Physical Properties of Self-Assembled Monolayers of Mercapto Oligo (ethylene oxide) Methyl Ether on Gold

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Abstract: Physical properties (chemical adsorption rate, viscoelasticity, thickness, and conformation) for self-assembled monolayers (SAMs) of mercapto oligo (ethylene oxide) methyl ethers on gold were determined by quartz crystal microbalance (QCM). The values of thickness, shear viscosity and elastic shear modulus of SAMs increase with unit number of oligo (ethylene oxide) segment. However, the chemical adsorption rate determined by a Langmuir isotherm does not show such a unit number regularity. Those results suggest that difference in unit number of oligo (ethylene oxide) segment can significantly affects physical properties of SAMs.

Key words: SAM, oligo (ethylene oxide), QCM, helical conformation, chemical adsorption rate

1 INTRODUCTION

Dynamic responses of nanostructured materials in thin films are surely hot topics. In such dynamic responses, surface resistance to protein adsorption is one of subjects and of great interest in the fields of potential applications such as blood-contacting devices, implanted devices, substrates for cell culture and diagnostic technologies. A number of surfaces fabricated by poly(ethylene oxide), oligo(ethylene oxide) (OEO), zwitter ionic groups, and those derivatives have been synthesized and characterized by ability to resist protein adsorption. Especially, OEO-terminated self-assembled monolayers (SAMs), HS(CH₂)ₘ(OCH₂CH₂)ₙOH and HS(CH₂)ₘ(OCH₂CH₂)ₙOCH₃, have been studied extensively. These studies were applied to construction of a theory, steric repulsion model. In the steric repulsion model, protein adsorption resistance of ethylene oxide (EO) segments is considered to derive from steric effects that oppose the EO-protein surface attractive forces (hydrophobic attraction and van der Waals attraction). This steric repulsion has a viscoelastic and an osmotic component. While the viscoelastic component is caused by compression and restriction of EO segments, the osmotic component is derived from solvation ability of EO segments. That is, the amount of hydration water for SAM depending on the solvation ability of EO segments is one of important factors to evaluate the protein adsorption resistance.

On the other hand, it has been reported that SAM on gold is highly dynamic with adsorption, desorption, and structural rearrangement playing an important role to determine macroscopic properties of SAM. Despite such profound understanding for SAM, insights into the SAM formation, namely, studies on chemical adsorption rate depending on unit number of EO segment to form SAM, seems to be lack.

In this paper, physical properties for mercapto oligo (ethylene oxide)methyl ethers, HS(CH₃CH₂O)ₙCH₃, is investigated by quartz crystal microbalance (QCM). In particular, we focus on variation of chemical adsorption rate, thickness, shear viscosity, elastic shear modulus and conformation depending on difference in unit number of EO segment. For this purpose, we employ HS(CH₃CH₂O)ₙCH₃.
(n = 5, 11 and 12). Those EO segments induce clear difference in physical properties depending on those unit numbers. The compounds HS(CH₂CH₂O)ₙCH₃, where n = 5, 11 and 12, hereafter are referred to as (EO)₅, (EO)₁₁, and (EO)₁₂, respectively.

2 EXPERIMENTAL

2.1 Synthesis of mercapto oligo(ethylene oxide) methyl ethers

Compounds (EO)₅, (EO)₁₁, and (EO)₁₂ were synthesized by the methods described in Supporting Information. In this study, we employed 1mM aqueous solutions of the compounds in all experiments.

2.2 QCM measurements

The 9MHz AT-cut QCM with a pair of gold electrodes was used in all experiments. QCM was purchased from Nihon Dempa Kogyo(Tokyo, Japan). Impedance analyzer(Agilent Technologies 4395A) was used for resonant-frequency properties of QCM. Impedance and phase data associated with 801 frequency data points centered at frequency of minimum impedance were recorded on a personal computer. Values of ΔF and ΔΩ at the 3rd, 5th, 7th, 9th overtone of fundamental resonant frequency were calculated from admittance analysis. On the other hand, time series of ΔF were measured by a series resonant TTL circuit (SEIKO EG&G QCA917-21, Japan).

The cell volume was 8 ml. The cell had a water jacket to keep temperature constant. One side of QCM was sealed with a blank quartz crystal casing, maintaining it in an air environment. QCM was mounted level with water surface and immersion depth of QCM was set at 0.5 cm. Gold electrodes of QCM were rinsed with the piranha solution (H₂SO₄:H₂O₂ (30%) = 3:1) prior to onset of measurements of impedance and time series. The cell temperature was adjusted to 25 ± 0.1°C. In impedance measurement, QCM immersed into compound solutions were left for 3 h prior to onset of impedance measurement. The compound solutions were stirred by a stirrer bar. The stirrer bar was stopped when the impedance properties of QCM were measured. In time series measurement, measurement of ΔF was started as soon as QCM was immersed into compound solutions, where the solutions were continuously stirred by stirrer bar at 300 rpm. Both impedance and time series measurement were carried out under the batch condition. The statistical values in experiments were obtained from completely repeated experiments.

2.3 Cyclic voltammetry

Dry masses of SAMs on gold electrodes were determined by cyclic voltammetry (CV) to calculate ρ_{ad} and h_{ad}. Treatments of QCM prior to onset of measurements in CV were the same as those in impedance measurements. The electrochemical reductive desorption method on gold surface was adopted to determine molecular concentrations of membranes. Cyclic voltammetry was carried out in 1 M potassium hydroxide solution at room temperature, using a PAR 263A (EG&G Princeton Applied Research) potentiostat equipped with an external potential scanner (model 175, EG&G PARC). The sweep rate was 20 mV/sec and the electrolyte solution was deaerated by flowing nitrogen. Saturated calomel electrode and Pt wire were used for the electrochemical measurements as reference and counter electrodes, respectively. As an example, cyclic voltammogram for (EO)₁₂ is illustrated in Supporting Information.

3 RESULTS AND DISCUSSION

3.1 Chemical adsorption rates onto gold surface

Chemical adsorptions of the compounds to form SAMs are described by

\[
\text{HS(EO)}_5 \text{CH}_3 + \text{Au} \xrightarrow{\Delta} \text{AuS(EO)}_5 \text{CH}_3 + \frac{1}{2} \text{H}_2, \tag{i}
\]

where k is adsorption constant. A Langmuir model was adopted to deduce kinetics of the chemical adsorption for compounds onto gold surface (Au(111)). The Langmuir isotherm is based on assumptions that adsorption is limited to monolayer, that all surface sites are equivalent, and that adsorption to one site is independent of occupancy condition of adjacent sites. The rate of surface reaction governed by the Langmuir isotherm is given by

\[
S = R_s (1 - e^{-kt}),
\]

where S is fraction of surface covered, R_s is maximum quantity of adsorption, and t is time.

Figure 1 shows time series of the frequency shift, ΔF, for chemical adsorptions of compounds in 1mM aqueous solutions. Fitting curves induced with the obtained data according to equation (1) are also shown in Fig. 1. Those are in good agreement with the experimental data. Therefore, the chemical adsorptions of compounds onto gold surface are considered to follow the Langmuir isotherm. As a result, the k values for (EO)₅, (EO)₁₁, and (EO)₁₂ are determined as 5.00 × 10⁻³ ± 3.1 × 10⁻⁴, 5.15 × 10⁻⁴ ± 5.0 × 10⁻⁵ and 7.11 × 10⁻⁴ ± 3.0 × 10⁻⁵ s⁻¹, respectively. The k value for (EO)₅ is the largest, and it is known that the k value decreases with an increase in molecular weight. However, the k value for (EO)₁₂ is larger than that for (EO)₁₁. This result suggests that the free energy to form SAM with (EO)₁₂ is smaller than that with (EO)₁₁. This phenomenon can bring to mind odd-even effect observed in SAM of n-alkanethiols, where the free energy of SAM with even number of methylene is smaller than that with odd number of methylene. Therefore, it is considered that the relationship between the k values of (EO)₁₁ and (EO)₁₂ shows a kind of odd-even
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1/2

Fig. 1 Time series of the chemical adsorption of (EO)₅, (EO)₁₁, and (EO)₁₂. (a) (EO)₅; (b) (EO)₁₁; (c) (EO)₁₂. Experimental data are plotted at 10s. Solid line and dashed line show experimental data and fitted values calculated from equation (1), respectively.

3.2 Physical properties of SAM

Next, in order to obtain further insight into SAM, we investigated physical properties of SAM in an aqueous solution, i.e., thickness, shear viscosity, elastic shear modulus and conformation. Here, properties of SAM are discussed according to the equation

\[ \Delta F = - \frac{h_s \cdot \rho_s \omega_s}{2 \pi \rho_s \eta_s} \left( 1 - \frac{\eta_s}{\rho_s} \times \frac{\eta_s \omega_s^2}{\rho_s (\mu_s + \omega_s^2 \eta_s)} \right), \]

(2)

\[ \Delta D = \frac{2h_s \cdot \rho_s \omega_s}{\rho_s \cdot \mu_s + \omega_s^2 \eta_s}, \]

(3)

where \( \Delta F \) and \( \omega_s \) are dissipation factor shift and angular frequency of QCM, \( h_s \) and \( \rho_s \) are quartz crystal thickness and density, \( \eta_s \) and \( \rho_s \) are bulk liquid viscosity and density, \( h_s, \rho_s, \mu_s \) and \( \eta_s \) are SAM’s thickness, density, elastic shear modulus and shear viscosity, respectively. Furthermore, the sensed mass, \( m_{QCM} \), is obtained as

\[ m_{QCM} = h_s \cdot \rho_s \]

(4)

In order to obtain the real thickness of SAM, CV was used as a complementary technique. CV can measure the number of molecules bound to gold per unit area, i.e., dry mass of SAM. The \( \rho_{eff} \) and \( h_{eff} \) of SAM can be yielded by combining CV and impedance data as

\[ \rho_{eff} = \frac{m_{QCM} - m_{CV}}{m_{QCM} + \rho_{SAM} \cdot m_{CV}} \cdot m_{CV}, \]

(5)

\[ h_{eff} = \frac{m_{QCM}}{\rho_{eff}}, \]

(6)

where \( m_{CV} \) is mass measured by CV, \( \rho_{water} \) is water density of 997 kg/m³ and \( \rho_{SAM} \) is SAM’s density estimated as 1200 kg/m³.[24, 25]

\( \Delta F \) and \( \Delta D \) of QCM were measured with different harmonics by using impedance analyzer. Values for \( \Delta F \) and \( \Delta D \) of 3rd, 5th, 7th, 9th overtone of fundamental resonant frequency were measured after 3 h of immersion into compound solutions, because \( \Delta F \) values for \((\text{OE})_5,(\text{OE})_{11}, \) and \((\text{OE})_{12}\) becomes constant more than ca.10, 50, and 47 min as shown in Fig. 1, respectively.

Figure 2 shows values for \( \Delta F \) and \( \Delta D \) of the compounds against different harmonics of QCM. On the basis of equations (2)-(6), physical properties of SAMs were calculated from values of \( \Delta F \) and \( \Delta D \) in Fig. 2 due to genetic algorithm of MATLAB. In this case, the frequency dependency of \( \mu_s \) and \( \eta_s \) was taken into account. According to the method of ref 22, those values were calculated at the fundamental frequency of QCM (9 MHz) with \( \rho_{eff} \) and \( h_{eff} \).

The results of physical properties are listed in Table 1. Values for \( h_s, \mu_s \) and \( \eta_s \) of SAM increase with molecular weight. Especially, \( \mu_s \) values show drastic shift with an increase in molecular weight. This may be caused by increase of interaction among the compounds.

3.2.1 Conformations of SAMs: \( h_s \) values

As shown in Table 1, when EO segment is assumed as 7/2 helical conformation rather than all-trans conformation, \( h_s \) values of SAMs for \((\text{EO})_5, (\text{EO})_{11}, \) and \((\text{EO})_{12}\) show good agreement with the expected ones. These results indicate that \((\text{EO})_5, (\text{EO})_{11}, \) and \((\text{EO})_{12}\) have the helical conformation (Fig. 3). The helical conformation of \((\text{EO})_5 \) consistent with the previous results measured by RAIRS[27]. That is, it is considered that the determination of SAM conformation based on the results of QCM is suitable.

3.2.2 Conformations of SAMs: mechanically trapped water

From CV results in Table 1, relative water contents[23] of \((\text{EO})_5, (\text{EO})_{11}, \) and \((\text{EO})_{12}\) are estimated at 2.6% (5.67 ng/cm²), 10.2% (41.1 ng/cm²), 13.6% (61.7 ng/cm²), respectively. It is observed that the mechanically trapped water increases with molecular weight. In the case of \((\text{EO})_5\) the mechanically trapped water of 2.6% is comparatively small. This means that \((\text{EO})_5 \) has the crystalline helical conformation. This result is consistent with the previous report[27].
On the other hand, relative water contents of the mechanically trapped water for $\upsilon_{\text{EO}}^{11}$ and $\upsilon_{\text{EO}}^{12}$ are more than 10% being comparatively large compared to that for $\upsilon_{\text{EO}}^{5}$. The hydrated water generates a conformation disorder. Therefore, it is considered that conformation for $\upsilon_{\text{EO}}^{11}$ and $\upsilon_{\text{EO}}^{12}$ is a mixture of the crystalline helical and amorphous structure. The same cases have been reported in SAMs of $\text{HS(CH}_2\text{CH}_2\text{O)}_n\text{CH}_3$, where $n = 5$, 11 and 12, are referenced to as (EO)$_5$, (EO)$_{11}$ and (EO)$_{12}$.

![Fig. 2](image1.png)  \(\Delta F\) and \(\Delta D\) vs frequency of QCM. (a) (EO)$_5$; (b) (EO)$_{11}$; (c) (EO)$_{12}$. ● and ■ denote \(\Delta F\) and \(\Delta D\), respectively. The error bar represents standard deviation. Measurements were repeated 6 times.

![Fig. 3](image2.png) Schematic illustration for 7/2 helical conformation of SAM on gold. (a) SAM of (EO)$_5$. (b) SAM of (EO)$_{11}$ without hydrated water. The sphere color means the type of atom: gray = carbon; white = hydrogen; yellow = sulfur; red = oxygen.

<table>
<thead>
<tr>
<th>Compound</th>
<th>(h_{\text{eff}}) (nm)</th>
<th>(\eta_s) (10(^{-3}) Pa·s)</th>
<th>(\mu_s) (10(^{4}) Pa)</th>
<th>CV (10(^{-10}) mol/cm(^2))</th>
</tr>
</thead>
<tbody>
<tr>
<td>(EO)$_5$</td>
<td>2.13</td>
<td>1.71</td>
<td>1.84</td>
<td>1.26</td>
</tr>
<tr>
<td>(EO)$_{11}$</td>
<td>4.27</td>
<td>3.38</td>
<td>3.42</td>
<td>1.73</td>
</tr>
<tr>
<td>(EO)$_{12}$</td>
<td>4.62</td>
<td>3.66</td>
<td>3.87</td>
<td>1.79</td>
</tr>
</tbody>
</table>

* Thicknesses of 7/2 helical and all-trans conformations were calculated on the basis of ref 24.

4 CONCLUSIONS

In this paper, the following novel points have been found.

1. Chemical adsorption rates for (EO)$_{11}$ and (EO)$_{12}$ show a kind of odd-even effect derived from unit number of EO segment similar to odd-even effect with methy-
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(2) Values of $h_n$, $\mu$, and $\eta$, of SAMs increase with unit number of EO segment. That is, $\langle EO\rangle_12 > \langle EO\rangle_11 > \langle EO\rangle_10$.

(3) SAM of $\langle EO\rangle_3$ has the crystalline helical conformation. On the other hand, conformation for SAMs of $\langle EO\rangle_11$ and $\langle EO\rangle_12$ are a mixture of the crystalline helical and amorphous structure.

It has become obvious that deference in unit number of EO segment significantly affects physical properties of SAM. Further investigation and systematic variation of EO segment will clear relationship between unit number of EO segment and physical properties of SAM.

Supporting Information
This material is available free of charge via the Internet at http://dx.doi.org/10.5650/jos.62. 45

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