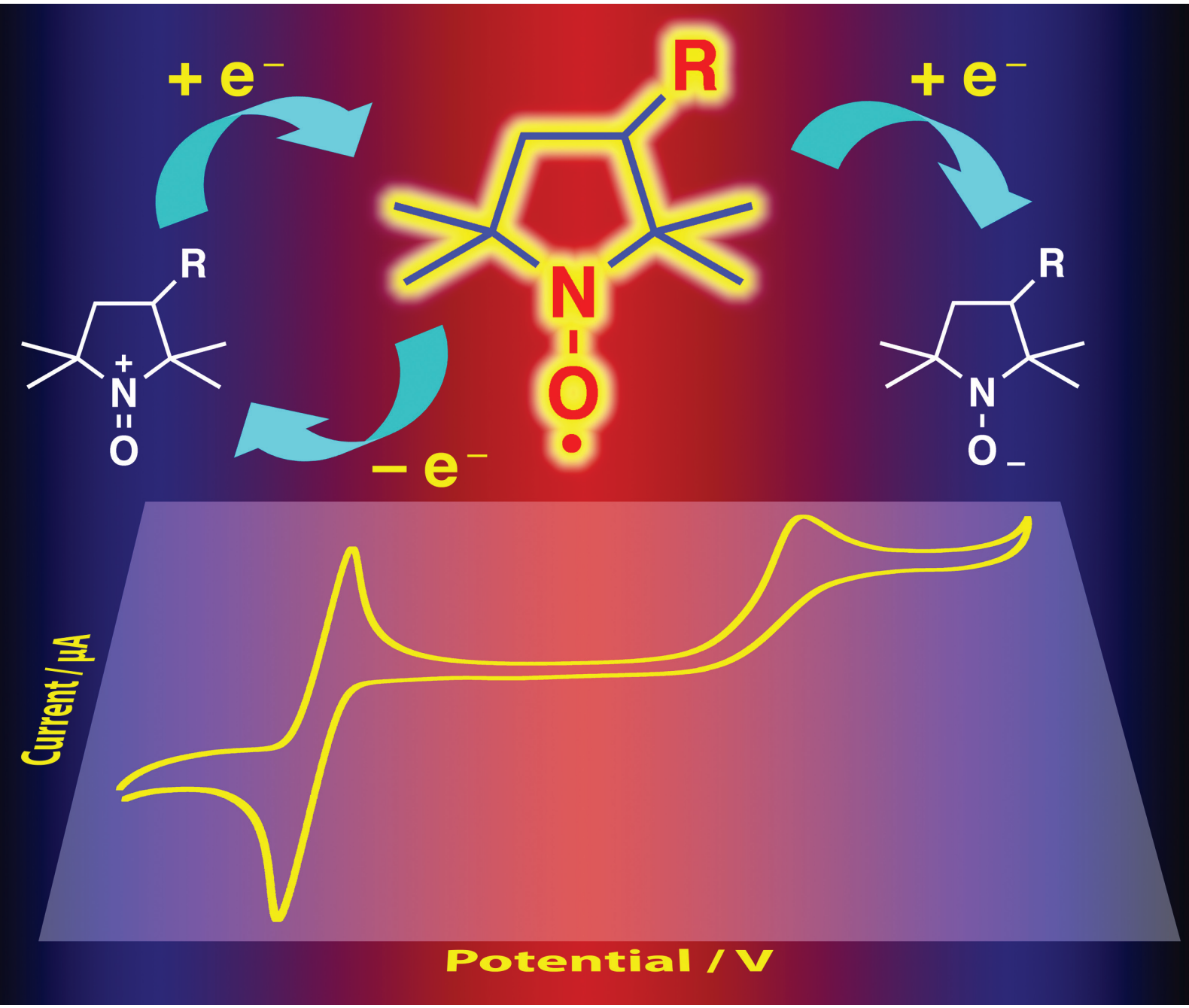
Organic & Biomolecular Chemistry

www.rsc.org/obc

Volume 5 | Number 24 | 21 December 2007 | Pages 3877–4024



ISSN 1477-0520

FULL PAPER
Kazunori Anzai *et al.*
Nitroxyl radicals: electrochemical redox behaviour and structure–activity relationships

EMERGING AREA
Michael Kirsch and Hans-Gert Korth
Generation, basic chemistry, and detection of *N*-nitrosotryptophan derivatives

RSC Publishing

Nitroxyl radicals: electrochemical redox behaviour and structure–activity relationships†

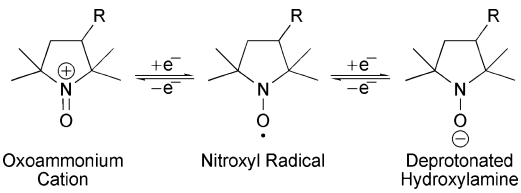
Sushma Manda,[a] Ikuo Nakanishi,[a,b] Kei Ohkubo,[b] Haruko Yakumaru,[c] Ken-ichiro Matsumoto,[a] Toshihiko Ozawa,[a,d] Nobuo Ikota,[e] Shunichi Fukuzumi[b] and Kazunori Anzai*[a]

Received 25th September 2007, Accepted 11th October 2007
First published as an Advance Article on the web 31st October 2007
DOI: 10.1039/b714765a

Comparative study of electrochemical redox behaviour of five different nitroxyl radicals leads to the direct correlation between one-electron redox potentials and group electronegativity of the β-substituent on the ring. β-Substituents with an electron-donating effect caused a negative shift in the one-electron oxidation and one-electron reduction potentials of the nitroxyl radicals. In a similar aspect, β-substituents with an electron-withdrawing effect behaved oppositely.

Introduction

Redox behaviour of nitroxyl radicals (NRs) has attracted great attention because of their use as contrast agents for magnetic resonance imaging (MRI),[1,2] superoxide dismutase (SOD) mimics,[3] spin labels,[4] and antioxidants.[5,6] Electron paramagnetic resonance (EPR)-measured rates of NR reduction have been shown to provide information on tissue redox status[7–9] and reactive oxygen species (ROS) generation *in vivo*.[9,10] Oxidation of hydroxylamines (HAs), reduced species of NRs, to NRs has also been used for *in vivo* EPR detection of ROS.[11–14] Furthermore, oxidation of NRs leads to scavenging of ROS[15] and is also responsible for the SOD-mimic activity of cyclic nitroxyls.[16] However, the highly oxidizing oxoammonium cation is also responsible for the pro-oxidative activity and potential adverse effects of the NRs.[17] Redox behaviour of NRs has been studied chemically[18,19] as well as electrochemically.[20] Besides, the structure of NRs has been found to be a controlling factor for the redox behaviour of NRs *in vivo*[21–25] as well as *in vitro* studies.[26–30] Therefore, a possible structure–activity relationship and any other factors affecting the redox behaviour of NRs become important considerations. Recently, we have reported the stereochemical and solvent effects on electrochemical one-electron oxidation of NRs.[31] We report herein the electrochemical redox behaviour of five nitroxyl radicals (Scheme 1), 3-hydroxymethyl-2,2,5,5-tetramethylpyrrolidine-*N*-oxyl (HM-PROXYL; **NR 1**), 3-carbamoyl-2,2,5,5-tetramethylpyrrolidine-*N*-oxyl (CM-PROXYL; **NR 2**), 3-carboxyl-2,2,5,5-tetramethylpyrrolidine-*N*-oxyl (carboxy-PROXYL; **NR 3**), 3-methoxycarbonyl-2,2,5,5-tetramethylpyrrolidine-*N*-oxyl (MC-PROXYL; **NR 4**), and 3-cyano-2,2,5,5-tetramethylpyrrolidine-*N*-oxyl (cyano-PROXYL; **NR 5**), to evaluate the possible correlation between their structure and redox behaviour in two different media.



NR 1 (R = CH_2OH), **NR 2** (R = $CONH_2$), **NR 3** (R = COOH)
NR 4 (R = COOMe), **NR 5** (R = CN)

Scheme 1 One-electron oxidation and reduction of cyclic nitroxyl radicals.

Results and discussion

The electrochemical one-electron reduction and one-electron oxidation potentials of the same series of NRs having β-blocking groups different from hydrogen were measured in two different solvents by cyclic voltammetry and second-harmonic alternating current voltammetry.[32–37] Cyclic voltammograms (CVs) (see ESI†) were explored to assess the reversible nature of one-electron redox processes of NRs. Representative CVs of NRs in methanol (MeOH, 0.1 mol dm^{-3} Bu_4NClO_4) and phosphate buffer (PB, pH 7.4, 0.1 mol dm^{-3}) at 298 K and with a scan rate of 0.1 V s^{-1} are shown in Fig. 1 and 2 respectively.

The intense reversible peaks [$E_{pa} - E_{pc}$ (ΔE_p) = ±70 mV] in the positive range were assigned to the one-electron oxidation potential of NRs.[38] The CVs also show slightly less intense irreversible responses (either $\Delta E_p > 70$ mV or absence of corresponding oxidation waves in opposite cycle) in the negative potential range which are assigned to the one-electron reduction of NRs.[38] Although the reduction process was found to be irreversible in both solvents, the corresponding anodic wave appeared in PB, which indicates

[a]*Radiation Modifier Team, Heavy-Ion Radiobiology Research Group, Research Center for Charged Particle Therapy, National Institute of Radiological Sciences (NIRS), Inage-ku, Chiba 263-8555, Japan. E-mail: anzai@nirs.go.jp; Fax: +81-43-255-6819; Tel: +81-43-206-3125*
[b]*Department of Material and Life Science, Graduate School of Engineering, Osaka University, SORST, Japan Science and Technology Agency (JST), Suita, Osaka 565-0871, Japan*
[c]*Mechanism Research Team, Medical Treatment for High Dose Exposure Research Group, Research Center for Radiation Emergency Medicine, National Institute of Radiological Sciences (NIRS), Inage-ku, Chiba 263-8555, Japan*
[d]*Yokohama College of Pharmacy, Yokohama 245-0066, Japan*
[e]*School of Pharmacy, Shujitsu University, Okayama 703-8516, Japan*

† Electronic supplementary information (ESI) available: Individual cyclic voltammograms of **NR 1**–**5**, both in MeOH and PB. See DOI: 10.1039/b714765a

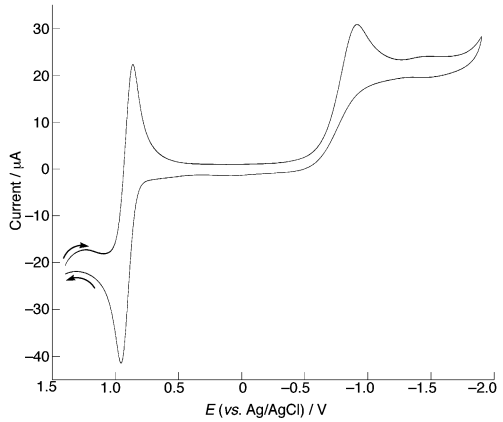


Fig. 1 Cyclic voltammogram of NRs (2.0×10^{-3} mol dm^{-3}) in MeOH (0.1 mol dm^{-3} Bu_4NClO_4) at 298 K. Scan rate: 0.1 V s^{-1}.

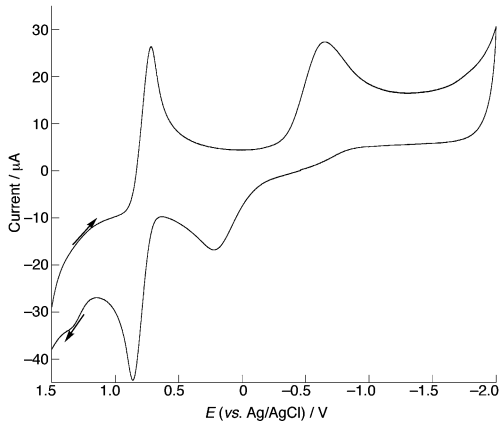


Fig. 2 Cyclic voltammogram of NRs (2.0×10^{-3} mol dm^{-3}) in PB (0.1 mol dm^{-3}, pH 7.4) at 298 K. Scan rate: 0.1 V s^{-1}.

the effect of solvent on the reversibility of the reduction process. Exact values of one-electron oxidation and reduction potentials were obtained by exploring the second-harmonic alternating current voltammograms (SHACVs) (Figs. 3 and 4). The values of one-electron oxidation potentials of NRs in both MeOH and PB were

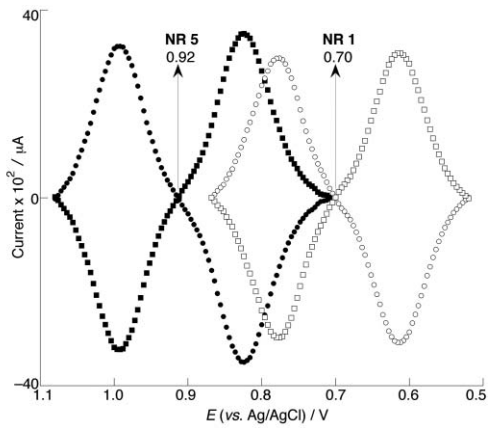


Fig. 3 Second-harmonic alternating current voltammograms showing one-electron oxidation potentials (*vs.* Ag/AgCl) of **NR 1** (○,□) and **NR 5** (●,■) (2.0×10^{-3} mol dm^{-3}) in MeOH (0.1 mol dm^{-3} Bu_4NClO_4) at 298 K. Scan rate: 4 mV s^{-1}; amplitude: 25 mV.

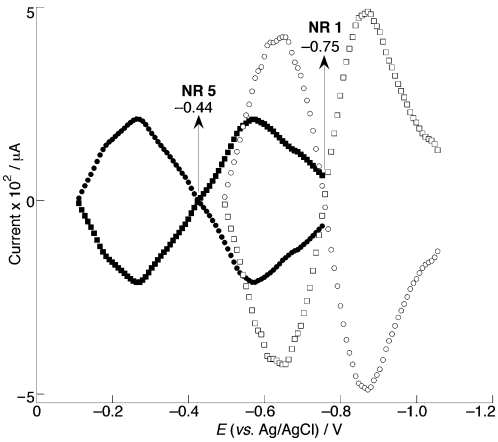


Fig. 4 Second-harmonic alternating current voltammograms showing one-electron reduction potentials (*vs.* Ag/AgCl) of **NR 1** (○,□) and **NR 5** (●,■) (2.0×10^{-3} mol dm^{-3}) in MeOH (0.1 mol dm^{-3} Bu_4NClO_4) at 298 K. Scan rate: 4 mV s^{-1}; amplitude: 25 mV.

compared with the one-electron oxidation potentials calculated using peak potentials from the reversible cyclic voltammetric response of nitroxyl radical–oxoammonium cation redox couples. The relative one-electron oxidation potentials obtained *via* two different approaches showed good consistency (Table 1). One-electron redox potentials of NRs, obtained by SHACV, were used in order to characterize the change in redox behaviour associated with substitutional change on the pyrrole ring. For all NRs in this study we assign the first one-electron oxidation potential and the first one-electron reduction potential for the formation of the corresponding oxoammonium cations and deprotonated hydroxylamines, respectively (Scheme 1).

The redox asymmetry and the reorganization energy of the examined NRs are of similar magnitude except there is a small change in the electronic environment of the molecule. Therefore, the redox nature of NRs can be subjected to alteration by substitutional changes in the pyrrole ring of nitroxyl radicals. Oxidation potentials were observed between the potential range from 0.70 to 0.92 and 0.61 to 0.80 V *vs.* Ag/AgCl in MeOH (0.1 mol dm^{-3} Bu_4NClO_4) and PB (pH 7.4, 0.1 mol dm^{-3}), respectively, varied with the substitutional change at the β-position on the ring and the solvent used (Table 1). Reduction potentials were found between the potential range from −0.75 to −0.44 and −0.79 to −0.50 V in MeOH and PB, respectively (Table 1), again associated

Table 1 One-electron oxidation ($E^a_{1/2}$) and reduction ($E^c_{1/2}$) potentials (*vs.* Ag/AgCl) of nitroxyl radicals (**NR 1–5**) in MeOH (0.1 mol dm^{-3} Bu_4NClO_4) and PB (0.1 mol dm^{-3}, pH 7.4) determined by SHACV at 298 K

	$E^a_{1/2}$/V		$E^c_{1/2}$/V	
Nitroxyl radical	PB	MeOH	PB	MeOH
NR 1	0.61 (0.60)	0.70 (0.70)	−0.79	−0.75
NR 2	0.64 (0.63)	0.76 (0.76)	−0.78	−0.69
NR 3	0.68 (0.68)	0.78 (0.78)	—	—
NR 4	0.69 (0.68)	0.79 (0.79)	−0.68	−0.65
NR 5	0.80 (0.79)	0.92 (0.95)	−0.50	−0.44

Potential values shown in parentheses denote one-electron oxidation potentials calculated using peak potentials from cyclic voltammograms.

with the substitutional change at the β-position on the ring and the solvent used. It is important to note that the substitutional change in the pyrrole ring, the presence of either an electron-withdrawing group (EWG) or an electron-donating group (EDG), has a dramatic impact on the redox behaviour of NRs, as the corresponding redox potentials are shifted positively or negatively by hundreds of millivolts. Therefore, group electronegativities of β-substituents were calculated to check their possible correlation with the one-electron redox potential shift observed for **NR 1–5**. Electronegativity values for the substituent group were calculated using the standard Pauling electronegativity values in the formula shown in eqn (1),

$$E_g = [V_c E_c + \Sigma N_i E_i] N^{-1} \quad (1)$$

where E_g is group electronegativity, V_c and E_c are the valence of the central atom and its atomic electronegativity value, respectively, N_i and E_i are the number of the bond of atomic or group i connecting to the central atom and the atomic or group electronegativity of i (atom or group) respectively and N is the sum of the valence of the central atom and the whole number of atom(s) and group(s) connecting to the central atom. Interestingly, a linear correlation ($r = 0.99$) was obtained on plotting the electronegativity values *vs.* the one-electron oxidation and reduction potentials of NRs both in PB and MeOH solvents (Fig. 5 and 6).

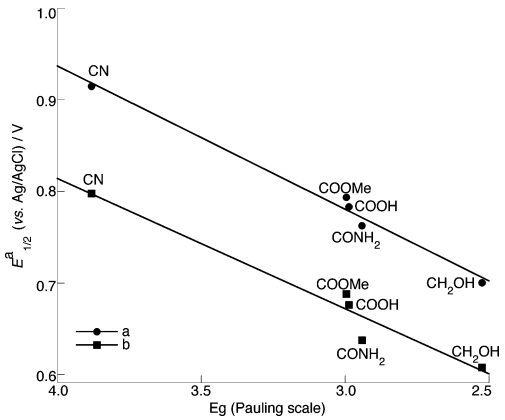


Fig. 5 Plots of Pauling electronegativity (E_g) *vs.* electrochemical one–electron oxidation ($E^a_{1/2}$) potentials. $E^a_{1/2}$ (*vs.* Ag/AgCl) of **NR 1–5** (2.0×10^{-3} mol dm^{-3}) in (a) MeOH (0.1 mol dm^{-3} Bu_4NClO_4), (b) PB (0.1 mol dm^{-3}, pH 7.4) obtained by SHACV at 298 K. Scan rate: 4 mV s^{-1}; amplitude: 25 mV.

NR 1, having the strongest EDG, and **NR 5**, having the strongest EWG, have been chosen for further explanation. The oxidation of **NR 1** was more favorable than that of **NR 5** as evidenced by the fact that the **NR 1** oxidation waves appeared at 0.70 and 0.61 V in MeOH and PB, respectively, which are more negative than those for **NR 5**, *i.e.* 0.92 and 0.80 V in MeOH and PB, respectively. The comparatively negative one-electron oxidation potential of **NR 1** is probably due to the better compensation of electron deficiency by the electron-donating nature of the hydroxymethyl group. **NR 5** gives rise to the most positive one-electron oxidation potential, followed by **NR 4**, **NR 3**, **NR 2** and **NR 1**. This trend shows harmony with the group electronegativity of the substituents present in the pyrrole ring of **NR 1–5**.

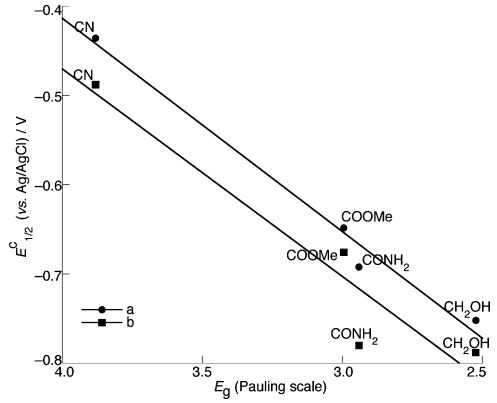


Fig. 6 Plots of Pauling electronegativity (E_g) *vs.* electrochemical one–electron reduction ($E^c_{1/2}$) potentials. $E^c_{1/2}$ (*vs.* Ag/AgCl) of **NR 1–5** (2.0×10^{-3} mol dm^{-3}) in (a) MeOH (0.1 mol dm^{-3} Bu_4NClO_4), (b) PB (0.1 mol dm^{-3}, pH 7.4) obtained by SHACV at 298 K. Scan rate: 4 mV s^{-1}; amplitude: 25 mV.

The one-electron reduction potentials also seem to be correlated with the substituent present on the ring. **NR 5**, with an EWG, is more susceptible to reduction than **NR 1**, with an EDG, which is evidenced by the fact that the **NR 5** reduction wave appeared at −0.44 and −0.49 in MeOH and PB respectively, which are relatively positive compared to those for **NR 1**, *i.e.* −0.75 and −0.79 V in MeOH and PB, respectively. There are negative shifts of one-electron reduction potential by magnitudes of 310 mV in MeOH and 300 mV in PB when a β-substituent cyano group is replaced by a hydroxymethyl group. This shift is an indication of a high degree of electron deficiency at the nitroxyl moiety caused by the electron-withdrawing nature of the cyano group, the β-substituent in **NR 5**. Consequently, there is an enhancement in the electrophilic nature of the electron deficient NRs at the expense of a decrease in their radical character. However, there is a decrease in electrophilic nature of the NRs by the presence of an EDG in the ring. The increasing order of the one-electron reduction potentials in the negative direction was obtained as **NR 5** < **NR 4** < **NR 2** < **NR 1**. Here again the harmony with the electronic nature of the substituent remained the same as observed for the one-electron oxidation potential.

Another interesting finding is that the one-electron oxidation or reduction potentials of the examined NRs were always negative in PB as compared to those in MeOH. Potential shift with varying of the solvent can be explained by the better solvation of the localized charge of polar species in the polar solvents. Finally, from the cyclic voltammetric and second-harmonic alternating current voltammetric analysis of five different NRs, the following information can be extracted: (a) the one-electron reduction and oxidation potentials are sensitive to the nature of the substituent at the β-position to nitrogen in the ring. Much more positive reduction and oxidation potentials in the presence of an EWG are indicative of the notion that the electron-withdrawing effect is strong enough to make the nitroxyl moiety more electrophilic. This fact may also be explained in terms of the comparatively more and less favorable electronic environment of NRs, with respect to the corresponding oxoammonium cation and deprotonated hydroxylamine, respectively, to stabilize the electron deficiency due to the presence of an EWG in the ring; (b) the oxidation

potential is influenced by the nature of the solvent. Thus, increased polarity of the solvent results in the negative shift in both reduction and oxidation potentials. This fact may be explained in terms of relative stabilization of the oxoammonium cation and deprotonated hydroxylamine in the polar solvent as we have reported previously.[31]

Experimental

CM-PROXYL (**NR 2**) and cyano-PROXYL (**NR 5**) were purchased from Sigma. Carboxy-PROXYL (**NR 3**) was purchased from Tokyo Chemical Industry Co. Ltd., Japan. HM-PROXYL (**NR 1**) was synthesized from carboxy-PROXYL and diazomethane.[21] MC-PROXYL (**NR 4**) was synthesized by reduction of carboxy-PROXYL with $LiAlH_4$ in THF.[21] Methanol (MeOH) were purchased from Nacalai Tesque, Inc., Japan and used as received. Phosphate buffer (PB) (pH 7.4; 0.5 mol dm^{-3}) was prepared in stock by dissolving 78.01 g sodium dihydrogen phosphate dihydrate ($NaH_2PO_4{\cdot}2H_2O$) in 1000 mL of water and pH was adjusted using 60% phosphoric acid (H_3PO_4). Finally the desired concentration (0.1 mol dm^{-3}) was obtained by dilution of stock solution. Tetrabutylammonium perchlorate (Bu_4NClO_4), used as a supporting electrolyte, was purchased from Tokyo Chemical Industry Co. Ltd., Japan and recrystallized from ethanol and dried under vacuum at 313 K prior to use. Solution concentrations for cyclic and second-harmonic alternating current voltammetric analysis were 2.0×10^{-3} mol dm^{-3} for all the nitroxyl radicals. Millipore Milli-Q water was used in all the experiments.

CVs and SHACVs were recorded with a conventional three electrode CH model ALS 630A electrochemical analyzer with glassy carbon disk working electrode, platinum wire counter electrode and Ag/AgCl reference electrode. Bu_4NClO_4 was used as a supporting electrolyte in the case of MeOH. The working electrode was polished with BAS polishing alumina suspension and a polishing cloth and rinsed with Millipore Milli-Q water followed by MeOH prior to each measurement. The electrode was then washed thoroughly with water, dried and cycled several times in the range of 1.5 to −1.9 V in order to assure the absence of a voltammetric signal due to the supporting electrolyte. All electrochemical measurements were performed at 298 K. In order to minimize the effect of molecular oxygen on the electrochemical behaviour of these radicals, the inert atmosphere in the electrochemical cell was maintained throughout the experiment by bubbling argon into the solution before the experiment and having a continuous argon flow over the solution during the experiment.

Conclusion

The modulation of the redox behaviour of NRs could be achieved by molecular engineering as evidenced by the linear relationship between Pauling electronegativity and redox potentials of the NRs with varied substitution at the β-position in the ring. The one-electron oxidation and reduction processes showed an opposite trend of potential shift with respect to the nature of substituent in the ring and this trend remains similar in both solvents, PB and MeOH. In a broad aspect, the better understanding of the electronic influence of a substituent which is able to alter the redox potentials, and hence the electrophilicity of the host compound, would help to design new compounds with controlled chemical as well as biological activity. This study would also be useful when the redox behaviour of NRs is explored *in vivo* as well as in *in vitro* studies.

Acknowledgements

This work was partially supported by Grant-in-Aid for Young Scientist (B) (nos. 19790043 and 19750034) (I.N. and K.O., respectively) from the Ministry of Education, Culture, Sports, Science and Technology, Japan.

Notes and references

1 K. Matsumoto, F. Hyodo, A. Matsumoto, A. P. Koretsky, A. L. Sowers, J. B. Mitchell and M. C. Krishna, *Clin. Cancer Res.*, 2006, **12**, 2455.
2 F. Hyodo, K. Matsumoto, A. Matsumoto, J. B. Mitchell and M. C. Krishna, *Cancer Res.*, 2006, **66**, 9921.
3 J. B. Mitchell, M. C. Krishna, A. Samuni, P. Kuppusamy, S. M. Hann, and A. Russo, *Toxicology Of The Human Environment: The Critical Role Of Free Radicals*, ed. C. J. Rhodes, Taylor & Francis, London, 2000, ch. 7, pp. 113-138.
4 *Spin Labeling: The Next Millennium*, ed. L. J. Berliner, Plenum Press, New York, 1998.
5 M. C. Krishna and A. Samuni, *Methods Enzymol.*, 1994, **234**, 580.
6 E. Damiani, C. Belaid, P. Carloni and L. Greci, *Free Radical Res.*, 2003, **37**, 731.
7 K. Matsumoto, M. C. Krishna and J. B. Mitchell, *J. Pharmacol. Exp. Ther.*, 2004, **310**, 1076.
8 P. Kuppusamy, H. Li, G. Ilangovan, A. J. Cardounel, J. L. Zweier, K. Yamada, M. C. Krishna and J. B. Mitchell, *Cancer Res.*, 2002, **62**, 307.
9 K. Yamada, D. Inoue, S. Matsumoto and H. Utsumi, *Antioxid. Redox Signaling*, 2004, **6**, 605.
10 K. Kasazaki, K. Yasukawa, H. Sano and H. Utsumi, *Free Radical Res.*, 2003, **37**, 757.
11 S. Liu, G. S. Timmins, H. Shi, C. M. Gasparovic and K. J. Liu, *NMR Biomed.*, 2004, **17**, 327.
12 H. Yokoyama, O. Itoh, M. Aoyama, H. Obara, H. Ohya and H. Kamada, *Magn. Reson. Imaging*, 2000, **18**, 875.
13 S. Dikalov, B. Fink, M. Skatchkov and E. Bassenge, *Free Radical Biol. Med.*, 1999, **27**, 170.
14 K. Saito, K. Takeshita, K. Anzai and T. Ozawa, *Free Radical Biol. Med.*, 2004, **36**, 517.
15 I. Nakanishi, K. Kawaguchi, K. Ohkubo, T. Kawashima, S. Manda, H. Kanazawa, K. Takeshita, K. Anzai, T. Ozawa, S. Fukuzumi and N. Ikota, *Chem. Lett.*, 2007, **36**, 378.
16 S. Goldstein, G. Merenyi, A. Russo and A. Samuni, *J. Am. Chem. Soc.*, 2002, **125**, 789.
17 A. Israeli, M. Patt, M. Oron, A. Samuni, R. Kohen and S. Goldstein, *Free Radical Biol. Med.*, 2005, **38**, 317.
18 P. O'Neill and T. C. Jenkins, *J. Chem. Soc., Faraday Trans. 1*, 1979, **75**, 191.
19 Y. Lin, T. Ogata, H. Watanabe, Y. Watanabe and T. Akatsuka, *Anal. Sci.*, 1997, **13**, 269.
20 L. Marx and B. Schollhorn, *New J. Chem.*, 2006, **30**, 430.
21 K. Anzai, M. Ueno, A. Yoshida, M. Furuse, W. Aung, I. Nakanishi, T. Moritake, K. Takeshita and N. Ikota, *Free Radical Biol. Med.*, 2006, **40**, 1170.
22 M. C. Krishna, W. DeGraff, O. H. Hankovszky, C. P. Sar, T. Kalai, J. Jeko, A. Russo, J. B. Mitchell and K. Hideg, *J. Med. Chem.*, 1998, **41**, 3477.
23 S. M. Hahn, L. Wilson, M. C. Krishna, J. Liebmann, W. DeGraff, J. Gamson, A. Samuni, D. Venzon and J. B. Mitchell, *Radiat. Res.*, 1992, **132**, 87.
24 A. M. Samuni, W. DeGraff, M. C. Krishna and J. B. Mitchell, *Biochim. Biophys. Acta*, 2001, **1525**, 70.
25 K. Takeshita, A. Hamada and H. Utsumi, *Free Radical Biol. Med.*, 1999, **26**, 951.
26 J. F. W. Keana and F. L. Van Nice, *Physiol. Chem. Phys. Med. NMR*, 1984, **16**, 477.
27 V. Yelinova, A. Krainev, A. Savelov and I. A. Grigor'ev, *J. Chem. Soc., Perkin Trans. 2*, 1993, 2053.

28 N. Kocherginsky and H. M. Swartz, *Nitroxide Spin Labels: Reactions In Biology And Chemistry*, CRC Press, Boca Raton, 1995.
29 L. Marx, R. Chiarelli, T. Guiberteau and A. Rassat, *J. Chem. Soc., Perkin Trans. 1*, 2000, 1181.
30 I. A. Kirilyuk, A. A. Bobko, I. A. Grigor'ev and V. V. Khramtsov, *Org. Biomol. Chem.*, 2004, **2**, 1025.
31 S. Manda, I. Nakanishi, K. Ohkubo, T. Kawashima, K. Matsumoto, T. Ozawa, S. Fukuzumi, N. Ikota and K. Anzai, *Chem. Lett.*, 2007, **36**, 914.
32 T. G. McCord and D. E. Smith, *Anal. Chem.*, 1969, **41**, 1423.
33 A. M. Bond and D. E. Smith, *Anal. Chem.*, 1974, **46**, 1946.
34 M. R. Wasielewski and R. Breslow, *J. Am. Chem. Soc.*, 1976, **98**, 4222.
35 E. M. Arnett, K. Amarnath, N. G. Harvey and J.-P. Cheng, *J. Am. Chem. Soc.*, 1990, **112**, 344.
36 M. Patz, H. Mayr, J. Maruta and S. Fukuzumi, *Angew. Chem., Int. Ed. Engl.*, 1995, **34**, 1225.
37 S. Fukuzumi, N. Satoh, T. Okamoto, K. Yasui, T. Suenobu, Y. Seko, M. Fujitsuka and O. Ito, *J. Am. Chem. Soc.*, 2001, **123**, 7756.
38 J. R. Fish, S. G. Swarts, M. D. Sevilla and T. Malinski, *J. Phys. Chem.*, 1988, **92**, 3745.