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Sensing Of Aqueous Phosphates By Polymers With Dual Modes Of Signal Transduction

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Accurate determination of levels of phosphate-related anions such as pyrophosphate and nucleotide-phosphates is an important factor in monitoring numerous metabolic processes. Very few sensors exist that display high selectivity and reliability, and that function in aqueous media without interference from endogenous substrates such as chloride anion. That is because selective and reliable sensing of anions is generally difficult to accomplish. As compared to isoelectric cations, anions often display a high energy of hydration, display tautomerism, and possess low surface-charge density, features that make the binding of anions less effective.

The increase in receptor–anion affinity may be achieved by utilizing positively charged moieties as a part of the receptor. Unfortunately, electrostatic interactions are nondirectional, and, as a result, all anions present in the medium are attracted to such a receptor. It is, therefore, desirable to also include weak directional interactions such as hydrogen bonding to improve the selectivity in receptor–anion association. Recently, new receptors that comprise both positive charges and hydrogen bond donors acting in a synergistic manner were prepared. Additionally, conductive polymers were shown to yield sensor materials for cations, biomacromolecules, and neutral analytes. Only a few such materials were used for anion sensing.

We reasoned that a conductive polymer with incorporated receptors capable of hydrogen bonding while being able to undergo an adjustable degree of p-doping could provide an inexpensive alternative to the synthesis of multifeature sensors (Figure 1). We decided to utilize the propensity of polythiophenes to undergo p-doping. The positive charge in the polymer can be adjusted by an externally applied potential. We also used receptors capable of change in color in addition to polymer conductivity, to obtain two independent modes of signal transduction in the sensor material, thus increasing the overall reliability of the sensing process.

In the design of a sensor material, we used a polythiophene conductive polymer with integrated hydrogen-bonding receptors. Right: Structures of monomers I and 1C, and sensor materials poly-1 and poly-1C.

Figure 1. Left: A schematic drawing of synergy in a p-doped conductive polymer with integrated hydrogen-bonding receptors. Right: Structures of monomers I and 1C, and sensor materials poly-1 and poly-1C.

In the design of a sensor material, we used a polythiophene conductive polymer with integrated quinoxaline moieties modified with two pyrrole units. Dipyrrolylquinoxaline (DPQ) is capable of binding anions via hydrogen bonding, while more or less a pronounced color change occurs. Because DPQ alone does not yield stable conductive polymers, we modified the quinoxaline ring with two polymerizable ethylenedioxythiophene (EDOT) units to obtain monomer I (Figure 1, right). To avoid potential polymerization through α-pyrrole positions, we also synthesized monomer 1C with chloro-substituents blocking the α-positions.

Careful evaluation of titrations of monomers I and 1C in DMSO with various aqueous anions showed that I and even more so 1C show changes in color upon binding of pyrophosphate \((\text{PP}_2^-)\), fluoride, and, to a lesser extent, phosphate \((\text{H}_2\text{P}_2^+)\) and cyanide anions. Analysis of anion-induced changes in the absorption spectra of I and 1C (Figure 2) allowed for determination of the respective binding constants (Table 1).

Oxidative electropolymerization of monomers I and 1C yielded conductive materials poly-1 and poly-1C. The band gaps were estimated as 1.39 eV for poly-1 and 1.36 eV for poly-1C.

To test the anion sensing ability of the polymers, the poly-1 and poly-1C films were titrated at a constant potential of 0.0 V by anions added as tetrabutylammonium (TBA) salts (5.0 mM, pH ≈ 6.5) in water while visible–NIR spectra were recorded (Figure 3). As expected, the addition of fluoride, pyrophosphate, and in the case of poly-1C also phosphate anions into the cell containing the sensor films resulted in gradual changes in the absorption spectra. The respective binding isotherms that show well-defined saturation were obtained, and apparent affinity constants were calculated (Table 1).

Additionally, we used the electrochemical quartz crystal microbalance method (EQCM) to confirm the anion binding in poly-1 and poly-1C. After the deposition of poly-1 on the EQCM probe, aqueous solutions of the anions were added. The addition of anions \((\text{PP}_2^-, \text{F}^-, \text{H}_2\text{P}_2^+ \text{but not Cl}^-)\) caused a rapid increase of the mass.
of the deposited polymer. EQCM titration experiments resulted in a typical saturation profile, thus confirming that the changes in vis-NIR spectra are, indeed, a result of anion binding.

To test both our hypotheses that p-doping of the conductive polymers may be used to tune anion-sensor affinity, and that conductive polymers may be used to obtain two independent modes of signal transduction useful in the sensing process, we have constructed sensing devices schematically shown in Figure 4 using an interdigitated ITO electrode (IME). Binding of anion to the polymer resulted in a change in conductivity. The low level p-doping (at 0.70 V) and anion binding resulted in a change in conductivity that is most pronounced at 0.70 V. The measured conductivity change was ~1000 Ohm cm at 0.70 V. The results are presented in Table 1.

Table 1. Affinity Constants for 1 and 1C, and Apparent Affinity Constants for Poly-1 and Poly-1C (M−1) in DMSO (0.1% H2O) Derived from Titrations with Aqueous Anions

<table>
<thead>
<tr>
<th>anion</th>
<th>1+</th>
<th>poly-1</th>
<th>1C</th>
<th>poly-1C</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>F−</td>
<td>&gt;10^6</td>
<td>48 000</td>
<td>&gt;10^6</td>
<td>24 000</td>
</tr>
<tr>
<td>Cl−</td>
<td>&lt;100</td>
<td>2000</td>
<td>&lt;100</td>
<td></td>
</tr>
<tr>
<td>PP−</td>
<td>&gt;10^6</td>
<td>61 100</td>
<td>&gt;10^6</td>
<td>11 000</td>
</tr>
<tr>
<td>H2PO−</td>
<td>&lt;100</td>
<td>3800</td>
<td>&lt;100</td>
<td>90 000</td>
</tr>
</tbody>
</table>

Figure 4. Left: A schematic representation of polymer deposition. Center: Optical micrograph of the interdigitation with poly-1 film as a function of a gate potential. Right: Change in conductivity of the poly-1 film as a function of a gate potential.

The poly-1C IME devices were then tested for anion sensing in custom-made spectroelectrochemical cells connected to a fiber optic spectrometer and bipotentiostat. The bipotentiostat was used to apply voltage on the ITO-interdigitation (gate potential 0.70 V, drain potential V_d = 40 mV) and record the drain current (i_d) passing through polymer-modified interdigitation while the vis-NIR spectra were recorded. As expected, the addition of anions resulted in dramatic changes in both vis-NIR spectra as well as drain current (conductivity) (Figure 5). The low level p-doping (at 0.70 V) and a corresponding positive charge in the polymer resulted in a dramatic increase of the anion affinity. For example, the apparent affinity constant (dm−1 mol−1) for poly-1/IPyrophosphate recorded at 0.70 V was calculated as K_ap=0.7 V = 260 000, while the constant recorded at 0.00 V was K_ap=0.0 V = 61 100. Similarly, for poly-1C, the values are K_ap=0.7 V > 10^6 and K_ap=0.0 V = 11 000. The conductivity measurements allowed for simultaneous observation of changes in drain current as a function of anion concentration, thus providing a second independent signal usable for sensing. Figure 5 shows examples of vis-NIR and conductivity data acquired simultaneously. It is also important that the sensing process is reversible and the deposited materials are reusable.

In summary, we have demonstrated a new approach to sensing of aqueous phosphate-related anions based on chromogenic conduc-

References

10. The polymers are green (pale blue) in the reduced (oxidized) form.
11. Apparent affinity constants were calculated using the equation for 1:1 stoichiometry. The equation uses the concentration of added anion to be a sum of a free anion (unbound) and anion bound by the receptor. The latter is considered equal to the receptor concentration. Because the receptor concentration on the surface of the material is unknown, the affinity constant is designated as “apparent”, and the respective values are relative. In fact, judging from the dynamic range of the sensors, the affinity of poly-1 and poly-1C for anions is equal to or higher than the affinity of the monomers 1 and 1C.
13. Abtech Scientific, Inc.; IME characteristics: digit length, 5 mm; number of digit pairs, 50; digit width, 10 mm; interdigit space, 10 mm.
14. For more details on experimental conditions, see Supporting Information.
15. Chloride anion, which is not bound by the monomers, is also not bound by poly-1 and poly-1C regardless of the doping level. Both poly-1 and poly-1C display K_ap=0.7 V = 1200 dm−1 mol−1 or lower.