 137.20, 139.06 ppm.

Preparation and titration of $TEMPO^+$[12]

HPF_6 (65 wt%, 115 μL, 0.50 mmol) was slowly added to a mixture of TEMPO (78.6 mg, 0.50 mmol) and water (0.2 mL) over a period of 3 min at room temperature. After stirring for 40 min, NaOCl (1.84 M, 136 μL, 0.25 mmol) was added over 3 min at 0 °C, and the mixture was stirred for a further 1 h. The product was filtered and washed with cold aqueous 5% $NaHCO_3$, water and cold diethyl ether. After drying, [$TEMPO^+$][PF_6] was obtained as a bright yellow solid (88 mg). A mixture of benzyl alcohol (11.4 μL, 0.11 mmol) and [$TEMPO^+$][PF_6] (15.2 mg, 0.050 mmol) in CH_2Cl_2 (4 mL) was stirred at room temperature for 17 h. The product was extracted with ether. The yield of benzaldehyde (98%) based on [$TEMPO^+$][PF_6] was determined by GC by using hexadecane as an internal standard.

Preparation and titration of $\mathbf{1}^+$

HPF_6 (65 wt%, 115 μL, 0.50 mmol) was slowly added to a mixture of **1** (111 mg, 0.25 mmol) and water (0.4 mL) over a period of 3 min at room temperature. After stirring for 40 min, NaOCl (1.84 M, 136 μL, 0.25 mmol) was added over 3 min at 0 °C, and the mixture was stirred for a further 1 h. The product was filtered and washed with cold aqueous 5% $NaHCO_3$, water and cold diethyl ether. After drying, [$\mathbf{1}^+$][PF_6] was obtained as a yellow solid (118 mg). A mixture of benzyl alcohol (10.4 μL, 0.10 mmol) and [$\mathbf{1}^+$][PF_6] (29.5 mg, 0.050 mmol) in CH_2Cl_2 (4 mL) was stirred at room temperature for 17 h. The product was extracted with ether. The yield of benzaldehyde (88%) based on [$\mathbf{1}^+$][PF_6] was determined by GC by using hexadecane as an internal standard.

Stoichiometric oxidation of benzyl alcohol by ionic TEMPO $\mathbf{1}^+$ (Table 6, entry 1)

A mixture of benzyl alcohol (10.2 mg, 0.094 mmol) and ionic TEMPO $\mathbf{1}^+$ (88% purity, 67 mg, 0.10 mmol) in [bmim][PF_6] (1.0 mL) was stirred at room temperature for 15 min. The product was extracted with diethyl ether (2 mL × 7). The yield was determined by GC analysis by using hexadecane as an internal standard.

Acknowledgements

This work was supported by the Overseas Advanced Educational Research Practice Support Program from the Ministry of

Education, Culture, Sports, Science and Technology of the Japanese Government.

Keywords: alcohols · ionic liquids · oxidation · oxygen · radicals

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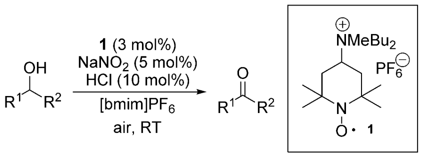
Received: April 26, 2016

Keeping the TEMPO: A recyclable TEMPO (2,2,6,6-tetramethylpiperidinyl-*N*-oxyl) derivative that can be used as catalyst in ionic liquid solvent for the aerobic oxidation of alcohols by using $NaNO_2$ and HCl as co-catalysts was designed. This ionic TEMPO derivative is an efficient, recyclable catalyst for the aerobic oxidation of a variety of primary and secondary alcohols.



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Ionic TEMPO in Ionic Liquids: Specific Promotion of the Aerobic Oxidation of Alcohols