Basic approach to development of environment-friendly oxidation catalyst materials. Mononuclear hydroperoxo copper(II) complexes

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Abstract

In this review, basic studies on the binding and activation of dioxygen species by copper complexes with originally designed ligands are described as the initial step for development of environment-friendly oxidation catalyst. In order to examine the stability/reactivity of such a mononuclear copper(II) complex, some copper complexes with hydroperoxide ion have been constructed using the ligands that have been prepared on the basis of the active center structures of metalloenzymes, and the effects of (i) hydrogen bond, (ii) hydrophobic sphere, (iii) coordination structure around metal, and (iv) coordinating atoms have been investigated systematically, from the point of view of synthetic, spectroscopic, structural, kinetic, and theoretical chemistries. It has also been found out that the decomposition rate constants and the O–O bond strengths of hydroperoxo copper(II) complexes are strongly correlated.

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Keywords: Dioxygen activation; Mononuclear copper complexes; Hydroperoxide; Environment-friendly materials; Ligand design

Contents

1. Introduction ................................................................. 035
2. Preparation of Cu–OOH species as a biologically active key intermediate ........................................... 036
3. Stabilization of Cu–OOH species by hydrogen bonding interaction with its proximal oxygen atom .......... 038
4. Activation of Cu–OOH species by hydrogen bonding interaction with its distal oxygen atom .............. 039
5. Regulation of reactivity of Cu–OOH species by change of the coordination structure from trigonal bipyramid to square plane ................................................................. 040
6. Regulation of stability/activity of the Cu–OOH species by change of the ligating atoms (N/O) of tripodal tetradentate ligands ........................................................................... 042
7. Relationship between the ν(O–O) stretching vibrations of Cu–OOH species and their decomposition rates . . . . 043
8. Theoretical analysis of [Cu(bppa)(OOH)]⁺ complex and its derivatives by ab initio molecular orbital calculations 043

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1. Introduction

Study on the structure–function relationship of metalloenzymes in biological systems is the starting point in development of environment-friendly catalyst materials, which may achieve their higher selectivity, efficiency, and reactivity under relatively mild conditions. Metalloenzymes showing oxidation and oxygenation functions using dioxygen are especially very important. We have investigated the preparation and characterization of model complexes of oxidases and oxygenases that play very important roles using oxygen species, such as dioxygen, hydroxide, hydroperoxide, and peroxide, for a last decade [1–23]. In this review, we describe the studies of mononuclear hydroperoxy copper species that are key as intermediates in biological oxidation systems catalyzed by copper enzymes, such as dopamine β-hydroxylase (DβH) [24–40] and peptidylglycine α-hydroxylating monoxygenase (PHM) [24–26,41–44].

Recently, the crystal structure of PHM was analyzed [41–44], which revealed to contain two copper sites, CuA and CuB. The former is coordinated with three histidine imidazoles and a water and the latter is bound with two histidine imidazoles, one methionine and one water, CuB(His)3(H2O)···CuA(His)2(Met)(H2O), and the dioxygen is supposed to bind at the CuA site. On the other hand, the active site structure of DβH has been speculated to be similar to that of PHM [31–38], although the crystal structure has not been reported yet. The oxidized DβH is considered to have a configuration of CuA(His)3(H2O)···CuB(His)2X(H2O) type on the basis of ESR [31,32], EXAFS [33–36], and biochemical studies [37,38], whereas the structure of the reduced form is not clear. The identity of ligand X is unknown, and the obtained data is consistent with either histidine or an oxygen donor ligand, although an S donor ligand from methionine is proposed to be present in the oxidized form with a long distance [29,35]. Considering the difference in the functions of DβH and PHM which hydroxylate the β-methylene site of dopamine and α-methylmethylene site of peptidylglycine, respectively, it is quite natural that their configurations and coordination atoms around copper active sites may be different each other.

Furthermore, the participation of a tyrosine residue in the catalytic mechanism of DβH has been previously proposed on the basis of mechanism-based inhibition [29] and 18O isotope effect studies [28]. In the latter case, the mechanism was put forth in which tyrosine is required for the reductive activation of Cu(II)–OOH to generate a copper-oxo species responsible for the hydrogen atom abstraction from substrate. It is very interesting to regulate activation of Cu(II)–OOH species by hydrogen bonding interaction between non-coordinating oxygen of hydroperoxide (distal oxygen) and tyrosine hydrogen (Scheme 1) [28,44].

Hydroperoxy or alkylperoxy copper(II) complexes have been studied as model compounds of hypothetical reaction intermediates in these oxidations [45–59]. Previously, X-ray structural characterization of binuclear acylperoxy copper(II) complexes [46] and mononuclear alkylperoxy copper(II) complexes [51] were reported by Karlin et al. and Kitajima et al. Subsequently, the preparations and characterizations of hydroperoxy copper(II) complexes using various ligands have been studied [45–59], but unfortunately they did not succeed in obtaining the crystal structures before our study [7].

We also carried out preparation and characterization of the copper complexes, and first succeeded in isolation of the novel mononuclear copper complex with a tripodal tetra-dentate ligand, bis(6-pivalamido-2-pyridylmethyl)(2-pyridylmethyl)amine (BPPA) (Chart 1) as the binding/activating model complex of hydroperoxide ion [7]. The design concept of this BPPA ligand is as follows. It has four characteristic functional groups: (i) slightly distorted four coordination sites for metal ion; (ii) two NH groups for hydrogen bonds to fix a small molecule such as oxygen species; (iii) two hydrophobic groups to protect from attack of external solvents and to prevent dinucleation of coordinated metal centers; (iv) pyridyl group exchangeable to the other substituents such as carboxylate group. Using various originally designed ligands with the unique functions as described below (Chart 2), the preparation, characterization, and stability/reactivity of the Cu–OOH species obtained from the reaction of their complexes with hydrogen peroxide were studied [7]. In this review, the effects of (i) hydrogen bond, (ii) hydrophobic sphere, (iii) coordination geometry around metal, (iv) coordinating

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**Scheme 1.**

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[Image: Scheme 1.png]
atoms have been described from the point of view of synthetic, spectroscopic, structural, kinetic, and theoretical chemistries, and the effects of various functional groups for the thermal stabilities (stability/reactivity) of hydroperoxo-copper complexes generated have been discussed in detail. Also strong relationship was found out between decomposition rate constant and O–O bond strength for hydroperoxo copper(II) complexes [60].

2. Preparation of Cu–OOH species as a biologically active key intermediate

Structural characterization of hydroperoxo intermediates in biological systems is very difficult because of their short lifetimes. Hydroperoxo or alkylperoxo copper(II) complexes could be sometimes prepared as model
compounds of hypothetical reaction intermediates in these oxidations [45–59]. However, the lower thermal instabilities of these compounds have prevented their characterizations. To confirm the structure of Cu(II–OOH species, the study was carried out by the following strategy: (i) Enzymatic systems use some non-covalent interactions, such as hydrogen bonding, hydrophobic, and electrostatic interactions, for biologically intrinsic functions such as molecular recognition (selectivity) and higher reactivity (efficiency). (ii) We designed some original ligands having such function sites. Novel tripodal tetradentate polypyridyl-amidine ligand BPPA was first prepared and the mononuclear copper complex with BPPA (1, Chart 1) was constructed. Using the ligand 1, we succeeded in first preparation of the mononuclear hydroperoxo copper(II) complex through the reaction with hydrogen peroxide. In this section, we describe isolation and structure characterization of the hydroperoxo copper(II) complex [Cu(bppa)(OOH)]^+ [7].

Addition of a large excess amount of hydrogen peroxide to an MeCN solution of [Cu(bppa(−))]ClO4 (1a) or [Cu(bppa)(CH3CO2)]ClO4 (1b) [7] at room temperature resulted in a slight color change from greenish blue to green. The absorption spectrum of the reaction product 1h, which is stable more than one month at room temperature, exhibited well-separated bands in the d–d region at 830 nm (250 M⁻¹ cm⁻¹) and 660 nm (150 M⁻¹ cm⁻¹) and an intense band near 380 nm (890 M⁻¹ cm⁻¹), in which the latter band can be assigned to the charge-transfer transition (LMCT) band of the hydroperoxo to copper(II) ion. ESR spectrum of the methanol solution of 1h (g∥ = 2.004, g⊥ = 2.207, |A∥| = 75, and |A⊥| = 109 G at 77 K in MeOH) was typical of a trigonal-bipyramidal mononuclear copper(II) complex, suggesting that the axial position is coordinated with an anionic donor ligand such as deprotonated hydroperoxide ion. Resonance Raman spectrum of the MeCN solution of 1h measured at room temperature (laser excitation wavelength of 441.6 nm) revealed a strong resonance-enhanced Raman band at 856 cm⁻¹ (Δν = 46 cm⁻¹) when 18O-labeled H2O2 was used. The behavior of the stretching vibration data indicates that the hydroperoxy moiety is bound to the copper(II) ion. The coordination of hydroperoxide to the Cu(II) atom has been also confirmed from mass spectroscopic behaviors. ESI mass spectrum of the MeCN solution of 1h, as measured with positive and negative ion modes, showed prominent peak clusters at m/z 584 and 784, respectively, whose observed masses and isotope patterns correspond to the [Cu(bppa)(OOH)]^+ and [[Cu(bppa)](OOH)][ClO4]− ions. The use of 18O-labeled H2O2 caused these features to shift, as expected, to m/z 588 and 788, respectively. It is thus clear from these findings that 1h can be best formulated as [Cu(bppa)(OOH)]^+. The electronic absorption, ESR, resonance Raman, and ESI mass spectra, as described above, represent the first evidence for the successful synthesis of a mononuclear hydroperoxo copper(II) complex in solution.

Fortunately, a dark green crystal suitable for X-ray diffraction measurement was obtained from an MeCN solution of 1h as stood in a cold room. The crystal structure of complex 1h (Fig. 1) revealed that coordination geometry around the copper(II) ion forms an axially compressed trigonal bipyramid, which is coordinated with three pyridine nitrogen atoms in the equatorial plane (Cu–N(2A) 1.999(5), Cu–N(2B) 2.136(4), Cu–N(2C) 2.051(6) Å) and is occupied by a nitrogen atom of the tertiary amine group (Cu–N(1) 1.999(5) Å) as one of the axial positions. Interestingly, another axial position is occupied by the hydroperoxide anion with a Cu–O(1P) bond length of 1.888(4) Å and Cu–O(1P)–O(2P) angle of 114.5°. The O–O bond distance (1.460(6) Å) is in good agreement with that of H2O2 (1.490 Å) [61] and the O(1P)–O(2P)–H(1P) valence bond angle (101.8°) is similar to that in H2O2 (96–102°) [62]. As was expected, hydrogen bonds were observed between the pivalamido NH groups of BPPA and the coordinated hydroperoxo oxygen. The distances between O(1P) and N(3A), N(3B) (2.78, 2.79 Å, respectively) correspond well to hydrogen bonding interactions (Fig. 1), which apparently contributes to fixation of the coordinated hydroperoxide ion.

These results clearly indicate that the copper complexes [Cu(bppa−)]ClO4 (1a) or [Cu(bppa)(CH3CO2)]ClO4 (1b) has reacted with hydrogen peroxide to generate [Cu(bppa)(OOH)]^+ (1h). It is also apparent that the N–H hydrogen bonding and hydrophobic tert-butyl groups contribute significantly to stabilization of extremely thermally unstable hydroperoxo species, which suggests that a particular
3. Stabilization of Cu–OOH species by hydrogen bonding interaction with its proximal oxygen atom

As described above, it was demonstrated that the thermal stability of the Cu(II)–OOH complex has been achieved by both of hydrogen bonding interaction and bulky hydrophobic groups [7]. In this session, especially the effect of hydrogen bond on stability of the generated hydroperoxo copper(II) species, [Cu(mppa)(OOH)]⁺ (2h), [Cu(mapa)(OOH)]⁺ (3h), [Cu(6-Met-pa)(OOH)]⁺ (5h), and [Cu(tpa)(OOH)]⁺ (4h) (Fig. 2), were prepared [60]. The effect was discussed using LMCT band from HOO⁻ to Cu(II), Raman shift of ν(O–O) stretching vibration, and decomposition rate of the Cu–OOH species, because the LMCT band shows the strength of Cu–O bond, the ν(O–O) stretching that of the O–O bond, and the decomposition rate those of the Cu–O and O–O bonds, respectively, and because they are closely correlated with each other. The LMCT bands of Cu–OOH species with the hydrogen bonding site, [Cu(mppa)(OOH)]⁺ (2h) and [Cu(mapa)(OOH)]⁺ (3h), were observed in the longer wavelength region than those without the hydrogen bonding site, [Cu(tpa)(OOH)]⁺ (4h) and [Cu(6-Met-pa)(OOH)]⁺ (5h); 3h (386 nm) > 2h (383 nm) > 4h (379 nm) > 5h (372 nm) (Table 1). These findings lead the following information; the Cu–OOH species without the hydrogen bonding site form a stronger Cu–O bond in comparison with those with the hydrogen bond. By the way, the weaker Cu–O bond is expected also by the steric interaction with pivalamido (2h) or amino groups (3h), which will lead the longer wavelength shift in LMCT band. However, the LMCT bands of species 2h and 3h were observed in the longer wavelength region than that of 5h, which has been explained in terms of the effect of hydrogen bond, because the bulkiness of methyl group is nearly equal to that of the amino group.

Table 1

| UV–vis* LMCT (HOO⁻ → Cu(II)) | ESR* | r.Ramanᵇ | ν₁(O=O)/cm⁻¹ |
|-------------------------------|------|----------|---------------|
|                               |      |          |               |
| BPPA (1h)                    | 380 (890) | 2.00 | 108 | 74 | 863 |
| MPPA (2h)                    | 383 (800) | 2.01 | 91 | 95 | 858 |
| MAPA (3h)                    | 386 (1150) | 2.01 | 91 | 99 | – |
| TPA (4h)                     | 379 (1700) | 2.01 | 83 | 95 | – |
| 6-MeTPA (5h)                 | 372 (540) | 2.01 | 83 | 95 | 847 |
| 4-OMe₂MPPA (6h)              | 380 (700) | 2.02 | 95 | 99 | – |
| 4-Cl₂MPPA (7h)               | 387 (500) | 2.01 | 95 | 99 | – |
| L1 (8h)                      | 381 (1100) | 1.99 | 82 | 114 | – |
| L1 (8h)ᵇ                     | 369 (1300) | 1.98 | 71 | 103 | – |
| L2 (9h)                      | 373 (1000) | 1.98 | 75 | 116 | – |
| L2 (9h)ᵇ                     | 369 (1300) | 1.98 | 76 | 103 | 848 |
| BPBA (10h)ᶜ                  | 350 (3400) | 2.26 | 175 | – | 834ᵇ |
| BPBG (11h)                   | 370 (1400) | 1.99 | 129 | 56 | 854 |
| BPAA (12h)                   | 373 (770) | 1.98 | 87 | 157 | 848 |

* In MeCN.
ᵇ In MeOH.
ᶜ In acetone.

Fig. 2. Possible structures of (a) [Cu(mppa)(OOH)]⁺ (2h), (b) [Cu(mapa)(OOH)]⁺ (3h), (c) [Cu(tpa)(OOH)]⁺ (4h), and (d) [Cu(6-Met-pa)(OOH)]⁺ (5h).
The strengths of Cu–O and O–O bonds should be reflected well to the ν(Cu–O) and ν(O–O) stretching vibrations of Cu–OOH species. As expected, the ν(Cu–O) band of 4h without the hydrogen bond was observed in the higher energy region in comparison with 1h, and the ν(O–O) band of 4h was detected in the lower energy region than 1h. These findings indicate that the hydroperoxide ion for 4h binds strongly to Cu(II) rather than 1h, which make the O–O bond of 4h weaken [60]. These results are in fair agreement with the above-mentioned considerations that there is strong relationship between the longer wavelength shift of LMCT and the hydrogen bonding interaction.

Stabilities of Cu–OOH species were discussed also from their decomposition rates. Although the Cu–OOH complex of BPPA, which has two hydrogen bonding and two hydrophobic sites, was very stable even at room temperature, those without such sites, 4h and 5h (kobs = 8.3 × 10⁻² and 1.4 × 10⁻² s⁻¹ at 283 K in acetonitrile, respectively), were unstable also in comparison with the Cu–OOH species of MMPA derivatives with one hydrogen bonding and one hydrophobic site, 2h, [Cu(4-OME₃mpppa)(OOH)]⁺ (6h), and [Cu(4-Cl₃mpppa)(OOH)]⁺ (7h) (kobs = 3.7 × 10⁻³, 4.5 × 10⁻³, and 3.1 × 10⁻³ s⁻¹ at 283 K in acetonitrile, respectively).

These findings make to expect that the stability of hydroperoxo species is raised up by the introduction of hydrogen bonding site to the Cu–OOH species.

4. Activation of Cu–OOH species by hydrogen bonding interaction with its distal oxygen atom

In recent detailed researches on the structure of DβH, it has been described that the hydroperoxide ion on Cu(II) ion is activated through hydrogen bonding interaction between non-coordinating hydroperoxide oxygen (distal oxygen) and Tyr-OH hydrogen (Scheme 1) [28,44]. From such a structural/functional interest of Cu–OOH model complexes, preparations and characterizations of some Cu(II)–OOH complexes have been reported [7,22,23,45–59]. The hydroperoxo copper(II) complex (1h) using BPPA ligand [7], which have been prepared previously by us, has been stabilized mainly by hydrogen bonding interaction between two pivalamido NH hydrogen and coordinating oxygen of hydroperoxide (proximal oxygen). At this stage, it is quite interesting to know the effect of the hydrogen bonding interaction with the distal oxygen of hydroperoxide ion, which has not been reported to our best knowledge. So we designed the novel hydroperoxo copper(II) complex which has the functional group forming a hydrogen bond with the distal oxygen [22]. We have synthesized a new ligand, N,N-diethyl-N’N’-bis(2-pyridylmethyl)ethylenediamine (L2) (9, Chart 2), which has no such a hydrogen bonding site (Fig. 3(b)), has been prepared as a reference of L1.

The two copper(II) complexes have been prepared from reactions of CuClO₄, H₂O with L1 and L2, respectively, in methanol, to give [Cu(L1)][ClO₄] (8a) and [[Cu(L2)]CO₃][ClO₄] (9a).

Addition of H₂O₂ (10 equiv.) to an acetonitrile or a methanol solution of 8a containing Et₃N (2 equiv.) at −40 °C generated a pale green colored species (8h). The electronic absorption spectrum of 8h in acetonitrile showed an intense absorption band at 381 nm (ε = 1000 M⁻¹ cm⁻¹) assignable to LMCT (OOH→Cu) and d–d bands at 635 nm (ε = 140 M⁻¹ cm⁻¹) and 770 nm (ε = 130 M⁻¹ cm⁻¹), and the corresponding spectrum of species 8h prepared in methanol gave an intense LMCT band at 369 nm (ε = 1300 M⁻¹ cm⁻¹) and d–d bands at 653 nm (ε = 145 M⁻¹ cm⁻¹) and 850 nm (ε = 160 M⁻¹ cm⁻¹), both of which are characteristic of a trigonal-bipyramidal geometry. ESR spectrum of 8h exhibited typical one suggesting the formation of trigonal-bipyramidal mononuclear copper(II) complexes with hydroperoxide ion in the axial position; g∥ = 1.99, g⊥ = 2.21, |A∥| = 82 G, |A⊥| = 114 G in acetonitrile and g∥ = 1.98, g⊥ = 2.20, |A∥| = 71 G, |A⊥| = 103 G in methanol. Resonance Raman spectrum of 8h measured in methanol at −80 °C (using 406.7 nm laser excitation) gave a weak resonance-enhanced Raman band at 814 nm (ε = 1000 M⁻¹ cm⁻¹) and that in methanol showed LMCT at 853 cm⁻¹, which shifted to 807 cm⁻¹ (Δν = 46 cm⁻¹) when ¹⁸O-labelled H₂O₂ was used. The formation of 8h was also confirmed from ESI mass spectrum measured in acetonitrile at −40 °C; a parent peak was observed at m/z 479 corresponding to the positive ion [Cu(L1)(OOH)]⁺.

Addition of H₂O₂ (10 equiv.) to an acetonitrile or a methanol solution of 9a containing Et₃N (2 equiv.) at −40 °C also gave a pale green colored species (9h). The electronic absorption spectrum of 9h in acetonitrile exhibited an LMCT band at 372 nm (ε = 1000 M⁻¹ cm⁻¹) and d–d bands at 662 nm (ε = 90 M⁻¹ cm⁻¹) and 814 nm (ε = 80 M⁻¹ cm⁻¹), and that in methanol showed LMCT at 369 nm (ε = 1100 M⁻¹ cm⁻¹) and d–d bands at 654 nm (ε = 120 M⁻¹ cm⁻¹) and 825 nm (ε = 150 M⁻¹ cm⁻¹).
with a hydroperoxide ion in the axial site; \( g_\parallel = 1.98, \ g_\perp = 2.23, \ |A_\parallel| = 75 \text{ G}, \ |A_\perp| = 116 \text{ G} \) in acetonitrile; \( g_\parallel = 1.97, \ g_\perp = 2.21, \ |A_\parallel| = 76 \text{ G}, \ |A_\perp| = 103 \text{ G} \) in methanol. Resonance Raman spectrum of a methanol solution of 9h measured at \(-80^\circ\text{C}\) (using 406.7 nm laser excitation) exhibited a weak resonance-enhanced Raman band at 848 cm\(^{-1}\), which shifted to 803 cm\(^{-1}\) (\( \Delta
\nu = 45 \text{ cm}^{-1}\)) when \(^{18}\text{O}-\text{labeled } \text{H}_2\text{O}_2\) was employed. The formation of 9h was also confirmed from positive ion ESI mass spectrum measured in acetonitrile at \(-40^\circ\text{C}\); a parent peak was observed at \( m/z \) 394 corresponding to \([\text{Cu}(\text{L}2)(\text{OOH})]^+\). The above findings indicate that in both cases the Cu(II) ions form trigonal-bipyramidal complexes with \( \text{HOO}^-\) ion in an end-on fashion in both solvents. However, interestingly the spectroscopies of the two Cu(II) complexes are subtly affected by solvents, MeCN and MeOH, as shown in Table 1. The \( \lambda_{\text{max}} \) values of LMCT and d–d bands and ESR parameters for 8h in MeCN are significantly different from the spectroscopic behaviors of 8h in MeOH, although the spectroscopic behaviors of 9h in both solvents of MeOH and MeCN are quite similar to each other. Considering that MeOH is a protic solvent that destroys the hydrogen bonding network [63], the species 8h in MeOH and 9h in both of MeOH and MeCN are thought all to form the same coordination geometry. The slightly larger \( \lambda_{\text{max}} \) of LMCT and larger \( |A_\parallel| \) value for 8h in MeCN in comparison with the other cases must suggest that the coordination of hydroperoxide ion to Cu(II) has been weakened by the hydrogen bond between the distal oxygen of hydroperoxide and NH hydrogen of L1.

Furthermore, the effect of hydrogen bond, when their decomposition rates were followed using the intensity change of decreasing LMCT bands, was apparently found out on the reactivity and stability of these hydroperoxo complexes [22]. The decomposition rates of 8h and 9h measured at \(-30^\circ\text{C}\) exhibited good first order kinetics in both solvents. In aprotic solvents such as MeCN, the decomposition rate of 8h (\( k_{\text{obs}} = 2.4(2) \times 10^{-2} \text{ min}^{-1}\)) was much faster than that of 9h (\( k_{\text{obs}} = 7.3(6) \times 10^{-3} \text{ min}^{-1}\)). On the other hand, in protic solvents such as MeOH, that of 8h (\( k_{\text{obs}} = 3.5(2) \times 10^{-3} \text{ min}^{-1}\)) was only slightly faster than that of 9h (\( k_{\text{obs}} = 2.0(3) \times 10^{-3} \text{ min}^{-1}\)). The decomposition rate of 8h is significantly affected by solvents, although that of 9h is also slightly influenced. These findings clearly indicate that 8h has been activated by the intramolecular hydrogen bonding interaction. It is quite interesting that the hydrogen bonding interaction with the proximal oxygen of Cu-coordinated hydroperoxide stabilizes the hydroperoxo copper(II) complex, while that with the distal oxygen might contribute to activation of the hydroperoxide ion. In the enzymatic reaction of D8H, it has been proposed that the hydroperoxide species intermediate bound on Cu(II) ion is activated through the hydrogen bonding interaction between non-coordinating hydroperoxide oxygen (distal oxygen) and Tyr-OH hydrogen (Scheme 1) [28,44], and the above results may support this proposal.

5. Regulation of reactivity of Cu–OOH species by change of the coordination structure from trigonal bipyramid to square plane

In the [Cu(bppa)(OOH)]\(^+\) complex, the high stability must have been attained by both effects of hydrogen bonding and hydrophobic interactions [7]. Furthermore, we would like also to suppose that the coordination structure around the metal ion might contribute to the stability as one more important factor. Because it is generally considered that the O–O bond of hydroperoxide ion, which is bound at the axial position of the Cu atom with the trigonal-bipyramidal geometry is weak, as based on the crystal field theory. So the strength of O–O bond will be correlated with the activity of the hydroperoxide species. This may be achieved by binding of hydroperoxide ion to the Cu site with a four-coordinate square-planar geometry, which is also expected from the increase in acidity of the central metal ion. Considering that the copper coordination sites in DPH and PHM are four-coordinate [1–44], the study on preparation and reactivity of the copper(II) complex with a four-coordinate square-planar or tetrahedral geometry is quite significant.

At this stage, it is very interesting to study the relationship between the reactivity of hydroperoxo copper(II) complexes and their geometry (trigonal-bipyramidal, square-pyramidal, tetrahedral, or square-planar). The relationship between the coordination geometries of hydroperoxo copper(II) complexes (square-planar and trigonal-bipyramidal) and their reactivities have never been discussed hitherto. As one of some four-coordination structures, we studied the preparation, characterization, and reactivity of the Cu–OOH species with ligand BPBA (10, Chart 2, Fig. 4), [Cu(bppa)(OOH)]\(^+\), which forces the square-planar geometry around the copper(II) ion by blocking of the apical site from attack of the other ligand due to bulky tert-butyl groups [23], and furthermore the distortion around the Cu(II) ion induced by tert-amine nitrogen and the Jahn-Teller effect will assist the protection of coordination to the apical sites.

Here we describe the synthesis, characterization and reactivity of the hydroperoxo copper(II) complex with square-planar geometry, whose reactivity have been compared with that having the trigonal-bipyramidal geometry [23]. Reaction of BPBA with an equimolar amount of Cu(ClO\(_4\))\(_2\)·6H\(_2\)O in methanol gave the complex [Cu(bppa)(MeOH)](ClO\(_4\))\(_2\) (10a). As expected from the design concept, the crystal structure of complex 10a revealed a square-planar geometry [23]. Judging from the findings that the electronic absorption (640 nm (125 M\(^{-1}\) cm\(^{-1}\)) in acetone) and ESR spectra (\( g_\parallel = 2.25, \ g_\perp = 2.07, \))...
[\text{Cu}_{\text{III}}] = 150 \text{ G in acetone at 77 K} \) are typical of a square-planar geometry, it may be suggested that the coordination geometry of 10a is also maintained in solution.

Addition of triethylamine (2 equiv.) and \( \text{H}_2\text{O}_2 \) (2 equiv.) to an acetone solution of 10a at \(-78^\circ\text{C}\) gave \([\text{Cu(bppa)(OOH)}]^+\) species accompanied by color change from blue to dark green, which showed an intense absorption band at 350 nm (3400 \text{ M}^{-1} \text{ cm}^{-1}) corresponding to LMCT (\( \text{HOO}^- \rightarrow \text{Cu(II)} \)) and d–d bands at 564 nm (150 \text{ M}^{-1} \text{ cm}^{-1}) with 790 nm (55 \text{ M}^{-1} \text{ cm}^{-1}) as a shoulder peak. The LMCT band is the shortest wavelength value among those of the hydroperoxo copper(II) species reported hitherto (380 nm for five-coordinate trigonal-bipyramidal \([\text{Cu(bppa)(OOH)}]^+\) (1b), 357 nm for five-coordinate square pyramidal \([\text{Cu}(\text{N}_3\text{S-type})(\text{OOH})]^+\) [59], 395 nm for five-coordinate \([\text{Cu}_2(\text{XLY-O})_n(\text{OOH})]^2+\) [45, 47, 49]. The LMCT band seen in the higher energy region and the ESR spectrum observed for 10h (\( g\| = 2.26, g\perp = 2.06, [A_{\text{II}}] = 175 \text{ G in acetone at 77 K} \)) suggest the formation of a square-planar copper(II) complex with a strongly coordinated hydroperoxide ion. The formulation of the square-planar hydroperoxo copper(II) complex was also demonstrated from the ESI-mass spectrum measured immediately after the reaction of 10a and \( \text{H}_2\text{O}_2 \) in acetone at \(-78^\circ\text{C}\), which has been observed as a parent peak at \( m/z \) 351.0 corresponding to the \([\text{Cu}(\text{bppa})(\text{OOH})]^+\) (10h). The Resonance Raman spectrum gave a Raman band characteristic of \( \nu(\text{O}–\text{O}) \) stretching vibration at 834 cm\(^{-1}\) as measured with 406.7 nm excitation.

As predicted in the design concept, the stability of 10h is quite lower. The decomposition rate of 10h in acetone, as followed by monitoring the absorption band at 350 nm, exhibited a first-order rate constant with \( k_{\text{obs}} = 1.88 \text{ s}^{-1} \) (\( t_{1/2} = 0.37 \text{ s} \)) at 10°C. The decomposition rate of 10h in the presence of dimethyl sulfide in acetone at \(-78^\circ\text{C}\) demonstrated a concentration dependence for the sulfide (4.63, 7.34, 11.2, and 15.2 \times 10^{-5} \text{ s}^{-1} for addition of 0, 25, 50, and 75 equiv. of sulfide, respectively). The reaction of 10h and sulfide obeyed pseudo-first order kinetics. In this reaction, the oxidation product, dimethyl sulfoxide, was obtained quantitatively against the copper complex concentration, as followed by GC.

On the other hand, the \([\text{Cu}(\text{tpa})(\text{OOH})]^+\) species (4h) with a trigonal-bipyramidal geometry, which was prepared to compare with the stability and reactivity of complex 10h, showed a quite higher reactivity in comparison with \([\text{Cu}(\text{bppa})(\text{OOH})]^+\) (1h). The decomposition rate of 4h in acetone, as followed by monitoring the intensity of absorption band at 380 nm, exhibited a first-order rate constant with \( k_{\text{obs}} = 8.3 \times 10^{-2} \text{ s}^{-1} \) (\( t_{1/2} = 8.4 \text{ s} \)) at 10°C. That in the presence of dimethyl sulfide in MeCN at \(-40^\circ\text{C}\) also became rapid and demonstrated concentration dependence for sulfide (1.6, 1.8, 1.9, and 1.9 \times 10^{-4} \text{ s}^{-1} for addition of 0, 5, 50, and 100 equiv. of sulfide, respectively). The oxidation product, dimethyl sulfoxide, obtained from this reaction was only 5% against the active species 4h, as followed by GC.

Furthermore, complex 10h exhibited catalytic oxidation for an organic substrate (Fig. 4) [23]. The reaction of dimethyl sulfide (500 equiv.) and complex 10a, which was prepared at 0°C in the presence of \( \text{Et}_3\text{N} \) (2 equiv.) in MeCN and was examined by successive addition of 100 equiv. of \( \text{H}_2\text{O}_2 \) every 15 min, showed catalytic behavior. The maximum TON (turn over number) was 120 when total amounts of 400 equiv. of \( \text{H}_2\text{O}_2 \) were added. Interestingly, detailed examination of the above reactions exhibited that their oxidations are selective [23]. That is, a further oxidation product such as dimethyl sulfone was not detected, suggesting that the active species of the hydroperoxo copper(II) complex generated is electrophilic. In addition, we tried the oxidation of thioanisole under the same experimental conditions, and the oxidation product, phenyl methyl sulfoxide, was obtained with the maximum TON of 300 when total amounts of 400 equiv. of \( \text{H}_2\text{O}_2 \) were added. Also in this reaction, a further oxidation product such as phenyl methyl sulfone was not detected. The hydroperoxo copper(II) complex which has indicated higher oxidation reactivity with such a larger TON is quite novel to our best knowledge.

As was expected, the hydroperoxo copper(II) complex with square-planar geometry 10h has demonstrated apparently larger reactivity than the trigonal-bipyramidal complex 4h. The above results will give a clue for the elucidation of the catalytic oxidation mechanism of metallo-oxidases.

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**Fig. 4.** Possible structure of \([\text{Cu}(\text{bppa})(\text{OOH})]^+\) (10h) (a), and oxidation reaction of sulfide to sulfoxide as catalyzed by 10h (b).
and for the development of oxidative catalytic hydroperoxo copper(II) complexes.

6. Regulation of stability/activity of the Cu–OOH species by change of the ligating atoms (N/O) of tripodal tetradentate ligands

The high stability of complex [Cu(bppa)(OOH)]$^{+}$ (1h) has been described above to be regulated mainly by the intramolecular hydrogen bond [7], and it was also stated that activation of the Cu–OOH species is achieved by the position of hydrogen bond and coordination geometry around the metal [7]. However, we obtained the interesting results that the coordinating atom may also contribute to the stability/activity of the Cu–OOH species; introduction of carboxylate coordination to the copper might unstabilize/activate the hydroperoxo copper(II) species generated, C–BPGA–OOH and C–BPAA–OOH systems (Chart 2, Fig. 5) [64]. Preparations and spectroscopic characterizations of Cu(II)–BPGA and Cu(II)–BPAA complexes were studied in acetonitrile and methanol solutions, and their complexes with hydroperoxide were studied by electronic absorption, resonance Raman and ESR spectroscopies [64]. The addition of hydrogen peroxide to the solution of each Cu(II) complex, [Cu(bppa)]$^{+}$ (11a) or [Cu(bppa)]$^{+}$ (12a), containing an 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 (ε = 1400 M$^{-1}$ cm$^{-1}$) and 359 nm (ε = 890 M$^{-1}$ cm$^{-1}$) for Cu–BPGA system (11h) and 373 nm (ε = 770 M$^{-1}$ cm$^{-1}$) and 358 nm (ε = 300 M$^{-1}$ cm$^{-1}$) for Cu–BPAA system (12h), respectively, in the UV region, which are assignable to the LMCT band of hydroperoxide to the copper(II) center. These are in higher energy region in comparison with those of 1h (380 nm (ε = 380 M$^{-1}$ cm$^{-1}$)). The LMCT bands of hydroperoxo copper(II) complexes in MeOH are affected sensitively, although those in MeCN are not influenced significantly. All the absorption spectra of the copper complexes in the visible region gave a spectral pattern characteristic of trigonal-bipyramidal geometry. These demonstrate that the copper(II) ions for 11h, 12h and 1h have a trigonal-bipyramidal geometry and the hydroperoxide anions occupy the axial sites. The fact that LMCT bands of the hydroperoxo copper(II) complexes with carboxylate oxygen were observed in higher energy region in comparison with that of 1h with pyridine ligand suggests that the hydroperoxide ions for 11h and 12h coordinate strongly to copper(II) ion as compared with 1h. The solvent effect observed for hydroperoxide-copper(II) complexes may suggest the formation of hydrogen bonds between hydroperoxide oxygen and pivalamido NH groups.

The frozen solution ESR spectra for 11h both in MeCN and MeOH at 77 K gave signals typical of the mononuclear Cu(II) complex with a $g_{||}$ of 1.99, $g_{\perp}$ = 2.22, $|A_{||}| = 129$ G, and $|A_{\perp}| = 56$ G in MeCN and $g_{||}$=2.07, $g_{\perp}$ = 2.23, $|A_{||}| = 133$ G, and $|A_{\perp}| = 58$ G in MeOH), which are very similar to those for 1h reported previously [7]. However, those for 12h gave the complicated spectra suggesting the mixture of square-pyramidal and trigonal-bipyrimal geometries, although the solution behavior at room temperature, as speculated from the electronic absorption spectrum, indicated the trigonal-bipyramidal one.

Resonance Raman spectra of a methanol solution containing the copper-hydroperoxo adducts 11h and 12h measured at −80°C (406.7 nm laser excitation) showed strong resonance-enhanced Raman peaks at 854 and 501 cm$^{-1}$ for Cu–BPGA–OOH system and 848 and 485 cm$^{-1}$ for Cu–BPAA–OOH system, respectively, which shifted to 808 and 492 cm$^{-1}$ for Cu–BPAA–OOH system ($\Delta$ν = 46 and 9 cm$^{-1}$) when $^{18}$O-labeled hydrogen peroxide was used. The former and latter values were assigned to ν(O–O) and ν(Cu–O) stretching vibrations, respectively. These frequencies reflect well the coordination mode between the copper and hydroperoxide: The ν(O–O) bands of 11h and 12h were observed in the lower energy region in comparison with 1h [7], and the ν(Cu–O) bands of 11h and 12h were detected in the higher energy region than 1h [7]. These findings indicate that the hydroperoxide ions bind strongly rather than 1h, which will make the O–O bonds of 11h and 12h weaken.

On the basis of these spectral behaviors, we concluded that the mononuclear hydroperoxo copper(II) complexes, [Cu(bppa)(OOH)] (11h) and [Cu(bppa)(OOH)] (12h), in solution phase are trigonal-bipyramidal and the introduction of carboxylate oxygen strengthens the coordination of external ligand such as hydroperoxide to copper ion. These make us expect as follows; the introduction of carboxylate coordination raises the activity of the hydroperoxo-copper(II) species.

In order to examine the reactivity of the Cu–OOH species, the thermal stabilities of these hydroperoxo species were pursued by monitoring intensities of their decreasing LMCT bands at 283 K. The decreasing behavior showed

![Fig. 5. Possible structures of (a) [Cu(bpga)(OOH)] (11h) and (b) [Cu(bpaa)(OOH)] (12h).](image-url)
the first order kinetics suggesting the decomposition of the hydroperoxo copper(II) species.

Hydroperoxo copper(II) complexes 11h and 12h are remarkably unstable and their decomposition rates \( k_{\text{obs}} = 1.2 \times 10^{-2}, 7.9 \times 10^{-3} \, \text{s}^{-1} \) at 283 K, respectively) are obviously faster than 1h \( k_{\text{obs}} = 2.8 \times 10^{-5} \, \text{s}^{-1} \) at 283 K in acetone [64]. It is clear that the hydroperoxo-copper species is labilized by the use of carboxylate oxygen and the hydroperoxo-copper complex 11h with carboxylate coordination of the five-membered chelate ring is unstable than 12h with that of the six-membered chelate ring. Furthermore, these Cu–OOH species, 11h, 12h and 1h, are rather stable in comparison with Cu–tpa–OOH species (4h) \( k_{\text{obs}} = 8.3 \times 10^{-2} \, \text{s}^{-1} \) at 283 K in acetone) [23]. This may be explained in terms of the hydrogen bonds between the coordinated hydroperoxide oxygen and pivalamido NH groups. As described above, the resonance Raman spectra measured in methanol solution may imply that O–O bond cleavages of hydroperoxo copper(II) complexes 11h and 12h are easier than that of 1h, because \( ^{16}\text{O}–^{16}\text{O} \) stretching vibrations of 11h and 12h (\( \nu(^{16}\text{O}–^{16}\text{O}) = 854 \) and 848 cm\(^{-1}\)) are lower than that of 1h (\( \nu(^{16}\text{O}–^{16}\text{O}) = 863 \, \text{cm}^{-1}\)) and Cu–16O frequencies of 11h and 12h (\( \nu(\text{Cu–}^{16}\text{O}) = 500 \) and 485 cm\(^{-1}\)) are higher than that of 1h (\( \nu(\text{Cu–}^{16}\text{O}) = 480 \, \text{cm}^{-1}\)).

Therefore, the order of the thermal stabilities of these hydroperoxo complexes is determined as follows; 4h < 11h < 12h << 1h. The stability of the hydroperoxo copper(II) complexes has been reduced by introduction of the carboxylate group, although they have partially been stabilized by the hydrogen bonding interaction.

7. Relationship between the \( \nu(\text{O}–\text{O}) \) stretching vibrations of Cu–OOH species and their decomposition rates

As described in the above sections, we have prepared many hydroperoxo complexes using the ligands with various functions, and have discussed their spectroscopic properties and stabilities/reactivities. The effects of hydrogen bond, steric repulsion, and coordinating atoms, coordination geometry, on the stabilities of Cu–OOH species were studied [60]. Interestingly, a strong correlation was observed between the decomposition rate constants for all Cu–OOH complexes, as measured under the same conditions at 283 K in acetone solution, and their O–O bond stretching vibrations (Fig. 6). Especially, decomposition rates for the Cu–OOH species are considered to have some correlation with their O–O stretching vibrations. That is, those with weaker O–O bond exhibit faster decomposition rate and those with stronger bond show slower rate. Furthermore, the introduction of pivalamido or amino NH group as the hydrogen bonding site with hydroperoxide ion elongates Cu–O bond and shortens the O–O one, which results in effective stabilization of the hydroperoxo copper(II) complexes.

These findings, although there is no report that has directly been discussed on the relationship between the \( \nu(\text{O}–\text{O}) \) stretching vibrations of the Cu–OOH species and their stabilities hitherto, clearly suggest that the instability of the Cu(II)–OOH species is closely correlated to their O–O bond stretchings, which could be an indicator of their stability/activity abilities.

8. Theoretical analysis of [Cu(bppa)(OOH)]\(^+\) complex and its derivatives by ab initio molecular orbital calculations

In order to study the effect of ligating atoms (N/O/S) for stability/reactivity of the Cu(II)–OOH species, the computational approaches by ab initio molecular orbital calculations were performed using the bond parameters obtained from the crystal structure of [Cu(bppa)(OOH)]\(^+\) (1h) [7]. The optimizations of [Cu(tpa)(OOH)]\(^+\) (4hc), [Cu(bpma)(OOH)] (11hc), and [Cu(bpma)(OOH)]\(^+\) (13hc) were carried out also based on that of [Cu(bppa)(OOH)]\(^+\) (1h) as an initial structure [7]. The bond parameters of fully optimized structures of [Cu(tpa)(OOH)]\(^+\) (4hc), [Cu(bpma)(OOH)]\(^+\) (1hc), [Cu(bpma)(OOH)] (11hc), and [Cu(bpma)(OOH)]\(^+\) (13hc) are listed in Table 2 together with their theoretically estimated Raman shift values. (Abbreviations: complex numbers, 1hc, 4hc, 11hc, and 13hc, denote those of the Cu–OOH complexes treated with the theoretical calculations.) Although the crystal structures of hydroperoxo copper(II) complexes except for 1h have not been reported yet, the optimized structure and bond parameters for 1hc agree well with its crystal structure. Based on these calculated results, the effects of coordinating atoms on the bonding and vibrational parameters around the metal ion have been theoretically discussed as follows.

Calculated vibrational frequencies of the peroxide O–O stretching modes are 892.7 and 879.0 cm\(^{-1}\) for [Cu(bppa)(OOH)]\(^+\) (1hc) and [Cu(tpa)(OOH)]\(^+\) (4hc),
respectively, whose tendency agrees well with that of their experimental values, although their absolute values are different from those obtained from the resonance Raman measurements \[60\]. These findings indicate that the O–O bond of \([Cu(bppa)(OOH)]^+\) \((1hc)\) is stronger than that of \([Cu(tpa)(OOH)]^+\) \((4hc)\). It is also apparent from the calculation results that difference in the O–O bond strengths arises from the presence/absence of hydrogen bond of O1P with NH groups. That is, for Cu–OOH complex \((1hc)\) having hydrogen bonds, the negative charges on O2P of peroxide group is attracted onto O1P atom, and then the O–O stretching vibration value becomes larger than that of \([Cu(tpa)(OOH)]^+\) \((4hc)\). This is observed also in the Cu–O stretching vibration as the opposite behavior. The Cu–O stretching vibration of \([Cu(tpa)(OOH)]^+\) \((4hc)\) \((506.6 \text{ cm}^{-1})\) is larger than that of \([Cu(bppa)(OOH)]^+\) \((1hc)\) \((464.2 \text{ cm}^{-1})\) indicating that the donation of peroxide to the Cu ion for \((4hc)\) is stronger than that for \((1hc)\).

For the Cu–OOH complexes with hydrogen bond, \((1hc)\), \((11hc)\), and \((13hc)\), it was found out that the complexes with larger positive charge on the Cu atom, \((11hc)\) and \((13hc)\), induced shorter O–O bond than \((1hc)\), although their Cu–O bond lengths are insensitive to the charge. The peroxide O–O bond lengths of \([Cu(bpga)(OOH)]\) \((11hc)\) \((1.462 \text{ Å})\) and \([Cu(bpma)(OOH)]\) \((13hc)\) \((1.457 \text{ Å})\) exhibited longer values than that of \([Cu(bppa)(OOH)]^+\) \((1hc)\) \((1.452 \text{ Å})\), suggesting that a stronger donation of the methionine S or negatively charged carboxylate O atoms to the Cu(II) ion inhibited the donating ability of the peroxide. Excess negative charges remained on the peroxide O atoms was affected as the electrostatic repulsion between two oxygen atoms of peroxide rather than the attractive interaction with Cu atom, which weaken the O1P–O2P bonds for \([Cu(bpga)(OOH)]\) \((11hc)\) and \([Cu(bpma)(OOH)]\) \((13hc)\). Moreover, the negative charge on the O1P atom for \([Cu(bppa)(OOH)]^+\) \((1hc)\) is larger than that for

### Table 2

| Bond lengths (Å) | [Cu(tpa)(OOH)]^+ \((4hc)\) | [Cu(bppa)(OOH)]^+ \((1hc)\) | [Cu(bpga)(OOH)] \((11hc)\) | [Cu(bpma)(OOH)]^+ \((13hc)\) |
|------------------|--------------------------|--------------------------|--------------------------|--------------------------|
| Cu–O1P           | 1.867                    | 1.887                    | 1.889                    | 1.887                    |
| Cu–N1            | 2.123                    | 2.048                    | 2.030                    | 2.069                    |
| Cu–N2A           | 2.088                    | 2.164                    | 2.181                    | 2.121                    |
| Cu–N2B           | 2.082                    | 2.179                    | 2.153                    | 2.186                    |
| Cu–X2Cb          | 2.153                    | 2.141                    | 2.004                    | 2.590                    |
| O1P–O2P          | 1.458                    | 1.452                    | 1.462                    | 1.457                    |
| O1P–N3A          | –                        | 2.850                    | 2.850                    | 2.832                    |
| O1P–N3B          | –                        | 2.854                    | 2.828                    | 2.905                    |
| \(\tau\) values | 0.87                     | 0.83                     | 1.01                     | 0.59                     |

### Raman shifts (cm\(^{-1}\))

| \(\nu^{16O-16O}\) | \((879.0)\) | \((892.7)\) | \((890.2)\) | \((876.9)\) |
| \(\nu(Cu-16O)\)   | \((506.6)\) | \((464.2)\) | \((479.3)\) | \((485.1)\) |

\(^a\)Labeling scheme of Cu-OOH complexes; \((a)\) [Cu(tpa)(OOH)]^+ \((4hc)\), \((b)\) [Cu(bppa)(OOH)]^+ \((1hc)\), \((c)\) [Cu(bpga)(OOH)] \((11hc)\), and \((d)\) [Cu(bpma)(OOH)]^+ \((13hc)\).

\(^b\)X = N \((1hc), 4hc\), O \((11hc)\), S \((13hc)\).
[Cu(tpa)(OOH)]⁺ (4hc), which suggests that the hydrogen bonding pivalamido NH groups attract O1P to hold the negative charge there.

Here, in order to estimate the unknown ligand X of CuB site in DβH [24–40], we tried to theoretically investigate the reactivity of Cu–OOH species from the difference in coordinating atoms, nitrogen, oxygen, and sulfur atoms. The reactivity is considered to be reflected to the Cu–O and O–O bond lengths and their corresponding stretching vibrations, υ(Cu–O) and υ(O–O), in which the latter are supposed to have close correlation with the reactivity of the Cu–OOH species as discussed in the above section. The estimated Cu–O and O–O bond lengths of the hydroperoxide ion for [Cu(tpa)(OOH)]⁺ (4hc), [Cu(bpga)(OOH)]⁺ (1hc), [Cu(bpga)(OOH)] (11hc), and [Cu(bppma)(OOH)]⁺ (13hc) are estimated as follows, 1.867 and 1.458 Å for 4hc, 1.887 and 1.452 Å for 1hc, 1.889 and 1.462 Å for 11hc, 1.887 and 1.457 Å for 13hc, respectively (Table 2) [60]. However, there was no significant relationship between the instability of the Cu–OOH complexes and their bond lengths, although the effect of the hydrogen bond was detected for the Cu–O bond lengths. The Cu–OOH complexes with the hydrogen bond (1hc, 11hc, and 13hc) showed the longer Cu–O bond in comparison with that without such a bond (4hc). It was not detected also in the O–O bond lengths. On the other hand, we found out important relationship between the instability and the υ(Cu–O) or υ(O–O) stretching vibration. Those of species 4hc (306.6 and 879.0 cm⁻¹, respectively), which showed faster decomposition rates in comparison with 1hc and 11hc, were found out in lower and higher frequency regions than those of 1hc (464.2 and 892.7 cm⁻¹, respectively) and 11hc (479.3 and 890.2 cm⁻¹, respectively). According to this consideration, the species 13hc having higher υ(Cu–O) and lower υ(O–O) frequencies (485.1 and 876.9 cm⁻¹, respectively) may exhibit the highest reactivity among these species. These findings suggest that the hydroperoxo copper complex with methionine sulfur-containing ligand may indicate a higher reactivity than those with the other nitrogen- and oxygen-containing ligands. Thus, we can propose methionine sulfur rather than nitrogen-containing and carboxylate ligands as the unknown X ligand activating hydroperoxide ion on the CuB site of DβH [60].

9. Summary and conclusion

The essential strategy in development of environment-friendly materials is to use a biological system itself or to synthesize the model system that has been mimicked from its active center. In order to construct such oxidation catalyst materials, we have approached some basic studies on the structure–function relationship of non-heme copper oxygenases using the model complexes which were originally designed and synthesized on the basis of the active center of metalloenzymes [1–23]. We have first succeeded in isolation and structure analysis of the hydroperoxo copper(II) complex with the tripodal tetradentate ligand, BPPA, [Cu(bppa)(OOH)]⁺ (1h) [7]. This complex is extremely thermally stable for one month or more. The crystal structure and spectroscopic analysis revealed that it has been achieved by the hydrogen bond of proximal oxygen of hydroperoxide with the pivalamido NH group and sterically bulky hydrophobic tert butyl groups. In this review, the effects of proximal hydrogen bond [7,60], distal hydrogen bond [22], coordinating atoms [64], and coordination geometry [23] for the stability/reactivity of the Cu–OOH species were discussed from the point of view of synthesis, crystal structure, spectroscopic characterization, theoretical analysis, and decomposition rate. And it has also been demonstrated that the resonance Raman shifts (υ(O–O) and υ(Cu–O)) are closely correlated to the decomposition rates of Cu–OOH species [60]. We succeeded in regulation of stability/reactivity of the hydroperoxo copper(II) complexes using our originally designed ligands, which are very important as a basic compound of oxidation catalyst. The information obtained from these studies on design concept, synthesis, structure, and function will contribute to the development of the oxidation catalyst materials.

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