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THE REACTION OF BENZIMIDAZOLIUM DERIVATIVES WITH SUPEROXIDE

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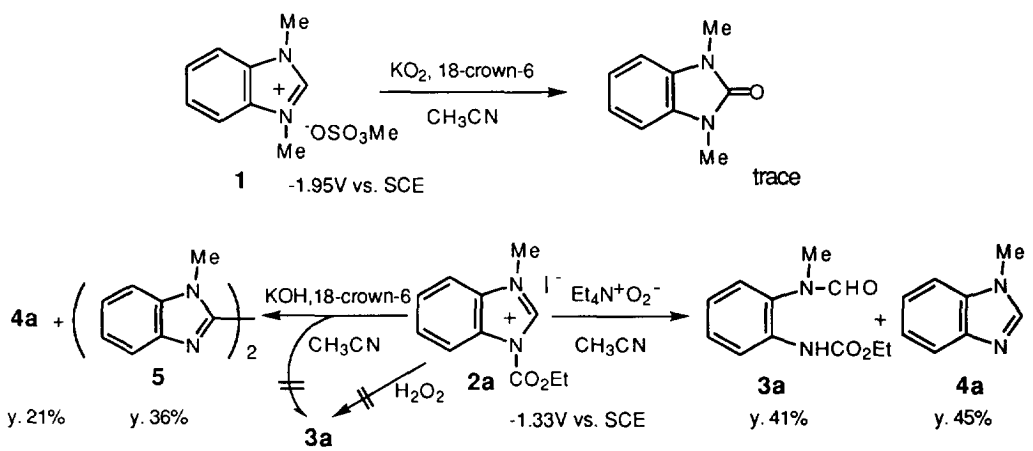
Abstract: 1-Ethoxycarbonyl-3-methylbenzimidazolium salts, which have an electron deficient imidazolium ring and a carbamate moiety, were allowed to react with superoxide to give ring-opened products and 1-methylbenzimidazoles. The products ratio varied on the change of the counter cation species of superoxide. When 1,1',3,3' - tetramethyl- 2,2'-bibenzimidazolium salt reacted with KO_2, chemiluminescence was observed which did not occur by the use of KOH or H_2O_2 as a reagent. Copyright © 1996 Elsevier Science Ltd

Superoxide is one of the most noteworthy active oxygen species,[1] and has been attracting much attention from both chemical and biological viewpoints. Since superoxide has both radical and anionic characters, it is capable of exhibiting nucleophilic,[2] radical,[3] and redox[4] behaviors, but it has low reactivity toward most of organic compounds. Therefore, most reports concerning the reaction of superoxide with organic compounds have shown that large amount of superoxide and/or superoxide activator were needed to proceed the reaction.[5] When large amount of superoxide was used as a reagent, it was not clear whether superoxide actualy reacted with substrate or not, because KOH or H_2O_2 was produced by decomposition of superoxide. Actually, in most cases of superoxide reaction, the reported products were also formed when KOH and/or H_2O_2 were used instead of superoxide.[6] These facts make chemical properties of superoxide ambiguous. To clarify the nature of reactivity of superoxide, we have studied its reaction using π-electron deficient azaaromatic compounds as substrates,[7] and it was revealed that azaaromatic quaternary salts which have high reduction potentials readily react with superoxide. In particular, when thiazolium salts which have multi reactive sites to nucleophiles were used as substrates, specific reactions for superoxide were discovered.[7e-g] These studies also revealed that the substrates whose reduction potentials were upper than -1.60V (vs.SCE in CH_3CN) could interact with superoxide. Therefore, even though imidazolium salts have lower reduction potentials than that of thiazolium salts and are reluctant to react with superoxide, it might be possible to make them react with superoxide by raising their reduction potentials. Therefore we designed 1-

ethoxycarbonyl-3-methylbenzimidazolium salts which have multi reaction sites and sufficient redox potentials for the reaction with superoxide. In this paper, we describe the detailed results concerning the reaction of superoxide with benzimidazolium derivatives.[8]

When 1,3-dimethylbenzimidazolium salt **1** reacted with KO_2, only trace amount of 1,3-dimethyl-2,3-dihydrobenzimidazol-2-one was obtained with an almost complete recovery of the starting material. Reduction potential of **1** (-1.95V vs. SCE in CH_3CN) is lower than that of thiazolium salts[7e-g] (-0.66 to -1.60 V vs. SCE in CH_3CN) and the lack of sufficient electron deficiency is thought to be the cause of low reactivity of **1** toward superoxide. The introduction of ethoxycarbonyl group raised the reduction potentials of imidazolium salts, that is, compound **2a** (-1.33V vs. SCE in CH_3CN) has high reduction potential than compound **1**. The introduced ethoxycarbonyl group concurrently made the second reactive site toward nucleophiles in the substrate. The reaction of compound **2a** with electrolytically generated supeoxide in acetonitrile gave a ring-opened product **3a** and 1-methylbenzimidazole **4a** in 41% and 45% yield, respectively (scheme I). When **2a** was reacted with KOH in the presence of 18-crown-6, a dimerized product **5** [9] (y.36%) was obtained other than **4a** (y.21%) without the formation of **3a**. The reaction of **2a**



Scheme I

with H_2O_2 neither gave **3a**. These results show that **3a** is a product which is formed specifically by superoxide. A substituent effect was investigated to examine the relation between reduction potentials and products distribution using benzimidazolium salts which have substituents at 5 and/or 6 positions (Table I). In method A, electrolytically generated superoxide was used in the presence of Et_4NClO_4, while KO_2 was used in the presence of 18-crown-6 in method B. Ring-opened product **3** and 1-methylbenzimidazole **4** were obtained in each case, and the substrates which have high reduction potentials tended to give **3** rather than **4**. Further, electrolytically generated superoxide had a tendency to give ring-opened products **3**. Particularly in the case of 5-nitrobenzimidazolium salt **2d**, product distribution was reversed between methods A and B. In the case of naphtoimidazolium salt **2b**, **4b** was seldom obtained, and there were many by-products. This is probably because C-4 (or C-9) position of **2b** is reactive to superoxide. Table II shows the results of 2-

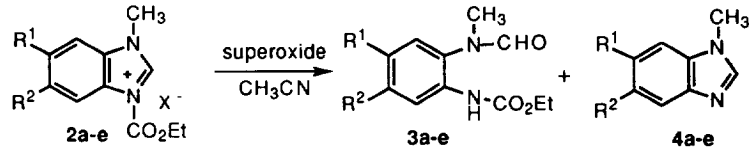


Table I

The Reaction of 1-Ethoxycarbonyl-3-methylbenzimidazolium Salts with Superoxide

Entry	Substrate	Substituent	E1/2 (V vs.SCE)	Method *	Yield of 3(%)	Yield of 4(%)
1	2a	$R^1 = R^2 = H$	-1.33	A	41	45
2	2a			B	6	52
3	2b	$R^1, R^2 = -(CH=CH)_2-$	-1.10	A	47	0
4	2b			B	33	trace
5	2c	$R^1 = R^2 = Me$	-1.36	A	29	23
6	2c			B	0	41
7	2d	$R^1 = NO_2$, $R^2 = H$	-0.47	A	61	33
8	2d			B	13	79
9	2e	$R^1 = R^2 = Cl$	-1.15	A	56	17
10	2e			B	38	14

* Method A: electrogenerated superoxide. Method B: potassium superoxide with 18-crown-6.

arylbenzimidazolium salts as the substrates. Also in these cases, the substrates which have higher reduction potentials tended to give ring-opened products **7a-d**. When **7a-d** were produced, superoxide was considered to attack on the 2-position of imidazolium ring followed by ring opening. In the cases of formation of **8a-d**, superoxide might attack on the carbonyl carbon followed by elimination of ethoxycarbonyl group. The results shown in Table I and II suggested that superoxide prefered to attack on the 2-position of imidazolium ring rather than on the carbonyl carbon in the reaction with benzimidazolium salts having high reduction potentials. 2-Aryl-substituted benzimidazolium salts gave less ring-opened products than the parent one **2a**.

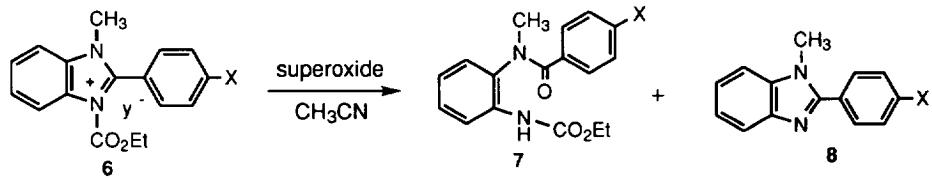


Table II. The Reaction of 2-Aryl-1-Ethoxycarbonyl-3-methylbenzimidazolium Salts with Superoxide

Substrate	X	Y	E1/2 (V vs.SCE)	Method*	Yield of 7 (%)	Yield of 8 (%)
6a	H	OSO_3Me	-1.25	A	32	53
6a				B	0	63
6b	NO_2	BF_4	-0.72	A	35	55
6b				B	18	67
6c	F	BF_4	-1.24	A	23	63
6c				B	24	58
6d	OMe	ClO_4	-1.35	A	9	50
6d				B	14	56

* Method A: electrogenerated superoxide. Method B: potassium superoxide with 18-crown-6.

In these cases the aryl group was thought to hinder an approach of superoxide at the 2-position of imidazolium ring. Difference of products ratio between methods A and B suggested that the counter cation effected on the reaction of superoxide. Thus we next examined the influence of counter cation on the reactivity of superoxide. 5-Nitrobenzimidazolium salts **2d** which exhibited remarkable difference of products ratio between methods A and B was used as a substrate (Table III). In method C, compound **2d** was subjected to the reaction with electrolytically generated superoxide after the addition of $KClO_4$ (1.0eq). In method D, to a stirred solution of acetonitrile containing KO_2, 18-crown-6, and Et_4NClO_4 (20eq), was added the substrate **2d**. In the case of method C, resulting products ratio was similar to that of method B. And in method D, the ratio was similar to that of method A. These results suggest that the change of the ratio was due to the counter cation species of superoxide. When 1.0 eq. of Et_4NClO_4 was added instead of 20 eq.

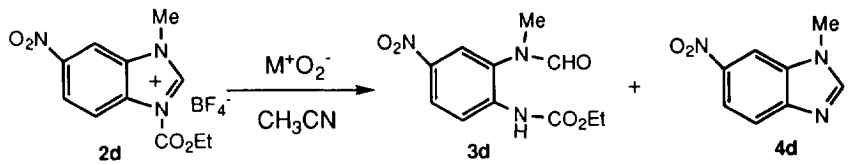
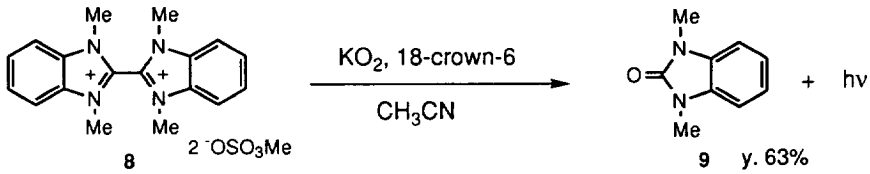


Table III. The Effect of the Counter Cation on the Distribution of **3d** and **4d**

method	conditions	M	yield of 3d+ 4d(%)	ratio 3d:4d
A	electroreduction of O_2 in TEAP/CH_3CN	Et_4N	94	65:35
B	KO_2 - 18-crown-6 in CH_3CN	K	92	14:86
C	(A) + 1.0eq. of $KClO_4$	K	89	19:81
D	(B) + 20eq. of Et_4NClO_4	Et_4N	63	49:51
E	(A) + 1.0eq.of $NaClO_4$	Na	77	53:47
F	(A) + 1.0eq.of LiClO4	Li	74	75:25

in method D, the change of the ratio did not occur. This fact suggests that there is a stronger interaction between superoxide and potassium ion than that between superoxide and tetraethylammonium ion. Further reactions in which NaClO4 (method E) or LiClO4 (method F) were added to the solution of method A were investigated and the results showed that the ratio of ring-opened product was highest when LiClO4 was added.[10]

Next 2,2'-bibenzimidazolium salt **8** was adopted as a substrate, which has moderately high reduction potential (-1.01V vs. SCE in CH_3CN). The compound has an analogous form as bithiazolium salts,[7f,g] which were revealed to have unique reactivity toward superoxide. When **8** reacted with superoxide in the presence of 18-crown-6, 1,3-dimethyl benzimidazolone (**9**) was obtained in 63% yield (scheme II).



Scheme II

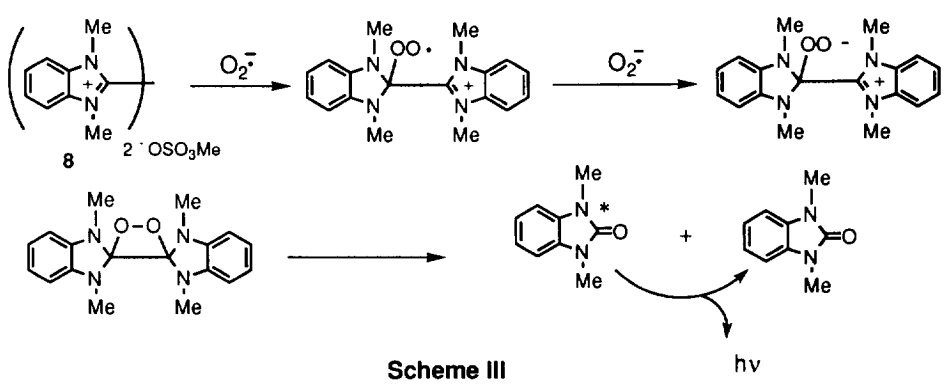
Table IV

Luminescent Intensity through the Reaction of **8** with KO_2, KOH, H_2O_2

system	counts / min.
in 0.1mM / DMSO of **8** • 100 μl	
1) 1.0mM KO_2 • 80μl	230,177
2) 1.0mM KOH • 80μl	95
3) 1.0mM H_2O_2 • 80μl	17
4) blank	14

Although it was not a specific product for superoxide because it was obtained from the reaction of **8** with KOH, a luminescence was observed in the case of KO_2. Table IV shows the luminescent intensities measured by a lumino meter when compound **8** reacted with KO_2, KOH, or H_2O_2. To the 100μl of 0.1mM DMSO solution of substrate **8** was added 80μl of 0.1mM DMSO solution of each reagent, and luminescent intensity was measured for one minute. When **8** reacted with KO_2, much higher luminescent intensity was observed than those with other reagents. These results suggest the production of dioxetane intermediate,[11] which decomposes to *N*,*N*'-dimethylbenzimidazolone and excited one, in the reaction of **8** with KO_2 (scheme III).

In this paper we have investigated the reactivity of benzimidazolium derivatives with superoxide, and it was revealed that ethoxycarbonyl group at the imidazolium nitrogen raised the reduction potential of these



Scheme III

compounds to make them more reactive to superoxide. When 1-ethoxycarbonyl-3-methylbenzimidazolium salt reacted with superoxide, one of the products was obtained which was not produced in the reaction with KOH or H_2O_2, therefore it was revealed to be a specific product for superoxide. Moreover, we have discovered that the counter cation of superoxide gave influence on products distribution. It is a first report that an influence of counter cation was clearly revealed on the reactivity of superoxide. And 2,2'-bibenzimidazolium salt gave superoxide-specific chemiluminescence, which suggested this type of compounds to have a potential for the superoxide detecting reagent with high specificity. The application of 2,2'-bibenzimidazolium derivetives to a superoxide detecting reagent are now under investigation.

ACKNOWLEDGMENT

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EXPERIMENTAL

All melting points were taken on a Yanaco micro melting point apparatus and are uncorrected. The mass spectra were measured with JEOL JMS-D300 and JMS-SX102A instruments. The nuclear magnetic resonance spectra were measured with JEOL JNM-FX100 and GX400 spectrometers using tetramethylsilane as an internal standard. Infrared spectra (IR) were recorded on a JASCO IR-810 spectrophotometer. Chemiluminescent intensities were measured by Micro Lumat LB 96p (EG & G BERTHOLD).

Reduction Potentials and Cyclic Voltammograms

The substrate (0.1 mmol) was dissolved in 10 ml of 0.1 M Et_4NClO_4 solution of CH_3CN. Reduction potentials and cyclic voltammograms were recorded on a Yanaco P-1100 polarographic analyzer using glassy carbon as working, platinum as counter, and SCE as reference electrode, respectively.

Starting Materials

1-Ethoxycarbonyl-3-methyl benzimidazolium salts **2a**-**2e** were prepared as follows. To a solution of benzimidazole (60 mmol) and ethyl chloroformate (66 mmol) in dichloromethane (60 ml) was added triethylamine (60 mmol) dropwise at 0° C. The mixture was stirred at rt for 1h and washed with water and brine. Organic layer was dried ($MgSO_4$) and evaporated off to give the corresponding 1-ethoxycarbonyl imidazole in 79-98% yields. In case of the preparation of **2a** and **2b**, dimethyl sulfate (30 mmol) was added to the benzene solution of the corresponding 1-ethoxycarbonylimidazole (10 mmol) and the mixture was stirred at rt for 20h. Then the mixture was washed three times with ether (20 ml) by decantation to give **2a** (y.79%) and **2b** (y.75%). 1-Ethoxycarbonyl-3,5,6-trimethyl benzimidazolium methosulfate prepared by the above method was reluctant to crystallize, so it was mixed with sat. $NaClO_4$ solution (4.0 ml) and a precipitated perchlorate salt was washed with water to give **2c** in 64% yield. In the cases of **2d** and **2e**, trimethyloxonium tetrafluoroborate (4.0 mmol) was added to the dichloromethane solution of the

corresponding 1-ethoxycarbonylbenzimidazole (2.0 mmol). The mixture was stirred at rt for 24h. Then the precipitate was filtered off, washed with ether to give **2d** (98%) and **2e** (57%). When 5-nitrobenzimidazole was subjected to the ethoxycarbonylation, both 5-nitro product and 6-nitro one were obtained. Then less polar one was reacted with trimethyloxonium tetrafluoroborate to give compound **2d**. The position of nitro group was determined by 2D NOESY experiment using compound **4d**, in which the NOE between N-methyl and 7-H protons was observed.

1-Ethoxycarbonyl-3-methylbenzimidazolium methosulfate (2a): Since this compound was hygroscopic, elemental analysis was carried out using the corresponding perchlorate salt. Colorless needles from methanol-ether; mp 148-149°C. Anal. Calcd for $C_{11}H_{13}ClN_2O_6$: C, 43.26; H, 4.30; N, 9.20. Found: C, 43.23; H, 4.27; N, 9.10. ^{1}H-NMR (DMSO-d_6) δ: 1.45 (t, 3H, *J*=7.0Hz), 3.33 (s, 3H), 4.16 (s, 3H), 4.66 (q, 2H, *J*=7.0Hz), 7.77-8.38 (m, 4H), 10.48 (s, 1H). ^{13}C-NMR (DMSO-d_6) δ: 18.71, 33.29, 53.55, 56.53, 113.41, 115.11, 115.16, 124.58, 126.45, 126.85, 132.08, 142.14.

1-Ethoxycarbonyl-3-methylnaphtho[2,3-d]imidazolium methosulfate (2b): Since this compound was hygroscopic, elemental analysis was carried out using the corresponding perchlorate salt. Colorless needles from acetonitrile-chloroform; mp 196°C (decomp.). Anal. Calcd for $C_{15}H_{15}ClN_2O_6$: C, 50.78; H, 4.27; N, 7.90. Found: C, 50.64; H, 4.08; N, 7.72. ^{1}H-NMR (DMSO-d_6) δ: 1.53 (t, 3H, *J*=7.1Hz), 3.37 (s, 3H), 4.27 (s, 3H), 4.67 (q, 2H, *J*=7.1Hz), 7.60-7.80 (m, 2H), 8.10-8.40 (m, 2H), 8.73 (s, 1H), 8.80 (s, 1H), 10.60 (s, 1H). ^{13}C-NMR (DMSO-d_6) δ: 13.86, 34.10, 52.71, 66.50, 112.26, 113.75, 126.85, 127.26, 127.39, 128.30, 128.75, 130.86, 130.99, 131.99, 147.12, 148.47.

1-Ethoxycarbonyl-3,5,6-trimethylbenzimidazolium perchlorate (2c): Colorless needles from methanol-ether; mp 168.5-169.5°C. Anal. Calcd for $C_{13}H_{17}ClN_2O_6$: C, 46.92; H, 5.15; N, 8.42. Found: C, 47.01; H, 5.13; N, 8.36. ^{1}H-NMR (MeOH-d_4) δ: 1.55 (t, 3H, *J*=7.1Hz), 2.51 (s, 6H), 4.18 (s, 3H), 4.78 (q, 2H, *J*=7.1Hz), 7.78 (s, 1H), 8.06 (s, 1H), 9.96 (s, 1H). ^{13}C-NMR (DMSO-d_6) δ: 13.80, 19.85, 20.13, 33.87, 66.48, 113.82, 115.45, 126.89, 130.50, 137.15, 138.57, 143.46, 147.02.

1-Ethoxycarbonyl-3-methyl-5-nitrobenzimidazolium tetrafluoroborate (2d): Colorless granules from acetonitril-ether; mp 195-196°C. Anal. Calcd for $C_{11}H_{12}BF_4N_3O_4$: C, 39.20; H, 3.59; N, 12.47. Found: C, 38.97; H, 3.47; N, 12.46. ^{1}H-NMR (MeOH-d_4) δ: 1.56 (t, 3H, *J*=7.0Hz), 4.28 (s, 3H), 4.68 (q, 2H, *J*=7.0Hz), 8.39-8.61 (m,3H), 8.88 (d, 1H, *J*=2.0Hz), 10.40 (s, 1H). ^{13}C-NMR (DMSO-d_6) δ: 13.79, 34.69, 67.23, 111.55, 117.22, 123.88, 132.08, 132.18, 146.10, 146.39, 148.36.

5,6-Dichloro-1-Ethoxycarbonyl-3-methyl-benzimidazolium tetrafluoroborate(2e): Colorless needles from acetonitrile-ether; mp 177-178°C. Anal. Calcd for $C_{11}H_{11}BCl_2F_4N_2O_2$: C, 36.60; H, 3.08; N, 7.76. Found: C, 36.86; H, 3.05; N, 7.67. ^{1}H-NMR (CD_3CN) δ: 1.51 (t, 3H, *J*=7.1Hz), 4.11 (s, 3H), 4.69 (q, 2H, *J*=7.1Hz), 8.22 (s, 1H), 8.44 (s, 1H), 9.62 (s, 1H). ^{13}C-NMR (MeOH-d_4) δ: 14.20, 35.12, 68.82, 117.16, 118.95, 129.65, 133.30, 133.73, 134.79, 147.21, 147.74.

1-Ethoxycarbonyl-3-methyl-2-phenylbenzimidazolium methosulfate (6a): This compound was prepared according to the method described for the synthesis of **2a** and **2b**. 54% yield from 2-phenyl benzimidazole. Since this compound was hygroscopic, elemental analysis was carried out using corresponding perchlorate salt. Colorless granules from methanol-ether; mp 260°C (decomp.). Anal. Calcd for $C_{17}H_{17}ClN_2O_6$: C, 53.61; H, 4.51; N, 7.36. Found: C, 53.81; H, 4.46; N, 7.32. ^{1}H-NMR (DMSO-d_6) δ: 1.04 (t, 3H, *J*=7.1Hz), 3.37 (s, 3H), 3.88 (s, 3H,), 4.32 (q, 2H, *J*=7.1Hz), 7.50-8.40 (m, 9H). ^{13}C-NMR (DMSO-d_6) δ: 13.26, 33.54, 53.09, 66.52, 114.31, 116.77, 123.27, 127.86, 128.87, 129.07, 129.58, 130.09, 130.39, 132.68, 147.17, 152.60.

1-Ethoxycarbonyl-3-methyl-2-(*p*-nitrophenyl)benzimidazoliumtetrafluoroborate (6b): This compound was prepared according to the method described for the synthesis of **2d** and **2e**. 65% yield from 2-(p-nitrophenyl) benzimidazole. Colorless needles from acetonitrile-ether; mp 198-199°C. Anal. Calcd for $C_{17}H_{16}BF_4N_3O_4$: C, 49.42; H, 3.91; N,10.17. Found: C, 49.79; H, 3.85; N, 10.12. ^{1}H-NMR (CD_3CN) δ: 1.16 (t, 3H, *J*=7.1Hz), 3.92 (s, 3H), 4.45 (q, 2H, *J*=7.1Hz), 7.80-8.60 (m, 8H). ^{13}C-NMR (DMSO-d_6) δ: 13.19, 33.49, 66.74, 114.33, 116.74, 123.77, 124.05, 127.96, 129.31, 129.38, 131.97, 132.02, 146.86, 149.82, 150.57.

1-Ethoxycarbonyl-3-methyl-2-(*p*-fluorophenyl)benzimidazolium tetrafluoroborate (6c): This compound was prepared according to the method described for the synthesis of **2d** and **2e**. 60% yield from 2-(p-fluorophenyl) benzimidazole. Colorless needles from acetonitrile-ether; mp 168.5-169.5°C. Anal. Calcd for $C_{17}H_{16}BF_5N_2O_2$: C, 52.87; H, 4.18; N,7.26. Found: C, 52.75; H, 4.01; N, 7.13. ^{1}H-NMR (CD_3CN) δ: 1.18 (t, 3H, *J*=7.1Hz), 3.85 (s, 3H), 4.44 (q, 2H, *J*=7.1Hz), 7.36-8.41 (m, 8H). ^{13}C-NMR (DMSO-d_6) δ: 13.16, 33.38, 66.40, 114.19, 115.98, 116.63, 119.47, 127.73, 128.97, 129.97, 131.77, 132.97, 133.06, 146.97, 151.75.

1-Ethoxycarbonyl-3-methyl-2-(*p*-methoxyphenyl)benzimidazolium perchlorate (6d): This compound was prepared according to the method described for the synthesis of **2c**. 87% yield from 2-(p-methoxyphenyl) benzimidazole. Colorless needles from methanol-ether; mp 131-133°C. Anal. Calcd for $C_{18}H_{19}ClN_2O_7$: C, 52.62; H, 4.67; N,6.82. Found: C, 52.44; H, 4.52; N, 6.67. ^{1}H-NMR (CD_3CN) δ: 1.20 (t, 3H, *J*=7.1Hz), 3.87(s, 3H), 3.93 (s, 3H), 4.36 (q, 2H, *J*=7.1Hz), 7.04-8.25 (m, 8H). ^{13}C-NMR (MeOH-d_4) δ: 13.77, 33.97, 56.35, 67.82, 114.62, 115.54, 117.88, 118.32, 129.04, 129.95, 130.04, 133.15, 133.37, 148.67, 154.27, 164.73.

1,1',3,3'-Tetramethyl-2,2'-bibenzimidazolium dimethosulfate (8): 1,1'-Dimethyl-2,2'-bibenzimidazole [9] (0.8 mmol) was dissolved in dimethyl sulfate (8.0 mmol), and the solution was heated at 120 °C for 7h. Then the reaction mixture was washed three times with ether (20 ml) by decantation to give **8** (0.78mmol). Since this compound was hygroscopic, elemental analysis was carried out using the corresponding perchlorate salt. Colorless prisms from H_2O-ethanol; mp >300 °C. Anal. Calcd for $C_{18}H_{20}Cl_2N_4O_8$: C, 44.00; H, 4.11; N, 11.41. Found: C, 44.09; H, 4.09; N, 11.34. ^{1}H-NMR (MeOH-d_4) δ: 3.52 (s, 6H), 4.27 (s, 12H), 7.78-8.16 (m, 8H). ^{13}C-NMR (MeOH-d_4) δ: 34.78, 55.00, 115.56, 130.82, 131.70, 135.21.

General Procedure for the Reaction of 1-Ethoxycarbonyl-3-methylbenzimidazolium Salts 2a-2e with Superoxide

Method A: The electrolysis was carried out with Nikko Keisoku potentiogalvanostat NPGS-2501 using platinum electrode. The electric current was measured with Nikko Keisoku digital coulomb meter, NDCM-4. In the cathode chamber of H cell containing 0.1 M tetraethylammonium perchlorate solution of acetonitrile (40 ml), a stream of oxygen was bubbled through a gas dispersion tube, and the potential was set and maintained at -0.87 V vs. SCE until 39Q of electric current was consumed. After oxygen bubbling was changed for argon bubbling, compound **2** (0.2 mmol) was added and the mixture was allowed to stand at room temperature for 3h under argon atmosphere. Then the reaction solvent in the cathode chamber was evaporated and the residue was dissolved in ether to remove insoluble supporting electrolyte. The residual solution was evaporated, and the residue was chromatographed on alumina (CH_2Cl_2) to give the products.
Method B: In the acetonitrile solution (6 ml) of the compound **2** (0.2 mmol), KO_2 (0.4 mmol) and 18-crown-6 (0.1 mmol) were added and the mixture was allowed to stand at room temperature for 3 h. Then ether was added to remove insoluble solid, and the filtered ether solution was evaporated off to leave the residue, which was chromatographed on alumina (CH_2Cl_2) to give the products.

***N*-Ethoxycarbonyl-*N'*-formyl-*N'*-methyl-1,2-phenylenediamine (3a)**: This compound was obtained as a mixture of two confomational isomers, thus the major and minor isomers were represented by A, and B, respectively. Colorless granules from hexane-ether; mp 108-109.5 °C. Anal. Calcd for $C_{11}H_{14}N_2O_3$: C, 59.45; H, 6.35; N, 12.60. Found: C, 59.62; H, 6.49; N, 12.37. ^{1}H-NMR ($CDCl_3$) δ: 1.32 (t, 3H, *J*=7.1Hz (A/B)), 3.16 (s, 3H (A)), 3.32 (s, 3H (B)), 4.16 (q, 2H, *J*=7.1Hz (B)), 4.19 (q, 2H, *J*=7.1Hz (A)), 6.58 (bs,1H (A/B)), 7.00-7.40 (m, 4H (A/B)), 8.04 (s, 1H (A)), 8.22(s, 1H (B)). ^{13}C-NMR ($CDCl_3$) δ: 14.40(A), 14.46(B), 37.59(B), 32.98(A), 61.32(B), 61.66(A), 120.97, 124.01, 125.00, 125.66, 128.18, 128.59, 129.60, 130.76, 133.75, 135.03, 153.36(A), 154.07(B), 162.53(B), 163.56(A). IR (KBr) 1720 (NHCOO), 1670 (NCHO) cm^{-1}. MS (*m/z*) 222 (M^+), 205, 193, 149(M^+- CO_2Et).

***N*-Ethoxycarbonyl-*N'*-formyl-*N'*-methyl-2,3-diaminonaphthalene (3b)**: This compound was obtained as a mixture of two confomational isomers, thus the major and minor isomers were represented by A, B, respectively. Yellow needles from ethyl acetate; mp 158.5-159.5 °C . Anal. Calcd for $C_{15}H_{16}N_2O_3$: C, 66.16; H, 5.92; N, 10.29. Found: C, 65.99; H, 5.82; N, 10.18. ^{1}H-NMR ($CDCl_3$) δ: 1.35 (t, 3H, *J*=7.1Hz (A/B)), 3.28 (s, 3H (A)), 3.43 (s, 3H (B)), 4.26 (q, 2H, *J*=7.1Hz (B)), 4.28 (q, 2H, *J*=7.1Hz (A)), 6.82 (bs, 1H (A)), 6.92 (bs, 1H (B)), 7.42-7.52 (m, 2H, (A/B)), 7.62 (s, 1H (A)), 7.65 (s, 1H (B)), 7.75-7.85 (m, 2H (A/B)), 8.28 (s, 1H (A)), 8.38 (s, 1H (B)), 8.48 (s, 1H (B)), 8.57 (s, 1H (A)). ^{13}C-NMR ($CDCl_3$) δ: 14.45(A), 14.51(B), 33.45(A), 38.02(B), 61.43(B), 61.76(A)), 117.72, 125.72, 127.33, 127.39, 127.46, 127.58, 129.53, 130.77, 132.12, 133.69, 153.45, 163.01(B), 163.54(A). IR (KBr) 1720 (NHCOO), 1660 (NCHO) cm^{-1}. MS (*m/z*) 272 (M^+), 244, 198.

***N*-Ethoxycarbonyl-*N'*-formyl-*N'*-methyl-4,5-dimethyl-1,2-phenylenediamine (3c)**: This compound was obtained as a mixture of two conformational isomers A and B. Pale yellow oil. ^{1}H-NMR ($CDCl_3$) δ: 1.29 (t, 3H, *J*=7.1Hz (B)), 1.31 (t, 3H, *J*=7.1Hz (A)), 2.23 (s, 3H (A/B)), 2.28 (s, 3H (A/B)), 3.17 (s, 3H (A)), 3.31 (s, 3H (B)), 4.18 (q, 2H, J=7.1Hz (B)), 4.22 (q, 2H, *J*=7.1Hz (A)), 6.44 (bs, 1H

(A)), 6.64 (bs, 1H (B)), 6.89 (s, 1H (A)), 6.91(s, 1H (B)), 7.57 (s, 1H (B)), 7.84 (s, 1H (A)), 8.12 (s, 1H (A)), 8.28 (s, 1H (B)). ^{13}C-NMR ($CDCl_3$) δ: 14.45(A), 14.52(B), 19.04(A), 19.29(B), 19.62(B),

19.78(A), 33.08(A), 37.60(B), 61.21(B), 61.58(A), 122.34, 126.26, 128.90, 132.19, 132.82, 138.33, 153.53, 162.46(B), 163.65(A). IR (KBr) 1735 (NHCOO), 1680 (NCHO) cm^{-1}. MS (*m/z*) 250 (M^+), 233, 177 (M^+-CO_2Et). Exact MS *m/z* (M^+); Calcd for $C_{13}H_{18}N_2O_3$: 250.132. Found: 250.133.

***N*-Ethoxycarbonyl-*N'*-formyl-*N'*-methyl-4-nitro-1,2-phenylenediamine (3d)**: This compound was obtained as a mixture of two conformational isomers A and B. Pale yellow granules from ether-hexane ; mp 143-144 °C . Anal. Calcd for $C_{11}H_{13}N_3O_5$: C, 49.43; H, 4.90; N, 15.73. Found: C, 49.18; H, 4.84; N, 15.90. ^{1}H-NMR ($CDCl_3$) δ: 1.33 (t, 3H, *J*=7.1Hz (B)), 1.35 (t, *J*=7.1Hz (A)), 3.24 (s, 3H (A)), 3.41(s, 3H (B)), 4.26 (q, 2H, *J*=7.1Hz (B)), 4.28 (q, 2H, *J*=7.1Hz (A)), 7.08(bs, 1H (A/B)), 8.05-8.52 (m, 4H (A/B)). ^{13}C-NMR ($CDCl_3$) δ: 14.32(A), 14.36(B), 33.09(A), 37.38(B), 62.16(B), 62.54(A), 119.30, 121.51, 122.32, 124.25, 125.44, 129.55, 129.75, 140.36, 141.58, 142.54, 143.20, 152.55(A), 153.05(B), 162.83(B), 162.97(A). IR (KBr) 1740 (NHCOO), 1635 (NCHO), 1515 (NO_2) 1345 (NO_2) cm^{-1}. MS (*m/z*) 267 (M^+), 250, 239, 194 (M^+- CO_2Et).

***N*-Ethoxycarbonyl-*N'*-formyl-*N'*-methyl-4,5-dichloro-1,2-phenylenediamine (3e)**: This compound was obtained as a mixture of two conformational isomers A and B. Colorless granules from ethylacetate-ether; mp 152-153 °C. Anal. Calcd for $C_{11}H_{12}Cl_2N_2O_3$: C, 45.38; H, 4.16; N, 9.62. Found: C, 45.15; H, 4.02; N, 9.40. ^{1}H-NMR ($CDCl_3$) δ: 1.32 (t, 3H, *J*=7.1Hz (A/B)), 3.17 (s, 3H (A)), 3.33(s, 3H (B)), 4.19 (q, 2H, *J*=7.1Hz (B)), 4.23 (q, 2H, *J*=7.1Hz (A)), 6.88 (bs, 1H (B)), 7.00(bs, 1H (A)), 7.24 (s, 1H (A/B)), 8.11 (s, 1H,(A/B)), 8.24 (s, 1H (B)), 8.34 (s, 1H (A)). ^{13}C-NMR ($CDCl_3$) δ: 14.35(A), 14.42(B), 33.05(A) 37.44(B), 61.81(B), 62.20(A) 121.80, 126.76, 127.27, 129.42, 129.62, 133.54, 133.91, 134.73, 152.81(A), 153.53(B), 162.56(B), 162.99(A). IR (KBr) 1735 (NHCOO), 1680 (NCHO) cm^{-1}. MS (*m/z*) 267 (M^+), 250, 239, 194 (M^+- CO_2Et).

The Reaction of 2-Aryl-1-Ethoxycarbonyl-3-methylbenzimidazolium salts with superoxide

Reaction procedure was according to that discribed for the reaction of benzimidazolium salts **2a-2e** with superoxide.

***N*-Benzoyl-*N'*-ethoxycarbonyl-*N*-methyl-1,2-phenylenediamine (7a)**: Colorless granules from ethyl acetate-ether; mp 140.5-141.5 °C. Anal. Calcd for $C_{17}H_{18}N_2O_3$: C, 68.44; H, 6.08; N, 9.39. Found: C, 68.03; H,5.93; N, 9.33. ^{1}H-NMR ($CDCl_3$) δ: 1.34 (t, 3H, *J*=7.1Hz), 3.36 (s, 3H), 4.25 (q, 2H, *J*=7.1Hz), 6.82-7.30 (m, 9H), 8.01 (br, 1H). ^{13}C-NMR ($CDCl_3$) δ 14.49, 37.27, 61.65, 120.17, 123.69, 126.57, 127.78, 127.84, 128.44, 128.74, 128.98, 130.24, 134.05, 153.32, 171.83. IR (KBr) 1725 (NHCOO), 1630 (MeNCO) cm^{-1}. MS (*m/z*) 298(M^+), 148, 105.

***N*-(*p*-Nitrobenzoyl)-*N'*-ethoxycarbonyl-*N*-methyl-1,2-phenylenediamine (7b)**: Colorless granules from ethyl acetate-ether; mp 188-189 °C. Anal. Calcd for $C_{17}H_{17}N_3O_5$: C, 59.47; H, 4.99; N, 12.24. Found: C, 59.60; H,4.95; N, 12.22. ^{1}H-NMR ($CDCl_3$) δ: 1.39 (t, 3H, *J*=7.1Hz), 3.33 (s, 3H), 4.22 (q, 2H, *J*=7.1Hz), 6.70-8.10 (m, 9H). ^{13}C-NMR ($CDCl_3$) δ: 14.48, 37.20, 61.98, 120.78, 123.08,

124.05, 128.37, 128.72, 129.48, 132.39, 134.11, 141.00, 148.34, 153.14, 169.59. IR (KBr) 1740 (NHCOO), 1635 (MeNCO), 1515 (NO_2), 1345 (NO_2) cm^{-1}. MS (*m/z*) 343 (M^+), 221, 193.

***N*-(*p*-Fluorobenzoyl)-*N'*-ethoxycarbonyl-*N*-methyl-1,2-phenylenediamine (7c)**: Colorless needles from ethyl acetate; mp 169-170 °C. Anal. Calcd for $C_{17}H_{17}FN_2O_3$: C, 64.54; H, 5.43; N, 8.86. Found: C, 64.56; H,5.48; N, 8.90. ^{1}H-NMR ($CDCl_3$) δ: 1.35 (t, 3H, *J*=7.1Hz), 3.34 (s, 3H), 4.25 (q, 2H, *J*=7.1Hz), 6.82-6.95 (m, 5H), 7.20-7.35 (m, 3H), 8.06 (br, 1H). ^{13}C-NMR ($CDCl_3$) δ: 14.48, 37.41, 61.71, 114.87, 115.10, 120.27, 123.84, 128.34, 128.90, 130.33, 130.87, 134.02, 162.31, 164.82, 170.68. IR (KBr) 1735 (NHCOO), 1640 (MeNCO) cm^{-1}. MS (*m/z*) 316 (M^+), 148, 122.

***N*-(*p*-Methoxybenzoyl)-*N'*-ethoxycarbonyl-*N*-methyl-1,2-phenylenediamine (7d)**: Colorless granules from ethyl acetate; mp 176-177 °C. Anal. Calcd for $C_{18}H_{20}N_2O_4$: C, 65.84; H, 6.14; N, 8.53. Found: C, 65.65; H,6.18; N, 8.34. ^{1}H-NMR ($CDCl_3$) δ: 1.32 (t, 3H, *J*=7.1Hz), 3.32 (s, 3H), 3.74 (s, 3H), 4.20 (q, 2H, *J*=7.1Hz), 6.56-7.24 (m, 8H), 8.00 (br, 1H). ^{13}C-NMR ($CDCl_3$) δ: 14.48, 30.91, 55.18, 61.63, 113.16, 113.73, 120.11, 123.79, 126.83, 128.56, 128.61, 130.08, 134.00, 153.34, 161.10, 171.35. IR (KBr) 1715 (NHCOO), 1630 (MeNCO) cm^{-1}. MS (*m/z*) 328 (M^+), 135.

Counter cation effects on the reactivity of superoxide with compound 2d

Method C: according to the procedure of method A, 0.2 mmol of superoxide were generated in a cathode chamber of H cell. After oxygen bubbling was changed for argon bubbling, $KClO_4$ (0.1 mmol) was added into the cathode chamber and the mixture was stirred for 5 min. Conpound **2d** (0.1 mmol) was then added and stirring was continued for 2h. The reaction solvent was evaporated and the residue was dissolved in ether to remove insoluble supporting electrolyte. The residual solution was evaporated to give a mixture of compound **3d** and **4d**. Yields and products ratio of **3d** and **4d** were determined by ^{1}H NMR using mesitylene as an internal standard. Method D: to the acetonitrile solution of Et_4NClO_4 (2.0 mmol) and 18-crown-6 (0.1 mmol)was added KO_2 (0.2 mmol), and the mixture was stirred for 5min. Compound **2d** was then added and stirring was continued for 2h. Ether was added to remove insoluble solid, and the filtered ether solution was evaporated off to give a mixture of compound **3d** and **4d**. Yields and products ratio of **3d** and **4d** were determined by ^{1}H NMR using mesitylene as an internal standard. Method E and F: according to the procedure of method C and $NaClO_4$ or $LiClO_4$ was used as additive instead of $KClO_4$.

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