Metal Ion-DNA Interactions on Surfaces: Kinetics and Sensing Perspectives

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Electrostatic interactions with metal ions are essential to the structural stability and polymorphism of oligonucleotides. Without the presence of mobile cations near the DNA strands to neutralize the negative charges of the phosphate groups, the repulsion between the phosphodiester backbones would drive the double helix apart. Beyond such a fundamental function and their importance as model systems for DNA-protein interactions, electrostatic metal ion-DNA interactions have also been found intriguing in the construction of nanometer electrical circuits and the development of DNA detection technology.[1] In contrast to the extensive studies in the literature from the thermodynamics point of view, little is known about the kinetics of metal ion-DNA interactions.

In a recent publication,[2] we described a simple procedure to study DNA-modified surface (DNA probe quantitation, cationic binding property, and electron-transfer kinetics) based on the voltammetric behavior of multiply-charged transition metal cations bound electrostatically to DNA strands. The key feature of our approach is the easy distinction of the surface waves from the signals of diffused species by using micromolar concentrations (μM) of the redox molecules. Our method is complementary to other electrochemical protocols proposed by many others,[3] with significant improvements in terms of simplicity and accuracy.

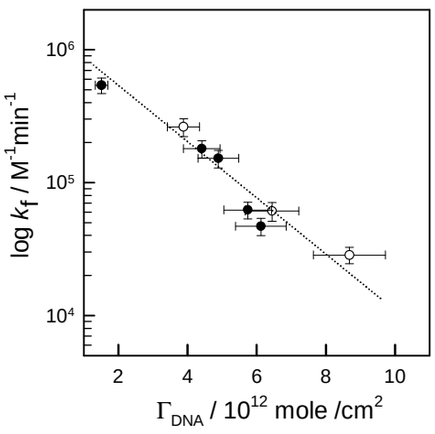

Figure 1. Binding rate constants of $[Ru(NH_3)_6]^{3+}$ as a function of the surface density of thiolate-DNA monolayers on gold. The surface densities of dsDNA/Au (open circles) were doubled for direct comparison with those of ssDNA/Au (closed circles). The dashed line is to direct the eyes only.

Herein, we report the application of our simple voltammetric approach to examine the kinetics of metal ion-DNA interactions on surfaces. In particular, the rate constants for binding and dissociation of metal cations (by using electroactive metal cations as model systems) to and from surface-confined DNA strands can be obtained by integration of the rate laws based on the time-dependent voltammetric responses. The rate constants (k_f) determined for binding $[Ru(NH_3)_6]^{3+}$ to thiolate DNA monolayers on gold are in the range of 10^4-10^5 M^{-1} min^{-1} and are highly dependent on the surface density of DNA (Figure 1). The dissociation constants obtained by another experimental technique (transfer of the incubated electrode into redox-free buffer for voltammetric measurements) agree approximately with the calculated values.[4]

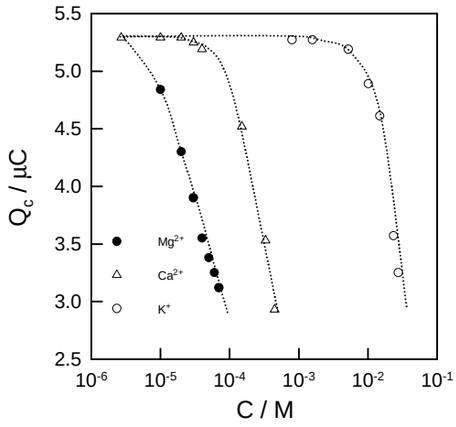

Figure 2. Integrated charge of the surface-confined $[Ru(NH_3)_6]^{3+}$ in the presence of different metal cations at different concentrations. The dashed line is to direct the eyes only.

We also investigated the sensing perspectives of DNA-modified surfaces towards non-electroactive metal cations by monitoring the ion-exchange voltammetry between these cations and their electroactive counterparts. After immobilization of redox cations to DNA monolayers formed on gold, the electrode responded to various metal cations, particularly, those are of great importance in biochemical synthesis (Mg^{2+}, Ca^{2+}, K^+). The sensitivity can reach a concentration as low as a few micromolar (μM), while the selectivity is in the decreasing order of $Mg^{2+} > Ca^{2+} > K^+$ (Figure 2). This is consistent with the binding affinity of these metal cations with DNA monolayers on surface.

Several aspects of our approach deserve further investigation including the detailed understanding of the electron/mass transport mechanism and the introduction of different DNA probes with varied sequences and structures. However, this work, essentially, demonstrates the potential of traditional electrochemistry as a powerful tool in the development of DNA-based sensing devices.

References

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3. For example, see, (a) A. B. Steel, T. M. Herne and M. J. Tarlov, Anal. Chem. 70(1998)4670-4677.
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