Citation for published version:

DOI:
10.1039/C4AN01591F

Publication date:
2014

Document Version
Peer reviewed version

Link to publication

University of Bath

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Switching of Electrochemical Characteristics of Redox Protein upon Specific Biomolecular Interactions

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Detection of specific protein analytes is a technique widely used in disease diagnosis. Central to this approach is the fabrication of a sensing platform displaying a functional recognition element specific for the analyte targeted for detection. The most commonly utilized type of recognition element used for this purpose are antibodies. However direct generation of surfaces with high functional binding activity when using antibodies frequently presents a challenge, due to the conformational changes undergone by these molecules when physiosorbed on a solid surface and/or variable activity when immobilized by covalent coupling techniques. Here, we present a novel label-free protein sensing platform based on a simplified and standardized immobilization process. The platform consists of self-assembled redox protein, Azurin (Az), that acts as scaffold, while sensing specificity is achieved through receptors that are coupled with chemical groups available on the surface of the Az protein. The redox activity of the Az within the sensing surface enables a label-free electrochemical detection method that can be readily miniaturized. We have observed a significant change in the electrochemical characteristic of the assay, upon a specific molecular interaction. A new model is also developed that can aid the future development of redox based bio-sensing techniques.

One of the consistent challenges remaining in the development of specific, high sensitivity platforms for biological sensing is the integration of recognition elements into the sensing surface used to provide the transduction signal. Antibodies, whilst providing a robust binding molecule, provide a challenge to the development of consistent biosensor surfaces due to direct immobilization frequently exhibiting unpredictable changes in function depending on the sensor substrate material in combination with immobilization mechanism used (i.e. physisorption, chemical conjugation and choice of chemical conjugation type used) [1,2]. Generic mechanisms of linking transduction of molecular binding events to a sensor platform therefore remain of interest in the development of sensor platforms.

Adsorbed, redox active Self-Assembled Monolayers (SAMs) on metal have attracted considerable research efforts in the past two decades[3,4]. Recently, in addition to providing a model system for investigating interfacial electron transfer processes, redox active SAMs have found a new application in biomolecular detection by monitoring changes in the electrochemical environment of ferrocene-SAMs upon biomolecular interaction[5]. The challenge in such application is the implementation of a controlled immobilization process for the detection platform. This is especially difficult in the case of protein sensing because proteins have a complicated structure and can change folding depending on the environment. As a result, the platform has to be tailor-made to a particular target. In our approach, receptors are coupled to a scaffold consisting of the redox metalloprotein, Azurin (Az). This scaffold enables a standard self-assembled process whereas the specificity is provided by coupling different receptors to the Az. Furthermore, the scaffold protein provides redox activity enabling label-free detection. For the first time, we observed a significant switching of electrochemical characteristics of the SAM upon specific biomolecular interactions, which can be used as the basis of a novel mechanism for interrogating biomolecular detection.

Az is a metalloprotein which contains a copper ion cofactor that is bound by five amino acids[6,7]. The natural function of Az is to mediate electron transfer in denitrifying bacteria, but an increasing number of applications in molecular electronics are reported[8,9]. By exploiting the Cys3-Cys26 disulfide bond on the Az, a compact and highly organized Az self-assembled monolayer can be formed on Au. Thiolated polyethylene glycol (PEG), which has been shown to reduce non-specific electrochemical signals in complex samples[10], is then used to passivate the remaining bare Au sites of the electrode, as shown in Figure 1a. When adsorbed onto the electrode, the copper ion can exchange electrons with the underlying electrode. To demonstrate the
applicability of the platform towards protein sensing, biotin was
coupled to Az via accessible amine groups present on the Az
protein (Figure 1b) using a simple amine coupling chemistry.
This provides a simple model system for the investigation of the
effects of protein binding through the use of Streptavidin as a
model analyte. The coverage of the biotinylated Az on gold
substrate was characterized with Quartz Crystal Microbalance
(QCM), yielding an approximate coverage of 4.6 x 10^15 cm^-2.
This is of the same order of magnitude as the theoretical
maximum coverage assuming Az has a circular shape of
diameter 5.5 nm. The binding of the Streptavidin with the
biotinylated Az platform was monitored with AC voltmmetry.
Electrochemical Impedance Spectroscopy (EIS) and also carried
out in real time with QCM. (Please refer to the supporting
information for the QCM measurements.)

![Azurin](image)

![Polyethylene glycol](image)

**Figure 1** (a) Schematic representation of the Azurin monolayer
(b) Structure model of Azurin. The lysine residues targeted by
the amine coupling chemistry during biotinylation are shown
highlighted in pink

The theoretical analysis of a redox SAM for biosensing
applications has been previously carried out. The governing
equations of the system are:

\[
E = E^\circ + \frac{RT}{nF} \ln \left( \frac{I_{c}}{I_{a}} \right)
\]

where

\[
E^\circ = E^\circ - \phi_{Az} - \phi_{f}
\]

\[
\phi_{Az} = \frac{2eI_{c}}{zF} \sinh \left[ \frac{\sigma_{Az} + \sigma_{PEt} + \sigma_{c} + \sigma_{Ab} - \sigma_{Ab} + \sigma_{c}}{\sqrt{RTz_{C}z_{F}}C_{0}} \right]
\]

\[
\sigma_{Az} = \frac{2eA_{c}}{1} \left[ E^\circ + \phi_{Az} - \phi_{f} \right] \left( \frac{RT}{nF} \ln \left( \frac{1 - f}{f} \right) \right)
\]

\[
\sigma_{PEt} = I_{c} \left[ \frac{1}{\sinh \left( \frac{2eI_{c}}{zF} \right)} \right]
\]

**Figure 2** Theoretical calculations investigating the effect of ionic
strength and the target charge on the formal potential. Input
parameters are: \(E^\circ = -0.25\) V, \(d_{f} - \phi_{Az} = -0.05\) V vs Hg/HgO/C, \(d_{s} = 2.6, d_{f} = 1.83\) nm, \(I_{c} = 1.4x10^{-6}\) mol cm^-2, \(\phi_{Az} = 0\) and \(I_{c} = 78.5\) (water)

**Figure 3** shows the indirect stain titration experiments for the
biotinylated Az, upon specific interaction with Streptavidin and
as a control, upon adding an antibody (an ovalbumin specific
serV-kappa fusion protein), and the specific reaction by adding
Streptavidin. Formal potentials were extracted from AC
voltmmetry in pH 7.8 phosphate buffer. It was observed that
the formal potential increased with increasing ionic strength for both
biotinylated Az and the control, whereas a complete opposite
trend was present after specific reaction with Streptavidin. This
is due to the positive charge carried by the Streptavidin. The
fitted value of \(\sigma_{Az} = -0.031\) C m^-2. After reaching with
Streptavidin, the fitted value of \(\sigma_{Az} + \sigma_{Ab} = -0.022\) C m^-2.
Subtracting \(\sigma_{Az}\) from \(\sigma_{Az} + \sigma_{Ab}\) gives an estimated
Streptavidin charge of +0.009 C m^-2. This positive charge of
the Streptavidin is also confirmed by EIS measurements on the
same electrode, as shown in Figure 3d. In the EIS, the measurement
buffer contains a negatively charged redox couple, [Fe(CN)₆]³⁻
and [Fe(CN)₆]⁴⁻. Overcoming the potential barrier created by the
SAM layer, the redox couple can exchange electrons with the
underlying Au electrodes. This is characterized by the charge
transfer resistance ($R_{b}$). After specific reaction with Streptavidin, a reduction in $R_{b}$ was observed, which suggests that Streptavidin has a net positive charge, therefore reducing the potential barrier for the negatively charged redox couple. The change transfer resistance is reduced by $36\Omega$.

![Image]

Figure 3 (a, b, c): Dependence of formal potential upon ionic strength: (a) biotinylated Az. For the predicted formal potential, the fitted parameters are $E^\circ = -0.128 V$, $\sigma_{Az} = -0.031 C \cdot m^{-2}$; (b) Control experiment of adding antibody to biotinylated Az. For the predicted formal potential, the fitted parameters are $E^\circ = -0.131 V$, $\sigma_{Az} = -0.031 C \cdot m^{-2}$; (c) Specific interaction with streptavidin. For the predicted formal potential, the fitted parameters are $E^\circ = -0.155 V$, $\sigma_{Az} = -0.022 C \cdot m^{-2}$; Other input parameters are: $(\phi_{K} - \phi_{H}) = 4.85 V$ vs Hg/HgSO$_4$, $d_{i} = 20$ (Az), $d_{i} = 5.5$ nm (Az size), $\Gamma_{Ac} = 7.6 \times 10^{-12}$ mol cm$^{-2}$ (from QCM) and $\Gamma_{Ac} = 78.5$ (water). (d) Electrochemical impedance spectroscopy of the same electrode used in (c).

The onset of the reversing trend happens at:

$$\sigma_{Az} + \sigma_{r} > \phi_{K}$$

In other words, the sensitivity of the platform is determined by $(\sigma_{Ac} + \phi_{K})$. According to Equation (2), $\sigma_{r}$ is a function of the coverage $\Gamma_{Ac}$ and $d_{i}$ and is calculated to be $0.0037 \ C \cdot m^{-2}$, by taking $\Gamma_{Ac} = 7.6 \times 10^{-12}$ mol cm$^{-2}$ (from QCM measurements) and $f = 0.5$ at the voltammetric peak. $\sigma_{Ac}$ is $0.022 \ C \cdot m^{-2}$ also calculated from Equation (2), therefore $(\sigma_{Ac} + \sigma_{r}) = 0.025 \ C \cdot m^{-2}$. In the case of Figure 3, the above inequality is satisfied since $\sigma_{Ac} + \sigma_{r} = 0.022 \ C \cdot m^{-2}$; To improve the sensitivity, one can minimize the dominating charge, $\sigma_{Ac}$, by increasing the distance between the PET and the electrode ($d_{i}$).

In conclusion, we have developed a novel protein sensing platform that allows simplification and standardization of creating different receptor layers by using a redox scaffold protein, Az. The applicability of the platform towards protein sensing was initially demonstrated with Streptavidin-Biotin interactions measured with QCM, EIS and AC voltammetry. The latter reveals a significant change of trend in the electrochemical behavior of the platform upon specific molecular interactions. On the basis of these results it is possible to envisage the described approach being extended to detection of additional protein analytes in a stepwise fashion using biotinylated recognition elements including antibodies. As such a novel type of label free electrochemically driven sensing platforms could be developed using the same approach.

Notes and references

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