

Synthesis, Characterization, and Thermal Stability of New Mononuclear Hydrogenperoxocopper(II) Complexes with N_3O-Type Tripodal Ligands Bearing Hydrogen-Bonding Interaction Sites

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In order to understand the effect of an oxygen-containing ligand on the physico-chemical properties and reactivities of hydrogenperoxocopper complexes, new copper(II) complexes with the N_3O-type tripodal ligand bearing pivalamido groups, *N*,*N*-bis(6-pivalamido-2-pyridylmethyl)glycine (Hbpga), and *N*,*N*-bis(6-pivalamido-2-pyridylmethyl)-β-alanine (Hbpaa), have been designed and synthesized. Copper(II) complexes without any external ligand and those with a monodentate ligand, such as azido and chloro, have been prepared and characterized with the aid of electronic absorption and ESR spectroscopic, cyclic voltammetric, and X-ray structure analytical methods. The redox potential values of the Cu(II) complexes, when they were compared with the Cu(II) complex of bis(6-pivalamido-2-pyridylmethyl)(2-pyridylmethyl)-amine (bppa), reported previously, shifted toward the negative side upon the introduction of a carboxylate group in the place of one pyridine of bppa. Reactions of [Cu(bpga)]ClO_4 (**1a**) and [Cu(bpaa)]PF_6 (**2a**) with hydrogen peroxide in the presence of triethylamine in both MeCN and MeOH solutions gave mononuclear copper(II) complexes with hydrogenperoxide(1−), Cu–bpga–OOH (**1d**) and Cu–bpaa–OOH (**2d**) systems, respectively. The intense absorption bands, assignable to LMCT ($HOO^- \rightarrow$ Cu(II)) and d–d bands, and ESR and resonance Raman spectra have revealed that they form trigonal bipyramidal copper complexes with OOH^- in an end-on fashion. The thermal stabilities of **1d** and **2d** have also been studied by following the reduction rate of the LMCT bands at 283 K. Those of copper(II) complexes with hydrogenperoxide(1−) have been reduced in the order **1d** > **2d** ≫ [Cu(bppa)(OOH)]$^+$ (**3d**), all of which are rather stable compared with that of Cu(II)–tpa–OOH (tpa = tris(2-pyridylmethyl)amine). These findings indicate that the hydrogenperoxocopper(II) complexes are activated by introducing carboxylate coordination, although they are stabilized by hydrogen-bonding interactions.

Mononuclear hydrogenperoxocopper species are very important as key intermediates in biological oxidations catalyzed by copper enzymes, such as dopamine β-hydroxylase (DβH)[1–18] and peptidylglycine α-hydroxylating monooxygenase (PHM).[1–3,19–24] Hydrogenperoxo or alkylperoxocopper(II) complexes have been studied as model compounds of hypothetical reaction intermediates in these oxidases.[25–35] During the last decade, the spectroscopic characterization of binuclear hydrogenperoxocopper(II) complexes[25–27] and the X-ray structural characterization of mononuclear acylperoxocopper(II) complexes[28] were reported by Karlin et al. and Kitajima et al. Subsequently, the preparations and characterizations of hydrogenperoxocopper(II) complexes have been studied using various ligands,[29–36] but their crystal structures were not reported. We previously succeeded in the first preparation, crystal structure analysis, and spectroscopic characterization of the hydrogenperoxocopper(II) complex with a tripodal ligand, bis-(6-pivalamido-2-pyridylmethyl)(2-pyridylmethyl)amine (bppa, Chart 1), which revealed that the hydrogenperoxide(1−) ion coordinated at the axial position of the Cu(II) ion with a trigonal bipyramidal geometry, and that its complex has been stabilized by hydrogen bonding interactions with two pivalamido NH hydrogens.[37]

Recently, the crystal structure of PHM has been determined and revealed to contain two copper sites, Cu_A and Cu_B. The former Cu_A is coordinated with three histidine imidazoles and a water, and the latter Cu_B is bound with two histidine imidazoles, one methionine and one water, $Cu_A(His)_3(H_2O)\cdots Cu_B(His)_2(Met)(H_2O)$; the binding site of dioxygen is proposed to be the Cu_B site. On the other hand, the active site of DβH has been speculated to have a structure similar to that of PHM, except for the methionine site, although the crystal structure has not yet been reported. On the basis of ESR,[8,9] EXAFS,[10–14] and biochemical studies, the oxidized DβH has been speculated to have a configuration of $Cu_A(His)_3(H_2O)\cdots Cu_B(His)_2X(H_2O)$ type,[15,16] although the structure of the reduced form has not yet analyzed. Previously, it was reported that ligand X was consistent with either histidine or an oxygen donor ligand,[15–18] but recent reports have mainly described that the S donor atom from methionine participates as the ligand.[6,13] The coordination environment has not yet been confirmed. Considering the difference in the functions of DβH and PHM, which hydroxylate the β-methylene site of dopamine and α-methylene site of peptidylglycine, respectively, it is quite natural that their configurations around the copper active sites are different from each other. At the present time, it is

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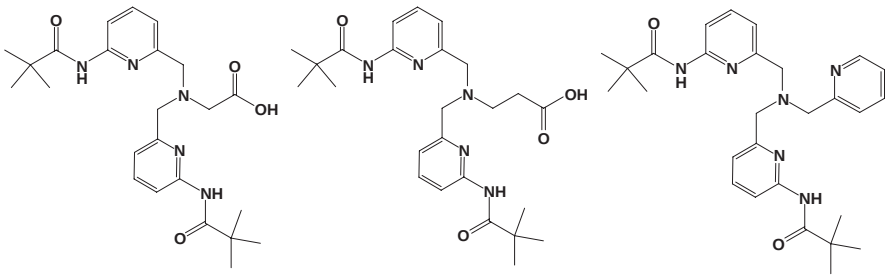

Hbpga **Hbpaa** **bppa**

Hbpga: *N*,*N*-Bis(6-pivalamido-2-pyridylmethyl)glycine
Hbpaa: *N*,*N*-Bis(6-pivalamido-2-pyridylmethyl)-β-alanine
bppa: Bis(6-pivalamido-2-pyridylmethyl)(2-pyridylmethyl)amine

Chart 1.

very important to examine the effect of introducing an O ligand in the place of pyridine N as one choice of the ligating atoms.

On the other hand, quercetin 2,3-dioxygenase (2,3-QD), which is a copper-containing dioxygenase[38–40] that catalyzes the cleavage of the O-heteroaromatic ring of flavonols in the presence of dioxygen to yield the corresponding phenolic carboxylic acid ester and carbon monoxide,[41] has recently been studied by X-ray crystallography[42] and ESR spectroscopy.[40] The crystal structure of *Aspergillus japonicus* 2,3-QD has revealed that the copper ion is chiefly bound in a distorted tetrahedral geometry with three histidine residues (His66, His68, and His112) and a water molecule. However, a minor mixed trigonal bipyramidal/square pyramidal coordination is also present. In the latter geometry, the water molecule is located in the equatorial plane, and the carboxylate side chain of Glu73 additionally coordinates to the metal ion. The function of the carboxylate group of Glu73 bound to the copper ion is of great interest, although it has not been understood clearly in the 2,3-QD enzyme system. It is therefore very important to study on the relationship between the structure around the metal ion and the enzymatic function.

Here, in order to understand the effect of oxygen-containing ligands for concerning the physico-chemical properties and reactivities of hydrogenperoxocopper complexes, we designed and synthesized two new tripodal ligands, *N*,*N*-bis(6-pivalamido-2-pyridylmethyl)glycine (Hbpga) and *N*,*N*-bis(6-pivalamido-2-pyridylmethyl)-β-alanine (Hbpaa) (Chart 1), which contain hydrogen bonding sites and a carboxylate group in the place of one pyridine group of bppa. These ligands make us expect the possible formation of mononuclear hydrogenperoxocopper(II) complexes with the same coordination geometry as the $[Cu(bppa)(OOH)]^+$ cation reported previously. In this paper, the preparation and characterization of the copper complexes with bpga and bpaa and the reaction behaviors of their complexes with hydrogen peroxide are described, and the effects of the carboxylate oxygen and the hydrogen-bonding interaction on the thermal stabilities of hydrogenperoxocopper complexes generated are discussed.

Experimental

Materials. The reagents and solvents employed were of the highest grade available. All solvents for spectroscopies were purified by further distillation before use. Other chemicals were used without further purification. Ligand bppa were prepared by a previously reported method.[37,43,44]

The symbols **1**, **2**, and **3** are labels for copper(II) complexes with ligands Hbpga, Hbpaa, and bppa, respectively; **a**, **b**, **c**, and **d** denote the copper(II) complexes without an external anion and with N_3^--, Cl^--, and HOO^--, respectively.

Physicochemical Measurements. Electronic absorption spectra at low temperature were taken on a JASCO Ubest-35 spectrophotometer. X-Band frozen solution ESR spectra were recorded at 77 K using a JEOL RE-1X ESR spectrometer. ^{1}H NMR spectra were measured on a BRUKER AVANCE-600 spectrometer and recorded with TMS as an internal standard. Cyclic voltammetric measurements were performed using a Bioanalytical Systems (BAS) CV-1B electrochemical analyzer. A three-electrode system was used with a 3-mm diameter glassy carbon electrode as the working electrode, a saturated calomel electrode (SCE) as the reference electrode, and a Pt-wire electrode as the counter electrode in a glass cell having a working compartment (approximately 3-mL in volume). All measurements were made at 25 °C under an argon atmosphere in solution with tetra(*n*-butyl)ammonium tetrafluoroborate (0.1 M) as a supporting electrolyte at a scan rate of 100 mV s^{-1}. Resonance Raman spectra were detected with a liquid nitrogen-cooled CCD detector (Model LN/CCD-1300-PB, Princeton Instruments) attached to a 100 cm single polychromator (Model MC-100DG, Ritsu Oyo Kogaku). The excitation was provided by the 406.7 nm line of an Kr laser. The Cu–$^{16}O_2$H samples were prepared by addition of hydrogen peroxide into an acetone or MeOH solution of the copper(II) complexes with the ligands at −78 °C. In order to confirm the experimental results that the hydrogenperoxide(1−) ion binds to mononuclear copper ion, the isotope effect was examined by the reaction of the copper(II) complexes with $H_2{}^{18}O_2$. All measurements were carried out with spinning cell kept at −78 °C by a stream of liquid N_2 gas.

X-ray Structure Analysis of 1a, 2a, 1b, and 1c. Each single crystal was mounted on a glass fiber. The diffraction data were collected with graphite-monochromated Mo Kα radiation on a Rigaku Mercury diffractometer with the ϕ scan technique at −100 °C.

All the structures were solved by a combination of direct method and Fourier techniques. Non-hydrogen atoms were anisotropically refined by full-matrix least-squares calculations. Hydrogen atoms, which were located from a difference Fourier map, were included but not refined. Refinements were continued until all shifts were smaller than one-tenth of the standard deviations of

Table 1. Crystallographic Data for [Cu(bpga)]ClO_4 (**1a**), [Cu(bpga)(N_3)] (**1b**), [Cu(bpga)Cl]·2CH_3OH (**1c**), and [Cu(bpaa)]PF_6 (**2a**)

	1a	**1b**	**1c**	**2a**
Formula	$C_{24}H_{32}ClCuN_5O_8$	$C_{24}H_{32}CuN_8O_4$	$C_{26}H_{40}ClCuN_5O_6$	$C_{25}H_{34}CuF_6N_5O_4P$
Formula weight	617.54	560.11	617.63	677.08
Crystal system	Monoclinic	Monoclinic	Triclinic	Monoclinic
Space group	$P2_1/n$ (#14)	$P2_1/n$ (#14)	$P\bar{1}$ (#2)	$P2_1/n$ (#14)
a/Å	9.386(1)	7.126(3)	10.175(3)	16.940(1)
b/Å	30.194(3)	37.36(2)	12.674(2)	9.4125(5)
c/Å	10.303(1)	10.329(4)	12.648(2)	19.866(2)
α/deg	—	—	91.036(8)	—
β/deg	99.316(5)	101.042(5)	93.239(8)	115.418(3)
γ/deg	—	—	105.250(10)	—
V/Å^3	2881.5(6)	2698(1)	1570.1(5)	2863.9(4)
Z	4	4	2	4
D_{calcd}/g cm^{-3}	1.423	1.378	1.306	1.570
$F(000)$	1284.00	1172.00	650.00	1396.00
μ(Mo Kα)/cm^{-1}	9.04	8.54	8.25	8.99
λ/Å	0.71070	0.71070	0.71070	0.71070
T/K	173	173	173	173
No. of refls measured	6316	5993	6195	6527
No. of refls used ($I > 3\sigma((I_0))$	5932	3277	3358	5191
R_1[a)]/R_w[b)]	0.086/0.332	0.068/0.152	0.081/0.238	0.051/0.170
GOF	1.83	1.68	1.31	1.10

a) $R_1 = \Sigma||F_o| - |F_c||/\Sigma|F_o|$. b) $R_w = [\Sigma w(|F_o|^2 - |F_c|^2)^2/\Sigma w(|F_o|^2)^2]^{1/2}$.

the parameters involved. Atomic scattering factors and anomalous dispersion terms were taken from International Tables for X-ray Crystallography IV.[45] All the calculations were carried out on a Japan SGI workstation computer using the teXsan crystallographic software package.[46]

Crystallographic data are summarized in Table 1 and have been deposited with Cambridge Crystallographic Data Centre as supplementary publication no. CCDC 244379–244382. Copies of the data can be obtained free of charge via www.ccdc.cam.ac.uk/conts/retrieving.html (or from the Cambridge Crystallographic Data Centre, 12 Union Road, Cambridge CB2 1EZ, UK; Fax: +44 1223 336033; ordeposit@ccdc.cam.ac.uk).

Synthesis of Ligands. *N*,*N*-Bis(6-pivalamido-2-pyridylmethyl)glycine (Hbpga): The reaction of glycine (2.9 g, 0.04 mol) and two molar amounts of 2-bromomethyl-6-pivalamidopyridine[43,44] (21.8 g, 0.08 mol) was carried out in a dioxane/H_2O (4:1) solution (300 mL) containing KOH (5.1 g, 0.08 mol). The reaction solution was stirred at 50 °C for 3 days, and then the solvent was removed by evaporation in vacuo. The resultant brownish crude oil was dissolved in ether, and left standing at room temperature to give colorless needle-like crystals of Hbpga. Yeild 12.3 g (68%). ^{1}H NMR (δ/ppm from TMS in $CDCl_3$) 1.36 (s, 18H), 3.64 (s, 2H), 3.97 (s, 4H), 6.91 (d, 2H), 7.67 (t, 2H), 8.16 (d, 2H), 8.16 (s, 2H). IR (KBr, cm^{-1}): ν 3435 (NH), 3195 (COOH), 1696 (C=O), 1604 (N–H), 1580, 1536, 1461 (py ring), 1411 (COO). ESI MS: m/z: 455 $[M + H^+]^+$, 477 $[M + Na^+]^+$, 492 $[M + K^+]^+$.

***N*,*N*-Bis(6-pivalamido-2-pyridylmethyl)-β-alanine (Hbpaa):** The reaction of β-alanine (3.6 g, 0.04 mmol) and two molar amounts of 2-bromomethyl-6-pivalamidopyridine[43,44] (21.8 g, 0.08 mol) was carried out in a dioxane/H_2O (4:1) solution (300 mL) containing KOH (5.1 g, 0.08 mol). The reaction solution was stirred at 50 °C for 3 days, and then the solvent was removed by evaporation in vacuo. The resultant brownish crude oil was dissolved in ether, and left standing at room temperature to give colorless needle-like crystals of Hbpaa, Yield 11.3 g (60%). ^{1}H NMR (δ/ppm from TMS in $CDCl_3$) 1.35 (s, 9H), 2.66 (t, 1H), 2.95 (t, 1H), 3.82 (s, 2H), 6.95 (d, 1H), 7.66 (t, 1H), 8.15 (d, 1H), 8.20 (s, 1H). IR (KBr, cm^{-1}): ν 3478 (N–H), 3238 (COOH), 1682 (C=O), 1601 (N–H), 1581, 1530, 1460 (py ring), 1407 (COO). ESI MS: m/z: 469 $[M + H^+]^+$, 491 $[M + Na^+]^+$.

Synthesis of Cu Complexes. [Cu(bpga)]ClO_4 (1a): To a stirred MeOH solution (10 mL) of $Cu(ClO_4)_2$·6H_2O (37 mg, 0.1 mmol) was added Hbpga (46 mg, 0.1 mmol) and KOH (6 mg, 0.1 mmol). From the resultant mixture that was allowed to stand at room temperature for a few days, a blue precipitate was obtained as a water-solvated one. A single crystal of [Cu(bpga)]ClO_4 suitable for X-ray structure analysis was obtained from a MeOH/acetone solution. Yield: 44.5 mg (72%). Anal. Calcd for $C_{24}H_{32}ClCuN_5O_8$·3.5H_2O: C, 42.35; H, 5.78; N, 10.29%. Found: C, 42.22; H, 5.36; N, 9.94%.

[Cu(bpga)N_3] (1b): To a stirred MeCN/acetone solution (10 mL) of [Cu(bpga)]ClO_4 (**1a**) (62 mg, 0.1 mmol) was added NaN_3 (5 mg, 0.1 mmol), and then a green product solvated with water and acetone precipitated immediately. After filtration, recrystallization of the precipitate in acetone gave plate-like green single crystals suitable for X-ray structure analysis. Yield: 30.8 mg (55%). Anal. Calcd for $C_{24}H_{32}CuN_8O_4$·0.25H_2O·1.5C_3H_6O: C, 49.41; H, 6.11; N, 18.62%. Found: C, 49.54; H, 6.03; N, 18.88%.

[Cu(bpga)Cl] (1c): To a stirred MeCN solution (10 mL) of [Cu(bpga)]ClO_4 (**1a**) (62 mg, 0.1 mmol) was added KCl (7.5 mg, 0.1 mmol), and then a green powder was precipitated as a water-solvated one immediately. After filtration, recrystallization of the precipitate in MeOH gave plate-like green single crystals suitable for X-ray structure analysis. Yield: 38.2 mg (69%). Anal. Calcd for $C_{24}H_{32}ClCuN_5O_4$·4H_2O: C, 46.08; H, 6.48; N, 11.09%. Found: C, 45.89; H, 6.18; N, 11.06%.

[Cu(bpaa)]PF_6 (2a): To a stirred MeOH solution (10 mL) of

Table 2. UV–Vis and ESR Spectral Data and Electrochemical Parameters for Copper Complexes in MeOH

Complex	UV–vis spectral data		ESR spectral data				Electrochemical data[a)]			
	LMCT[b)]/nm (ε/M^{-1} cm^{-1})	d–d/nm (ε/M^{-1} cm^{-1})	$g_\parallel$	$g_\perp$	$\lvert A_\parallel \rvert$ /G	$\lvert A_\perp \rvert$ /G	E_{pa} /mV	E_{pc} /mV	ΔE /mV	$E_{1/2}$ /mV
[Cu(bpga)]ClO_4 (**1a**)	—	678 (120), 860 (60)	2.26	2.06	171	—	—	—	—	—
[Cu(bpaa)]PF_6 (**2a**)	—	660 (90)	2.23	2.06	179	—	—	—	—	—
[Cu(bppa)]$(ClO_4)_2$ (**3a**)	—	606 (100)	2.22	2.06	182	—	—	—	—	—
[Cu(bpga)N_3] (**1b**)	380 (1900)	682 (160), 871 (190)	2.01	2.27	73	129	−416	−502	86	−459
[Cu(bpaa)N_3] (**2b**)	383 (1090)	694 (110)	2.27	2.08	125	—	−266	−368	102	−317
[Cu(bppa)N_3]ClO_4 (**3b**)	389 (2000)	652 (200), 842 (200)	2.29	2.03	158	90	−145	−255	110	−200
[Cu(bpga)Cl] (**1c**)	—	626 (100)	2.32	2.06	140	—	−160	−361	201	−261
[Cu(bpaa)Cl] (**2c**)	—	714 (100)	2.25	2.06	158	—	—	—	—	—
[Cu(bppa)Cl]ClO_4 (**3c**)	—	700 (180), 854 (240)	2.28	2.06	157	—	−60	−135	75	−98

a) Reduction and oxidation potentials are given vs SCE in MeCN. b) LMCT (N_3^- → Cu(II)).

$Cu(ClO_4)_2 \cdot 6H_2O$ (37 mg, 0.1 mmol) were added Hbpaa (47 mg, 0.1 mmol), KOH (6 mg, 0.1 mmol) and $NaPF_6$ (6 mg, 0.1 mmol). Then, a blue powder was precipitated as a water-solvated one. After the precipitate was allowed to stand at room temperature for a few days, a single crystal of [Cu(bpaa)]PF_6 suitable for X-ray structure analysis was obtained. Yield: 35.9 mg (53%). Anal. Calcd for $C_{25}H_{34}CuF_6N_5O_4P \cdot 1.25H_2O$: C, 42.92; H, 5.26; N, 10.01%. Found: C, 42.77; H, 4.95; N, 9.68%.

[Cu(bpaa)(X)] (X = N_3 (2b), Cl (2c)): The preparation of [Cu(bpaa)N_3] was carried out by the addition of NaN_3 (5 mg, 0.1 mmol) to an MeCN solution (10 mL, 1 mM) of [Cu(bpaa)]PF_6 (**2a**) (68 mg, 0.1 mmol). That of [Cu(bpaa)Cl], which was prepared by the same method as in the case of [Cu(bpaa)N_3], was performed by the addition of KCl (7.5 mg, 0.1 mmol) to an MeCN solution (10 mL, 1 mM) of [Cu(bpaa)]PF_6 (**2a**) (68 mg, 0.1 mmol).

Reactions of [Cu(L)]ClO_4 (L = bpga, bpaa, bppa) with Hydrogen Peroxide. The starting complexes Cu(II)–L^- (L = bpga, bpaa, bppa) were prepared by mixing each Cu(II)–L complex (4.0 mmol) (L = bpga (**1a**), bpaa (**2a**), bppa (**3a**)) and triethylamine (4.2 mmol) in a methanol or acetonitrile solution (4 mL) at room temperature. The Cu(II)–L–OOH species were prepared by the addition of H_2O_2 (0.4 mol) at −40 °C. The formation and decomposition of the hydrogenperoxo species were monitored by following the increase and decrease in the intensities of their LMCT bands, respectively, using λ_{max} = 370, 373, and 380 nm, for [{Cu(L)-(OOH)}$^{n+}$ (L = bpga (**1d**), bpaa (**2d**), bppa (**3d**)) in acetone, respectively. Since the former two hydrogenperoxocopper(II) species **1d** and **2d** were accompanied by immediate decomposition after formation, the exact values of the molar absorption coefficients could not be estimated. The values given in the results and discussion sections are described as rough ones.

The thermal stabilities of these hydrogenperoxocopper(II) species were estimated by following the intensity change of the LMCT band under a constant temperature (at 293 K). Since the decreasing behaviors of the LMCT bands in these hydrogenperoxo complexes were of first order (Fig. S1), the decomposition processes were analyzed with first-order kinetics, where the $\ln(([A_t] - [A_\infty])/([A_0] - [A_\infty]))$ values were plotted vs time (where $[A_0]$ and $[A_t]$ denote the intensities of LMCT bands observed at initial and a time, respectively). As described above, the decompositions of the hydrogenperoxocopper(II) species, **1d** and **2d**, began simultaneously with the generations. The generation rates were dependent on the concentrations of H_2O_2, but the concentration dependence of the decomposition rates was not observed, as can also be understood from the finding that the decomposition reaction proceeded by first-order kinetics. Thus, all of the kinetics of the decomposition rates were measured in the presence of an excess amounts of H_2O_2 (100 equiv.).

Results and Discussion

Formation of Cu(II)–L–X Complexes (L = bpga, bpaa, bppa; X = N_3, Cl) and Their Spectroscopic Properties. [Cu^{II}(bpga)]ClO_4 (**1a**) and [Cu^{II}(bpaa)]PF_6 (**2a**) were synthesized by the reaction of equimolar amounts of $Cu^{II}(ClO_4)_2 \cdot 6H_2O$ and each ligand L in methanol, whose electronic absorption and ESR spectral data are given in Table 2, together with the previous data of [Cu^{II}(bppa)]$(ClO_4)_2$ (**3a**).[43] All of the complexes showed spectral behaviors characteristic of the square-planar or square-pyramidal geometry when they did not have any additional ligand. Judging from the d–d bands and ESR parameters, it is suggested that the copper(II) complexes prefer the square-planar geometry more in the order of **1a** < **2a** < **3a**, because the d–d band at 600–680 nm shifted to a higher energy region,[47–55] and the $|A_\parallel|$ value became larger in this order.[47,51,54,56–60]

The addition of NaN_3 to copper(II) complexes **1a** and **2a** in CH_3CN gave [Cu^{II}(bpga)(N_3)] (**1b**) and [Cu^{II}(bpaa)(N_3)] (**2b**), respectively, accompanied by a solution color change from blue to green. The electronic absorption and ESR spectral data for [Cu^{II}(L)(N_3)], **1b** and **2b**, are listed in Table 2 together with those of **3b**.[43] The electronic absorption spectrum of azido complex **1b** exhibited d–d transition bands centered at 682 nm (160 M^{-1} cm^{-1}) and 871 nm (190 M^{-1} cm^{-1}), and an intense absorption band assignable to the LMCT band from the N_3^- anion to the copper(II) ion at 380 nm (1900 M^{-1} cm^{-1}). Those of [Cu(bpaa)(N_3)] (**2b**) appeared at 694 nm (110 M^{-1} cm^{-1}) and at 383 nm (1090 M^{-1} cm^{-1}) (Table 2), respectively. The frozen solution ESR spectrum of the azido complex **1b** at 77 K gave signals typical of the Cu(II) complex with a d_{z^2} ground state ($g_\parallel = 2.01$, $g_\perp = 2.27$, $|A_\parallel| = 73$ G, and $|A_\perp| = 129$ G), and that of **2b** at 77 K gave signals typical for the Cu(II) complex with a $d_{x^2-y^2}$ ground state ($g_\parallel = 2.27$, $g_\perp = 2.08$, and $|A_\parallel| = 125$ G), which are characteristic of trigonal-bipyramidal ($g_\parallel < g_\perp$) and square-pyramidal geometries ($g_\parallel > g_\perp$), respectively. Considering that complex **3b** consisted of only a five-membered chelate ring has a trigonal bipyramidal geometry, it is quite natural that complex **1b** gives

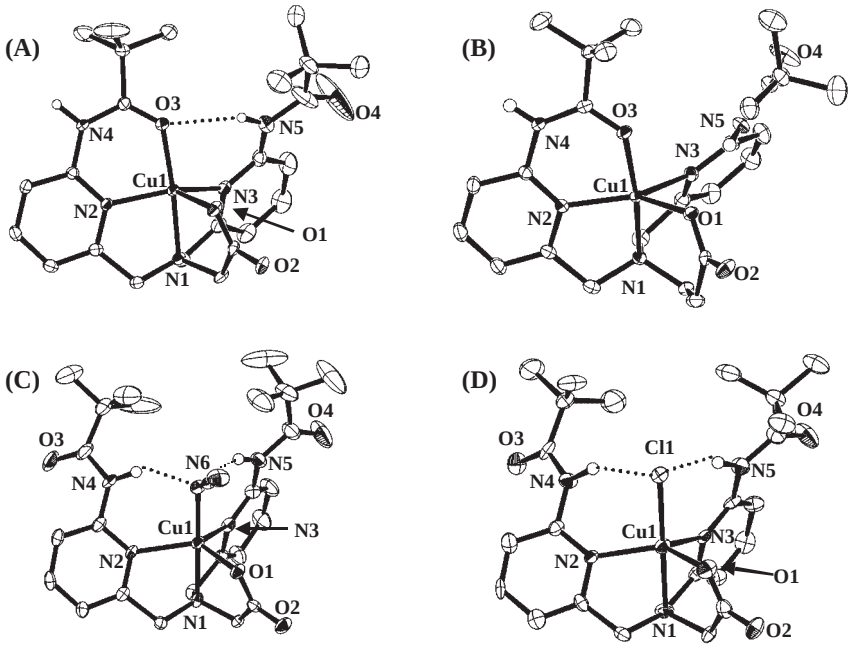

Fig. 1. Crystal Structures of the cation parts of mononuclear copper complexes, showing 30% probability thermal ellipsoids. The hydrogen atoms except for amido NH are omitted for clarity: (A) $[Cu(bpga)]ClO_4$ (**1a**), (B) $[Cu(bpaa)]PF_6$ (**2a**), (C) $[Cu(bpga)(N_3)]$ (**1b**), (D) $[Cu(bpga)Cl]\cdot 2CH_3OH$ (**1c**).

the same trigonal-bipyramidal one. The square-pyramidal geometry in complex **2b** would have been induced by the formation of a six-membered chelate ring due to the coordination of propionic acid of bpaa. These spectral behaviors agree well with their electronic absorption spectral features observed in the d–d transition energy region (Table 2).[47–55]

The addition of KCl to the copper(II) complexes **1a** and **2a** in MeCN caused the solution color to change from blue to green, indicating the formations of $[Cu^{II}(bpga)Cl]$ (**1c**) and $[Cu^{II}(bpaa)Cl]$ (**2c**), respectively. Electronic absorption and ESR spectral data for $[Cu^{II}(L)Cl]$, **1c** and **2c**, are listed in Table 2 together with those of **3c**.[43] The electronic absorption spectrum of chloro complex **1c** exhibited a d–d transition band centered at 626 nm (100 M^{-1} cm^{-1}), and that of **2c** appeared at 714 nm (100 M^{-1} cm^{-1}). The frozen solution ESR spectrum of the chloro complex **1c** at 77 K gave signals typical of the Cu(II) complex with a $d_{x^2-y^2}$ ground state ($g_\parallel = 2.32$, $g_\perp = 2.06$, $|A_\parallel| = 140$ G) and that of **2c** at 77 K also gave signals typical of the Cu(II) complex with a $d_{x^2-y^2}$ ground state ($g_\parallel = 2.25$, $g_\perp = 2.06$, $|A_\parallel| = 158$ G). The ESR spectral patterns of **1c** and **2c** are characteristic of a square-pyramidal geometry ($g_\parallel > g_\perp$), which agree well with their electronic absorption spectral features observed in the d–d transition energy region (Table 2).[47–55]

The above spectral behaviors of the copper(II) complexes in solution suggested that the copper(II) complexes with tripodal ligand forming a five-membered chelate ring prefer the trigonal-bipyramidal geometry more when they have a stronger external ligand, such as azido.

Crystal Structures of $[Cu(bpga)]ClO_4$ (1a), $[Cu(bpaa)]PF_6$ (2a), $[Cu(bpga)(N_3)]$ (1b), and $[Cu(bpga)(Cl)]$ (1c). ORTEP drawings of the metal coordination parts for $[Cu(bpga)]ClO_4$ (**1a**), $[Cu(bpaa)]ClO_4$ (**2a**), $[Cu(bpga)(N_3)]$ (**1b**), and $[Cu(bpga)(Cl)]$ (**1c**), which were fortunately obtained as a single crystal, are shown in Fig. 1. The selected bond lengths and angles around the copper ions are listed together in Table 3. The coordination geometries around the Cu(II) ions for all of the complexes are nearly trigonal bipyramidal, as described below, although their solution structures were square-planar or square-pyramidal, except for the azido complexes.

All of the crystal structures of the Cu(II) complexes formed a trigonal-bipyramidal geometry with two pyridine nitrogens and carboxylate oxygen of each ligand in the trigonal plane and with one tertiary amine nitrogen and one pivalamido oxygen/azido/chloro in the axial positions. Judging from the geometric parameter (τ) around the Cu(II) ion ($\tau = (\beta - \alpha)/60$, where α and β represent two basal angles ($\beta \geq \alpha$)),[61] the coordination geometries for **1a** (0.53) and **2a** (0.55) are defined as a distorted trigonal bipyramidal, and those for **1b** (0.87) and **1c** (0.67) are both nearly trigonal bipyramidal, as listed in Table 3. That of $[Cu(bppa)(N_3)]ClO_4$ (**3b**), reported previously,[43,44] was also trigonal-bipyramidal. As shown in the above spectroscopic and structural results, it is apparent that the Cu(II) complexes with a tripodal ligand and an azido ion are easy to form a trigonal-bipyramidal structure both in solution and in solid states.

In the molecular structures of **1b** and **1c**, hydrogen bonds were observed between the pivalamido NH group of bpga and coordinated azido or chloro ion, respectively. The distances, N(4)···N(6) = 2.980(6), N(5)···N(6) = 2.939(6) Å for **1b**, N(4)···Cl(1) = 3.285(8), N(5)···Cl(1) = 3.152(9) Å for **1c**, agree well with the general hydrogen bonding ones (Fig. 1), which makes it clear that it contributes to the fixation of the azido ion, as found in the Cu–tppa and Cu–bppa complexes with a pivalamido group (tppa: tris(6-pivalamido-2-pyridylmethyl)amine), as previously reported.[44,62,63]

Electrochemical Properties. In order to estimate the effect of the coordination of carboxylate oxygen to the Cu(II)

Table 3. Selected Bond Lengths and Angles of $[Cu(bpga)]ClO_4$ (**1a**), $[Cu(bpga)(N_3)]$ (**1b**), $[Cu(bpga)Cl]\cdot 2CH_3OH$ (**1c**), and $[Cu(bpaa)]PF_6$ (**2a**)

	1a	**1b**	**1c**	**2a**
		Bond length/Å		
Cu(1)–O(1)	2.129(4)	1.991(4)	1.969(7)	1.980(2)
Cu(1)–O(3)	1.949(3)	—	—	1.946(2)
Cu(1)–N(1)	2.007(4)	1.999(5)	2.012(7)	1.987(3)
Cu(1)–N(2)	1.974(3)	2.170(5)	2.241(7)	1.977(3)
Cu(1)–N(3)	2.079(4)	2.114(5)	2.109(7)	2.166(3)
Cu(1)–N(6)	—	1.945(5)	—	—
Cu(1)–Cl(1)	—	—	2.240(3)	—
N(4)···X[a)]	—	2.980(6)	3.285(8)	—
N(5)···X[a)]	3.165(4)	2.939(8)	3.152(9)	3.239(3)
		Bond angle/deg		
O(1)–Cu(1)–N(1)	81.9(1)	83.1(2)	83.8(3)	98.2(1)
O(1)–Cu(1)–N(2)	112.0(1)	112.7(2)	107.2(3)	137.2(1)
O(1)–Cu(1)–N(3)	99.4(1)	127.0(2)	135.5(3)	91.76(10)
O(1)–Cu(1)–X[a)]	102.6(1)	97.2(2)	93.0(2)	91.33(10)
N(1)–Cu(1)–N(2)	84.8(1)	81.6(2)	78.9(3)	83.8(1)
N(1)–Cu(1)–N(3)	80.5(2)	80.0(2)	79.9(3)	78.9(1)
N(1)–Cu(1)–X[a)]	174.9(1)	179.2(2)	175.9(2)	170.4(1)
N(2)–Cu(1)–N(3)	142.9(2)	113.9(2)	109.7(3)	130.0(1)
N(2)–Cu(1)–X[a)]	91.3(1)	99.0(2)	104.6(2)	89.4(1)
N(3)–Cu(1)–X[a)]	100.9(2)	99.3(2)	100.8(2)	100.61(10)
		τ value		
	0.53	0.87	0.67	0.55

a) X = O(3) for **1a** and **2a**, N(6) for **1b**, and Cl(1) for **1c**.

complexes, the electrochemical properties of the azido complexes were examined in MeCN under Ar vs SCE. The cyclic voltammograms of **1b**, **2b**, **3b**, **1c**, and **3c** were measured, which showed that all of them had a reversible one-electron redox potential wave. The electrochemical data of their Cu(II) complexes are listed in Table 2. In the azido complexes (**1b**, **2b**, and **3b**), the redox potentials, $E_{1/2}$, of the Cu(II) complexes with carboxylate coordination, **1b** and **2b**, are lower than **3b** with pyridine,[43] and that the redox potential of **1b** with bpga functioning as a five-membered chelate ring is lower than that of **2b** with the bpaa ligand forming a six-membered chelate ring; **1b** (−459 mV) < **2b** (−317 mV) < **3b** (−200 mV). The $E_{1/2}$ values of the chloro complexes (**1c** and **3c**) also indicated that the Cu(II) complex with carboxylate coordination is lower than that without it, **1c** (−261 mV) < **3c** (−98 mV), although that of **2c** was not assigned because of its complicated waves. The above findings suggest that the coordination of oxygen atom makes the redox potential of the copper complex shift to the negative side, and that the stronger coordination of the carboxylate ligand with a five-membered chelate ring makes that of the copper complex shift to the negative one compared with that of the weaker ligand with a six-membered chelate ring. It is quite reasonable that the coordination of carboxylate oxygen in the place of pyridine nitrogen results in a decrease of their redox potentials, because it reduces the Lewis acidity of the metal ion.

Reaction of Copper(II) Complexes with Hydrogen Peroxide and Their Characterizations. The preparations and spectroscopic characterizations of Cu(II) complexes with hydrogenperoxide(1−) were performed in acetonitrile and methanol solutions, which were studied by electronic absorption, resonance Raman, and ESR spectroscopies. The addition of hydrogen peroxide to the solution of each Cu(II) complex, **1a** or **2a**, containing equimolar amount of triethylamine at −40 °C exhibited an apparent color change from blue to light green. The absorption spectra of these light green solutions in MeCN and MeOH showed intense bands at 370 nm ($\varepsilon = \sim$1400 $M^{-1}\,cm^{-1}$) and 359 nm ($\varepsilon = \sim$890 $M^{-1}\,cm^{-1}$) for the Cu–bpga system (**1d**) and 373 nm ($\varepsilon = \sim$770 $M^{-1}\,cm^{-1}$) and 358 nm ($\varepsilon = \sim$300 $M^{-1}\,cm^{-1}$) for the Cu–bpaa system (**2d**), respectively, in the UV region, which are assignable to a charge transfer (CT) transition band of hydrogenperoxide(1−) to the copper(II) center[32–37] (Fig. 2, Table 4). These were observed in a higher energy region compared with those of **3d** (380 nm ($\varepsilon = \sim$890 $M^{-1}\,cm^{-1}$) and 390 nm ($\varepsilon = \sim$630 $M^{-1}\,cm^{-1}$), respectively). The LMCT bands of hydrogenperoxocopper(II) complexes in MeOH were significantly affected, although those in MeCN were not much influenced. All of the absorption spectra of the copper complexes in the visible region gave spectral patterns characteristic of a trigonal bipyramidal geometry.[47–55] These results demonstrate that the copper(II) ions for **1d**, **2d**, and **3d** form a trigonal bipyramidal geometry with the hydrogenperoxide(1−) anion at the axial site. The fact that the LMCT bands of the hydrogenperoxocopper(II) complexes with the carboxylate oxygen were observed in a higher energy region, as compared with that of **3c** with pyridine, suggests that the hydrogenperoxide(1−) ions for **1d** and **2d** strongly coordinate to the copper(II) ion, as compared with **3d**. Considering that MeOH is a protic solvent which destroys the hydrogen-bonding network,[64] the solvent

effect observed for hydrogenperoxocopper(II) complexes may suggest the formation of hydrogen bonds between hydrogenperoxide(1−) and pivalamido NH groups.

The frozen solution ESR spectra for **1d** both in MeCN and MeOH at 77 K gave signals typical of the mononuclear Cu(II) complex with a d_{z^2} ground state ($g_{\parallel} = 1.99$, $g_{\perp} = 2.22$, $|A_{\parallel}| =$ 129 G, and $|A_{\perp}| = 56$ G in MeCN and $g_{\parallel} = 2.07$, $g_{\perp} = 2.23$, $|A_{\parallel}| = 133$ G, and $|A_{\perp}| = 58$ G in MeOH) (Table 4), which are very similar to those for **3d**, reported previously.

The resonance Raman spectra of a methanol solution containing the hydrogenperoxocopper(II) adducts **1d** and **2d**, measured at −80 °C (406.7 nm laser excitation), showed strong resonance-enhanced Raman peaks at 854 and 501 cm^{-1} for the Cu–bpga–OOH system and 848 and 485 cm^{-1} for the Cu–bpaa–OOH system (Fig. 3), respectively, which shifted to 808 and 492 cm^{-1} for the Cu–bpga–OOH system ($\Delta\nu = 46$ and 9 cm^{-1}) when ^{18}O-labeled hydrogen peroxide was used, although it was not measured for the Cu–bpaa–OOH system. The former and latter values are assigned to ν(O–O) and ν(Cu–O) stretching vibrations, respectively. These frequencies well reflect the coordination mode between copper and hydrogenperoxide(1−). The ν(O–O) bands of **1d** and **2d** were observed in the lower energy region compared with that of **3d**,[37] and the ν(Cu–O) bands of **1d** and **2d** were detected in the higher energy region compared to that of **3d**.[37] The hydrogenperoxide(1−) ions for **1d** and **2d** bind strongly compared to **3d**, which makes the O–O bonds of **1d** and **2d** weaken compared with **3d**.

Based on these spectral behaviors, we concluded that the mononuclear hydrogenperoxocopper(II) complexes, [Cu(bpga)(OOH)] (**1d**) and [Cu(bpaa)(OOH)] (**2d**), in the solution phase form a trigonal bipyramidal geometry, and the introduction of carboxylate oxygen to the copper ion strengthens the coordination of an external ligand, such as hydrogenperoxide(1−) and azido. These findings allow us to expect that the introduction of carboxylate coordination to copper ion raises the reactivity of the hydrogenperoxocopper(II) species.

Thermal Stability of the Mononuclear Hydrogenperoxocopper(II) Complexes with Carboxylate Groups. In our previous report, we described that the copper(II) complex of bppa with two pivalamido groups at the 6-position of the pyridine ring forms the hydrogenperoxo species, $[Cu(bppa)(OOH)]^+$ (**3d**), which is very stable in solution for more than one month at room temperature.[37] The crystal structure of the mononuclear hydrogenperoxocopper(II) complex, $[Cu(bppa)(OOH)]^+$ (**3d**), revealed that the pivalamido NH groups of bppa interact with the ligated hydrogenperoxide(1−) oxygen atom by a hydrogen bond to keep its higher thermal stability.[37] The above-mentioned experimental results made us expect the following things: The introduction of carboxylate co-

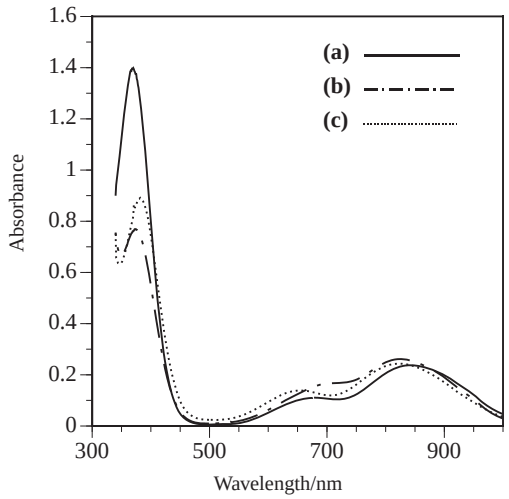

Fig. 2. UV–vis spectra of hydrogenperoxocopper complexes in acetonitrile at −40 °C; (a) [Cu(bpga)(OOH)] (**1d**), (b) [Cu(bpaa)(OOH)] (**2d**), (c) $[Cu(bppa)(OOH)]^+$ (**3d**).

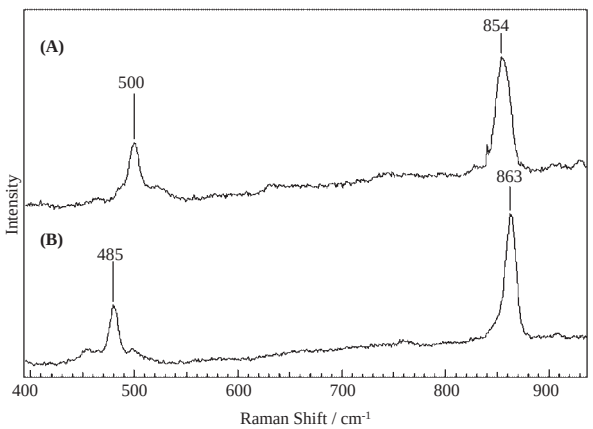

Fig. 3. Resonance Raman spectra of hydrogenperoxocopper complexes in methanol; (A) [Cu(bpga)(OOH)] (**1d**), (B) $[Cu(bppa)(OOH)]^+$ (**3d**).

Table 4. UV–Vis, ESR, Resonance Raman Spectral Data for [Cu(L)(OOH)] Complexes

Ligand (L)	UV–vis spectral data		ESR spectral data				rR spectral data/cm^{-1}		Solvent
	LMCT[a]/nm ($\varepsilon/M^{-1}\,cm^{-1}$)	d–d/nm ($\varepsilon/M^{-1}\,cm^{-1}$)	$g_{\parallel}$	$g_{\perp}$	$\lvert A_{\parallel}\rvert$ /G	$\lvert A_{\perp}\rvert$ /G	$\nu(^{16}O–^{16}O)$ ($\nu(^{18}O–^{18}O)$)	$\nu(Cu–^{16}O)$ ($\nu(Cu–^{18}O)$)	
[Cu(bpga)(OOH)] (**1d**)	370 (1400)	675 (110), 837 (240)	1.99	2.22	129	56	—[d]	—[d]	MeCN
[Cu(bpaa)(OOH)] (**2d**)	373 (770)	720 (170), 820 (260)	1.98	2.26	87	157	—[d]	—[d]	MeCN
$[Cu(bppa)(OOH)]^+$ (**3d**)[b]	380 (890)	660 (150), 830 (250)	2.01	2.21	91	95	856 (810)	—[c]	MeCN
[Cu(bpga)(OOH)] (**1d**)	359 (890)	673 (100), 868 (170)	2.07	2.23	133	58	854 (808)	501 (492)	MeOH
[Cu(bpaa)(OOH)] (**2d**)	358 (300)	691 (110), 780 (100)	2.01	2.26	122	122	848 (—[d])	485 (—[d])	MeOH
$[Cu(bppa)(OOH)]^+$ (**3d**)	390 (630)	652 (80), 819 (140)	2.00	2.22	111	79	863 (817)	481 (471)	MeOH

a) LMCT ($HOO^- \rightarrow$ Cu(II)). b) Ref. 37. c) Not detected. d) Not measured.

ordination to the copper might activate the generated hydrogenperoxocopper(II) species, Cu–bpga–OOH and Cu–bpaa–OOH systems. Therefore, the thermal stabilities of these hydrogenperoxo species at 283 K were traced by monitoring the decrease of their LMCT band intensities. The absorption spectral changes in acetone are depicted in Fig. 2. The decrease in the LMCT bands obeyed first-order kinetics. The effect of the introduced carboxylate groups on the thermal stabilities of hydrogenperoxocopper(II) species are described in detail in the following discussion.

It is clear that decay in the LMCT band indicates the decomposition of the hydrogenperoxocopper(II) species, which is proposed to proceed according to a homolytic cleavage of the hydrogenperoxo O–O bond.[65] We have thus considered the stability of the hydrogenperoxocopper(II) complexes using the decomposition rates as follows.

Hydrogenperoxocopper(II) complexes **1d** and **2d** are remarkably unstable, and their decomposition rates ($k_{obs} = 1.2 \times 10^{-2}$; 7.9×10^{-3} s^{-1} at 283 K, respectively) in acetone are appropriately faster than **3d** ($k_{obs} = 2.8 \times 10^{-5}$ s^{-1} at 283 K). Here, surprisingly, **3d** is activated by the irradiation of a xenon lamp to decompose, although it is quite stable even at room temperature in the absence of irradiation. In any case, the hydrogenperoxocopper species was labilized by using carboxylate oxygen, and the hydrogenperoxocopper complex **1d** with carboxylate coordination of the five-membered chelate ring was more unstable than **2d** with that of the six-membered chelate ring. This clearly indicates that the thermal stabilities of their hydrogenperoxocopper(II) complexes decrease extensively by the coordination of carboxylate groups to the metal center. Furthermore, these Cu–OOH species (**1d**, **2d**, and **3d**) are rather stable compared with the Cu–tpa–OOH species ($k_{obs} = 8.3 \times 10^{-2}$ s^{-1} at 283 K in acetone).[35] This may be explained in terms of the hydrogen-bonding effect between the coordinated hydrogenperoxide(1−) oxygen and the pivalamide NH groups. As described above, the resonance Raman spectra measured in methanol solution (Fig. 3) may imply that O–O bond cleavages of hydrogenperoxocopper(II) complexes **1d** and **2d** are easier than that of **3d**, because the ^{16}O–^{16}O stretching vibrations of **1d** and **2d** ($\nu(^{16}O–^{16}O) = 854$ and 848 cm^{-1}, respectively) are lower than that of **3d** ($\nu(^{16}O–^{16}O) = 863$ cm^{-1}), and the Cu–^{16}O frequencies of **1d** and **2d** (ν(Cu–^{16}O) = 500 and 485 cm^{-1}, respectively) are higher than that of **3d** (ν(Cu–^{16}O) = 480 cm^{-1}).

Therefore, the order of the thermal stabilities of these hydrogenperoxo complexes is determined as follows: **1d** < **2d** ≪ **3d**. The hydrogenperoxocopper(II) complexes are partially stabilized by the hydrogen-bonding interaction, although the stability is reduced by an adverse effect of the carboxylate groups ligating to the metal ion.

Conclusion

In order to understand the effect of the coordination of carboxylate oxygen on the physico-chemical properties and reactivities of hydrogenperoxocopper complexes, we prepared new copper(II) complexes with tripodal ligands bearing a carboxylate group and hydrogen-bonding interaction sites, bpga and bpaa, which were studied based on the electronic absorption and ESR spectroscopies, cyclic voltammetry, and X-ray crystal structure analysis. The crystal structures of the azido and chloro complexes, **1b** and **1c**, revealed that pivalamido groups substituted at the pyridine 6-positions can interact with axially coordinated azido and chloro anions, respectively, by hydrogen bonds. The hydrogenperoxocopper(II) complexes, **1d** and **2d**, showed spectral behaviors similar to the hydrogenperoxocopper(II) complex **3d**, which have been previously reported to have the trigonal bipyramidal structure. However, the thermal stabilities of **1d** and **2d** have been remarkably lowered than that of **3d**. From the resonance Raman spectral data, it was suggested that O–O bond cleavages of hydrogenperoxocopper(II) complexes, **1d** and **2d**, were easier than that of **3d**, indicating that O–O bonds of **1d** and **2d** are weaker than that of **3d**, and that Cu–O bonds of **1d** and **2d** are stronger than that of **3d**. The stability of hydrogenperoxocopper(II) complexes is reduced by the use of carboxylate groups, although they are stabilized by an adverse effect of the hydrogen-bonding interaction. These findings indicate that the ligating amino acid residues and configurations around the copper ion will be affected as differences in the oxidation abilities of copper enzymes.

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Supporting Information

Figure S1 in PDF format. This material is available free of charge on the Web at: http//www.csj.jp/journals/bcsj/.

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