

## Photocatalytic Oxidation of 2-Mercaptoethanol to Disulfide using Sb(V)-, P(V)-, and Ge(IV)-porphyrin Complexes

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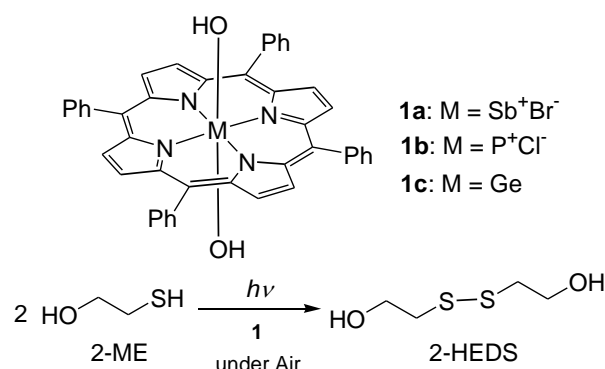
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**ABSTRACT:** Visible-light irradiation of MeCN solution containing di(hydroxo)metallo(tetraphenyl)porphyrin complex (tppM(OH)<sub>2</sub>: **1a**; M=Sb(V)<sup>+</sup>Br<sup>-</sup>, **1b**; M=P(V)<sup>+</sup>Cl<sup>-</sup>, **1c**; M=Ge(IV)) and 2-mercaptoethanol (2-ME) as a substrate under aerated condition gave bis(2-hydroxyethyl)disulfide (2-HEDS) as an oxidative product of 2-ME. It is indicated that the oxidation of 2-ME should proceed with a photocatalytic process by **1**, because the turn over number (TON) for the formation of 2-HEDS was over unit. The TON was determined to be 642 as a maximum value when **1a** was used as a sensitizer. The formation of 2-HEDS was extremely slow under argon atmosphere. The fluorescence of **1** was not quenched by 2-ME at all, and the free energy change ( $\Delta G$ ) with electron transfer (ET) from 2-ME to excited triplet state of **1**<sup>(3)1\*</sup> was estimated as a negative value. The quenching rate constant ( $k_r$ ) of **1**<sup>(3)1\*</sup> by 2-ME, obtained by the kinetics for the formation of 2-HEDS, strongly depends on  $\Delta G$ . These findings indicate that **1**-sensitized oxidation was initiated by photoinduced ET from 2-ME to **1**<sup>(3)1\*</sup> to generate both radical cation of 2-ME (2-ME<sup>•+</sup>) and porphyrin radical anion (**1**<sup>•-</sup>), resulting that the formation of 2-HEDS can be proceeded by the dimerization of 2-ME<sup>•+</sup>, and through a catalytic cycle due to returning to **1** by the ET from **1**<sup>•-</sup> to molecular oxygen.

The formation of disulfide bonds is an important function for controlling the structure and stability of proteins<sup>1</sup> and nanoparticles such as CdSe.<sup>2</sup> There are many studies on the oxidation of thiols for the synthesis of disulfides using an oxidant such as molecular bromine,<sup>3,4</sup> anhydrous potassium phosphate,<sup>5</sup> I<sub>2</sub>/CeCl<sub>3</sub>·7H<sub>2</sub>O,<sup>6</sup> silica chloride<sup>7</sup>, manganese (VII) oxide<sup>8</sup> and Rh complex.<sup>9</sup> Although the harmful and expensive oxidants and catalyst were used in these systems, the developments of oxidation process using a clean, safe, and economical oxidant are recently desirable from viewpoints of the alternative to environmental-friendly chemical process. On the other hand, we found that di(hydroxo)antimony(tetraphenyl)-porphyrin complex (**1a**) adsorbed on silica gel catalyzed the photooxidation of cyclohexene to cyclohexanol under visible light irradiation,<sup>10,11</sup> and that di(hydroxo)germanium(tetraphenyl)-porphyrin complex (**1c**) adsorbed on silica gel also catalyzed the photooxidation of methanol to formaldehyde under same condition.<sup>12</sup> In both cases, the oxidations were initiated by photoinduced electron transfer from **1a** and **1c** to molecular oxygen (O<sub>2</sub>). Accordingly, there is an advantage of being able to utilize O<sub>2</sub> as an oxidant in our systems. Little is known about the formation of disulfide bond from thiol using a photochemical process. Although the production of disulfides by directly irradiation toward thiophenol derivatives was

reported,<sup>13</sup> there is no report on photocatalytic production of disulfide from thiol under mild conditions. Here we will report on **1**-sensitized oxidation of 2-mercaptoethanol (2-ME) to bis-(hydroxyethyl)disulfide (2-HEDS) at room temperature and under air atmosphere (Scheme 1).

**Scheme 1.** **1**-Sensitized oxidation of 2-ME to 2-HEDS



2-ME, 2-HEDS, iron(III) nitrate hydrate (Fe(NO<sub>3</sub>)<sub>3</sub>·9H<sub>2</sub>O) and some organic solvents were purchased from Wako Pure Chemical Industries as a guaranteed reagent grade (GR) and used without further purification. **1** were synthesized according to the literature.<sup>11, 12, 14</sup> The quantitative analysis of 2-HEDS was performed on GC-MS (Shimadzu QP-2000) with a capillary column (DB-1; 25 m × 0.25 mm × 0.25 μm). UV-vis absorption spectra and fluorescence spectra of the reaction solution were obtained with a JASCO V-550 spectrophotometer and a Shimadzu RF 5300PC spectrophotometer, respectively. An MeCN solution (10 mL) containing **1** (0.33 mmol), 2-ME (0.2 – 1.0 M, usually 1 M) was prepared and introduced into a glass tube (20 mmφ × 36 mm). Photoreactions were performed in a glass tube at room temperature under air atmosphere by an irradiation of 550 nm light obtained the glass-filter with Xenon lamp (500 W). The photon number was measured to be 19.0 × 10<sup>-6</sup> einstein / min. at 550 nm using the photoreaction of cumene with **1c** as an actinometer.<sup>15</sup>

The results of photooxidation of 2-ME to 2-HEDS sensitized by **1** under various conditions are summarized in Table 1. 2-HEDS was formed in the **1a**-photosensitized reactions in MeCN, THF and toluene, depending on the polarity of solvent. Since the use of MeCN gave much reactivity, MeCN was selected as a proper solvent for the photoreaction. In MeCN, the use of **1b** and **1c** as a sensitizer also gave the formation of 2-HEDS. It was confirmed that no formation of 2-HEDS was observed without both **1** and visible light.

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In the case of both tetraphenylporphyrinatozinc(II) (**2**) and tetraphenylporphyrin (**3**), 2-HEDS was not also formed at all. The quantum yield ( $\Phi_{s-s}$ ) and turn over number (TON) for the formation of 2-HEDS were estimated to be 0.030 and 642 for **1a**, 0.017 and 465 for **1b**, and 0.012 and 300 for **1c**, respectively (Table 1). Furthermore, the decompositions of **1** were not observed during photoreaction because the absorptions (Soret band) of **1** were not changed after the photoreaction at all. Therefore, **1** works as a photocatalyst in this system, and **1a** showed a highest reactivity among **1a-1c**.

**Table 1.** Photooxidation of 2-ME to 2-HEDS Sensitized by 1-3<sup>a</sup>

Mtp	Conditions		2-HEDS		
			Yield/ $\mu$ mol	TON <sup>b</sup>	$\Phi_{s-s}$
<b>1a</b>	Air	MeCN	212	642	0.030
	Air	THF	182	552	0.022
	Air	Toluene	147	445	0.017
	Ar	MeCN	26	64	0.003
	Ar	MeCN <sup>b</sup>	206	624	0.034
	O <sub>2</sub>	MeCN	50	179	0.007
<b>1b</b>	Air	MeCN	153	465	0.017
	Ar	MeCN	54	164	0.007
<b>1c</b>	Air	MeCN	99	300	0.012
	Ar	MeCN	31	94	0.004
<b>2</b>	Air	MeCN	0	0	0.000
<b>3</b>	Air	MeCN	0	0	0.000

<sup>a</sup> Reaction conditions: [2-ME]=1.0 M, [1]=0.33  $\mu$ mol, solvent=10 mL Irradiation time was 6 h. <sup>b</sup> In the presence of Fe<sup>3+</sup> cation.

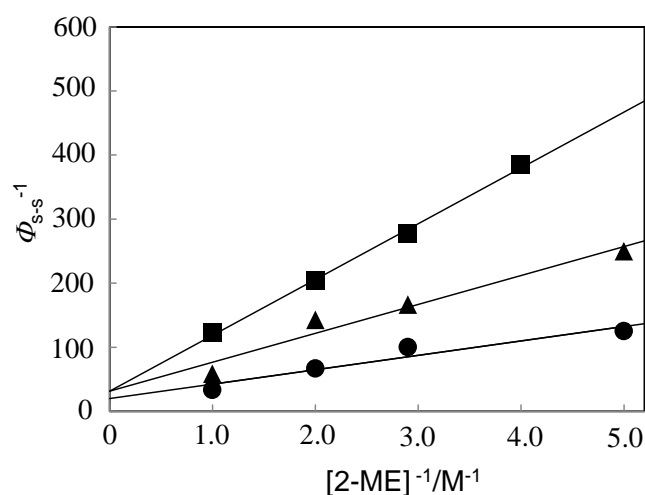
Next, when the photoreactions using **1** were performed under argon atmosphere, the amounts of 2-HEDS were extremely decreased (Table 1). These results indicate that the oxidant should be O<sub>2</sub>. In the oxidation using O<sub>2</sub>, it is generally suggested that the oxidation process should proceed via an auto-oxidation mechanism or a singlet oxygen formed by triplet-triplet energy transfer from an excited state of dye molecules to O<sub>2</sub>. In the photoreaction by **1a**, 2-HEDS was formed with same yield in the presence of Fe<sup>3+</sup> (Fe(NO<sub>3</sub>)<sub>3</sub>) as an electron acceptor under argon atmosphere, but extremely decreased rather under excess O<sub>2</sub> than under aerated condition (Table 1). These results suggest that both auto-oxidation mechanism and the singlet oxygen mechanism should not be contributed to the formation of 2-HEDS at all, and that the O<sub>2</sub> should act as an electron acceptor for **1** in this system.

A reaction mechanism was elucidated by the fluorescence quenching experiment of **1** and the kinetic analysis for  $\Phi_{s-s}$ . The fluorescences of **1** were not quenched at all in the presence of 2-ME (1 M). Similar result was obtained even in the presence of Fe<sup>3+</sup>. These results show that an initial step of photoreaction can proceed from the excited triplet state of **1** (<sup>3</sup>**1**\*), not excited singlet state of **1** (<sup>1</sup>**1**\*). It is suggested that the initial step is a photoinduced electron transfer (PET) process from 2-ME to <sup>3</sup>**1**\*, because the free energy changes ( $\Delta G$ ) calculated by Rehm-Well equation<sup>16</sup> are much exoergic ( $\Delta G = -0.52$  eV for **1a**,  $\Delta G = -0.24$  eV for **1b**, and  $\Delta G = -0.09$  eV for **1c**), as shown in Table 2. Assuming the reaction route shown in Scheme 2,  $\Phi_{s-s}$  is expressed using Equation 1 where  $\Phi_{isc}$  is the quantum yield of intersystem crossing of **1**,  $\alpha$  is the efficiency of charge separation,  $\beta$  is the efficiency of product formation from an intermediate,  $k_d$  and  $k_r$  are the rate constants for the deactivate process from <sup>3</sup>**1**\* to ground state and that for electron transfer from 2-ME to <sup>3</sup>**1**\*, respectively

$$\Phi_{s-s} = \Phi_{isc} \cdot \alpha \beta \cdot \frac{k_r [2-ME]}{k_d + k_r [2-ME]} \quad (1)$$

$$\frac{1}{\Phi_{s-s}} = \frac{1}{\Phi_{isc} \cdot \alpha \beta} \cdot \left( 1 + \frac{k_d}{k_r [2-ME]} \right) \quad (2)$$

According to equation 1, the reciprocal of  $\Phi_{s-s}$  is proportional to the reciprocal concentration of 2-ME ([2-ME]) (Equation 2). Figure 3 shows a double reciprocal plot (Stern-Volmer type plot) of  $\Phi_{s-s}$  against [2-ME] in **1**-sensitized photooxidation under aerated



**Figure 1.** Double reciprocal plots of the  $\Phi_{s-s}$  against the concentration of 2-ME in the oxidation sensitized by **1a** (●), **1b** (▲) and **1c** (■), respectively.

conditions where  $\Phi_{s-s}$  was measured at various concentration of 2-ME. In fact, all plots laid well on a straight line. These results strongly indicate the single excited species of **1** should be responsible for a reaction from 2-ME (Scheme 2). Table 2 summarizes the kinetic parameters obtained from both slope and intercept values in each plot. The  $k_r/k_d$  values can be regarded as the rate constant of PET, assuming that  $k_d$  value is almost same among **1** under aerated condition because the quenching of triplet state of porphyrins by O<sub>2</sub> is known to very fast in the porphyrin systems.<sup>17</sup> The  $k_r/k_d$  values depended on  $\Delta G$ . This result strongly indicates that the PET from 2-ME to <sup>3</sup>**1**\* occurred in the photooxidation system, as shown in Scheme 2. Moreover, the dependence of reactivity on the solvent polarity can be also explained reasonably using the PET mechanism. The limiting quantum yield ( $\Phi_{lim}$ ) for the formation of 2-HEDS is shown in Table 2. Since the values of  $\Phi_{isc}$  on metalloporphyrins are generally estimated to be around 0.9, total efficiency ( $\alpha\beta$ ) of reductive process including PET became 4.9 % for **1a**, 1.2 % for **1b** and 8.3 % for **1c**, respectively. These percentages directly show relative values of  $\alpha$ , because  $\beta$ , which is related on the efficiency of dimerization of free 2-ME<sup>•+</sup>, can be almost same among **1**. The reason why **1c** shows the highest  $\alpha$  might be attributed to the suppression of back ET owing to the faster ET from radical anion of **1c** (**1c**<sup>•-</sup>) to O<sub>2</sub>, leading the formation of a superoxide radical anion (O<sub>2</sub><sup>•-</sup>), because the reductive force of **1c**<sup>•-</sup> can be the strongest in **1**, judging from the reduction potential of **1**.

A plausible reaction mechanism was shown in Scheme 2. Upon visible light irradiation, **1**<sup>•-</sup> is formed by a PET from 2-ME to

$^3\mathbf{1}^*$ , leading the formation of a radical cation of 2-ME (2-ME $^{+\bullet}$ ) and  $\text{O}_2^{\bullet-}$ . 2-ME $^{+\bullet}$  is converted to thionyl radical (2-ME $^{\bullet}$ ) through the deprotonation process of 2-ME $^{+\bullet}$  rapidly, leading to the formation of 2-HEDS by coupling reaction between two 2-ME $^{\bullet}$ . On the other hand,  $\mathbf{1}^*$  is oxidized by  $\text{O}_2$ , to return to original  $\mathbf{1}$ .

**Table 2.** Reduction Potential of  $\mathbf{1}$ ,  $\Delta G$  and Kinetic Parameters in 1-sensitized Oxidation of 2-ME

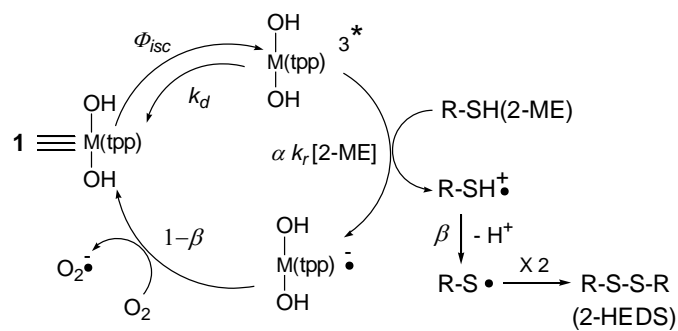
Mtpp	$E_{1/2}^{\text{red}}/\text{V}^{\text{a}}$	$\Delta G/\text{eV}^{\text{b}}$	$k_r/k_d$	$\Phi_{\text{lim}}$
<b>1a</b>	-0.51	-0.52	1.01	0.044
<b>1b</b>	-0.79	-0.24	0.36	0.011
<b>1c</b>	-1.12	-0.09	0.24	0.075

<sup>a</sup> Reduction potentials of  $\mathbf{1}$  vs. SCE <sup>b</sup>  $\Delta G = E^{\text{ox}}(2\text{-ME}) - E^{\text{red}}(\mathbf{1}) - E^{\text{T}}$  where triplet energy ( $E^{\text{T}}$ ) = 1.63 eV<sup>15</sup> and the oxidation potential of 2-ME ( $E^{\text{ox}}$ ) = 0.6 vs. SCE.<sup>18</sup>

Thus, the formation of 2-HEDS from 2-ME proceeds catalytically with  $\mathbf{1}$ . It is suggested that when  $\text{Fe}^{3+}$  was used as an electron acceptor instead of  $\text{O}_2$  under argon atmosphere, the photooxidation of 2-ME can proceed accompanying the reduction of  $\text{Fe}^{3+}$  by  $\mathbf{1}^*$  formed with PET. Furthermore, the decrease of reactivity under excess  $\text{O}_2$  can be attributed to a retardation of PET from  $^3\mathbf{1}^*$  to 2-ME due to the effective energy transfer from  $^3\mathbf{1}^*$  to  $\text{O}_2$ .

In conclusion, it was elucidated that the production of 2-HEDS from 2-ME could be proceeded by the dimerization of 2-ME $^{+\bullet}$  formed by PET from  $^3\mathbf{1}^*$  under visible light irradiation. Therefore,  $\mathbf{1}$  can be a candidate for an oxidative catalyst to lead the formation of disulfide bond from thiol by utilizing  $\text{O}_2$  as an oxidant.

**Scheme 2.** A possible reaction mechanism for 1-sensitized oxidation of 2-ME to 2-HEDS



**KEYWORDS:** High-valent metalloporphyrin, Photooxidation, Disulfide bond formation

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