Water-Soluble Cationic Conjugated Polymers: Response to Electron-Rich Bioanalytes

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<tr>
<td>As Published</td>
<td><a href="http://dx.doi.org/10.1021/ja4095395">http://dx.doi.org/10.1021/ja4095395</a></td>
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<tr>
<td>Publisher</td>
<td>American Chemical Society (ACS)</td>
</tr>
<tr>
<td>Version</td>
<td>Author's final manuscript</td>
</tr>
<tr>
<td>Accessed</td>
<td>Sun Dec 30 17:37:33 EST 2018</td>
</tr>
<tr>
<td>Citable Link</td>
<td><a href="http://hdl.handle.net/1721.1/84619">http://hdl.handle.net/1721.1/84619</a></td>
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Water-Soluble Cationic Conjugated Polymers: Response to Electron-Rich Bioanalytes
Water-Soluble Cationic Conjugated Polymers: Response to Electron-Rich Bioanalytes

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Supporting Information Placeholder

ABSTRACT: We report the concise synthesis of a symmetrical monomer that provides a head-to-head pyridine building block for the preparation of cationic conjugated polymers. The obtained poly(pyridinium phenylene) polymers display appealing properties such as high electron affinity, charge-transport upon n-doping, and optical response to electron-donating analytes. A simple assay for the optical detection of low micromolar amounts of a variety of analytes in aqueous solution was developed. In particular, caffeine could be measured at a 25 µM detection limit. The reported polymers are also suitable for layer-by-layer (LbL) film formation.

Conjugated polymer semiconductors have advantageous properties (flexibility, low weight, good processability in solution) that make them useful for optoelectronic and electrochemical devices including organic solar cells, light-emitting diodes, field-effect transistors, biosensors, etc. In contrast to p-type conjugated polymers, which are currently the leading class of organic semiconductors, n-type (or electron-transporting) conjugated polymers are still in limited supply and are often hampered by lower performance and stability. This lack of suitable n-type polymeric materials has hindered progress in all polymer organic electronics, and research in polymer photovoltaic devices is largely focused on fullerene-based acceptor molecules, in spite of the poor visible light absorption and band-edge variability of such compounds. In addition to the widespread organic electronics applications, conjugated polymers have been extensively studied for chemical and biological sensing, such as the detection of vapors, anions, or biomolecules. Of particular relevance to the present study are the solution-based optical detection schemes for electron-rich bioanalytes.

The incorporation of electron-deficient N-heterocyclic aromatics into conjugated polymers to produce n-type compounds with high electron affinities was successfully employed in our laboratory and by others. We recently reported a new class of n-type conjugated polymers based on a pyridinium-phenylene scaffold, that possess reversible redox activities, useful electron affinities, and high electrical conductivities. In these compounds, electron-deficient pyridinium rings were introduced by intramolecular cyclization reactions.

Building on this success, we now introduce a related class of poly(pyridinium phenylene), which are more synthetically accessible, thereby facilitating the development of electrochemical and photophysical applications. Further, we demonstrate that these electron-deficient polymers are sensitive to electron-rich analytes and display fluorescence responses to analytes of biological and physiological interest. In particular, an aqueous solution of one of the reported polymers is able to differentiate indole among a series of biologically relevant analytes, and to measure caffeine concentrations down to 25 µM.

Our simplified synthetic scheme conveniently generates monomeric unit 3 with minimal synthetic and purification steps (Scheme 1). The synthesis involves Sonogashira coupling of 5-bromo-2-iodopyridine with propargyl ether to afford precursor 1 in good yield. In the presence of Wilkinson’s catalyst and excess of protected hex-3-yne-1,6-diol (2), diyne 1 undergoes [2+2+2] cycloaddition to afford symmetrical monomer 3. The low yield of this optimized cyclization reaction is mostly attributed to interactions between the metal catalyst and the pyridine rings, and is largely compensated by the simplicity of the synthesis. Furthermore, most of the unreacted alkyne 2 can be recycled.

Scheme 1. Two-step synthesis of monomer 3

Siloxyethyl-substituted homopolymer P1 and copolymer P2 were obtained reacting monomer 3 under Yamamoto and Sonogashira coupling conditions, respectively (Scheme 2). In the case of P1, we observed that microwave irradiation combined with high temperature heating in THF was required in order to enhance the molecular weight of the product. This observation is attributed to an improved solubility of P1 in hot THF. Similarly, we observed no formation of Sonogashira-coupling product when monomer 3 and pentiptycene diacetylene 4 were reacted under standard (e.g., overnight heating to reflux) conditions. It appears that the lower reactivity of the aryl bromide 3 under Sonogashira conditions, although advantageous for the selective synthesis of precursor 1, is significantly enhanced by the use of superheated solvent in a sealed vessel microwave reactor. Polymers P1 and P2 were found to be soluble in common organic solvents, allowing their convenient purification and characterization. Finally, polyelectrolytes P3 and P4 were obtained by subjecting precursors to intramolecular nucleophilic substitution reactions, and purified by reprecipitation from H2O/THF (P3) or DMSO/H2O followed by washing with H2O, MeOH and CH3Cl (P4). Homopolymer P3
was found to be soluble in water and trifluoroethanol, whereas copolymer P4 was found to only display significant solubility in DMSO or in formic acid. Meta-stable aqueous solutions of P4 could be prepared by dissolving the polymer in formic acid followed by dilution with water, and these formulations were stable for several hours before precipitation became visible.

Scheme 2. Synthetic routes to polymers P3 and P4.

The polycationic polymers P3 and P4 were characterized by 1H NMR spectroscopy, absorbance and fluorescence measurements, and by cyclic voltammetry. The optical and electrochemical properties are summarized in Table 1. The absorbance and emission bands of P3 and P4 are red shifted relative to the precursor polymers P1 and P2, as a result of the enhanced planarity induced by cyclization, and of the incorporation of electron accepting pyridinium (Figures 1a and b, S7 and S8). The pentylypyrene fragment of P4 induces broader absorbance and emission bands, a larger Stokes shift, and red-shifted bands compared to P3. The electron affinities (EA) of P3 and P4 are evaluated based on the onset reduction potential in thin film cyclic voltammetry measurements, and are estimated at 3.95 and 3.91 eV, respectively. These values are comparable to those of well-known electron transporters PCBM (4.2 eV) and the polaron-bipolaron theory for conjugated polymer doping.

Taking advantage of the polycationic nature of polymers P3 and P4, we investigated the possibility of forming well defined films using the layer-by-layer deposition (LbL) technique in association with anionic poly(styrene sulfonate) (PSS). The absorbance spectra shown in Figure 2a and S12-S13 demonstrate that LbL films are efficiently formed upon alternate exposure of an ITO-coated glass substrate to aqueous solutions of P3 (or P4) and PSS. The absorbance was found to increase linearly with the number of deposited layers, indicating a well-behaved deposition process. Cyclic voltammetry performed on LbL-deposited films (25 bilayers) indicates that the multilayer films remain stable during redox changes. As expected, the peak currents were found to increase linearly with the scan rates (Figure 2b, S14-S15). Spectroelectrochemical experiments reveal electrochromism similar to that observed with polymer thin films, with a significantly improved reversibility in the case of P3 (Figure 2d). Following application of a sufficiently reducing potential, the initially orange film turns blue due to the reduction of P3. The initial color is recovered upon reoxidation, and the color changes occur within about 5 s.

Table 1. Optical and electrochemical properties of P3 and P4 in solution (s) or thin films (f).

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<tr>
<th>Polymer</th>
<th>λ_{max} (nm)</th>
<th>g_{max} (L·mol^{-1}·cm^{-1})</th>
<th>E_{IP} (eV)</th>
<th>E_{red} (eV)</th>
<th>E_{onset} (V)</th>
<th>EA (eV)</th>
<th>IPd (eV)</th>
<th>PL_{max} (nm)</th>
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<tr>
<td>P3 (s)</td>
<td>402</td>
<td>33000</td>
<td>2.95</td>
<td>3.29</td>
<td>-0.85</td>
<td>419</td>
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<tr>
<td>P3 (f)</td>
<td>411</td>
<td>451</td>
<td>2.75</td>
<td>3.29</td>
<td>-0.85</td>
<td>445</td>
<td></td>
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<tr>
<td>P4 (s)</td>
<td>423</td>
<td>11500</td>
<td>2.60</td>
<td>3.29</td>
<td>-0.85</td>
<td>522</td>
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<td></td>
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<tr>
<td>P4 (f)</td>
<td>413</td>
<td>494</td>
<td>2.51</td>
<td>3.29</td>
<td>-0.85</td>
<td>556</td>
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- E_{IP}: Band gap estimated from the onset (λ_{onset}) of the absorption spectra.
- E_{red}, E_{onset}: Formal and onset reduction potentials (vs. SCE).
- EA: Electron affinity obtained based on EA = E_{onset} + 4.4 (eV).
- IPd: Ionization potential calculated from IP = EA + E_{IP} (eV).

Figure 1. a) Normalized absorbance (red) and emission (blue) spectra of polymer P3 in aqueous solution (solid line) and thin film (dotted line); b) Normalized absorbance (red) and emission (blue) spectra of polymer P4 in formic acid/PBS (5-95) solution (solid line) and thin film (dotted line); c) Cyclic voltammogram of P3 (black curve, 100 mV · s^{-1}) and in situ conductivity measurement (blue curve, 5 mV · s^{-1}). The deviations below zero are the result of overlapping current from Faradaic processes; d) Spectroelectrochemistry of P3 (thin film).
Nevertheless, the fact that indole responds differently than any other studied analyte (including closely-related tryptophan, that induces an 11% increase in fluorescence intensity) potentially provides a powerful level of selectivity, where a single specific analyte is detected against several others.

To evaluate its utility as a sensory material, we investigated the response of copolymer P4 to a series of analytes of biological interest. Although P4 is relatively weakly emissive in solution, its high ionization potential (and associated high excited-state electron affinity) is particularly well-suited to interact with electron-rich analytes. Indeed solutions of P4 in water (15 µg mL⁻¹, formate buffer, pH 3.6) give responses to 100 µM of electron-donating aromatic analytes (Figure 3a). The majority of the heterocycles give an enhancement in the emission, however indole induces a 48% decrease in the fluorescence intensity. This quenching is consistent with our previous work on high ionization potential conjugated polymers and was rationalized by electron-transfer quenching from the electron-donating analyte to the polymer.  

In order to gain more insight into the quenching mechanism, we performed Stern-Volmer quenching experiments, observing both the emission intensity and lifetime as a function of the indole concentration. The linear increase in quenching with the concentration of indole illustrated in Figure 3b reveals a Stern-Volmer constant $K_{SV} = 9.5(0.6) \cdot 10^3$ M⁻¹ and an estimated detection limit of 25 µM. The fluorescence lifetime ($\tau = 0.4$ ns) was found to be invariant as indole was added to the solution, pointing towards a static quenching mechanism. The fact that the other investigated analytes produced an increase in the emission intensity admittedly was unexpected and suggests a more complex interaction mechanism between the analytes and the polymer. Copolymer P4 has large hydrophobic surfaces and we assume that intra- and intermolecular hydrophobic interactions have a strong impact on the polymer structure in solution, that can be influenced by the presence of interacting aromatic molecules. For example, although phenylalanine does not possess an easily oxidizable aromatic ring, it still induces a strong fluorescence increase. Further, the importance of the hydrophobic iptycenes in the sensing process is confirmed by the fact that homopolymer P3 shows no significant optical response in the presence of the tested analytes. Nevertheless, the fact that indole responds differently than any other studied analyte (including closely-related tryptophan, that induces an 11% increase in fluorescence intensity) potentially provides a powerful level of selectivity, where a single specific analyte is detected against several others.

![Figure 2](image1.png) a) Absorbance spectra of P3/PSS films with increasing numbers of bilayers; b) Cyclic voltammograms of a 25-bilayer film of P3/PSS at different scan rates (inset: peak currents for oxidation (open circles) and reduction (filled circles) vs. scan rate); c) Spectroelectrochemistry of a 25 bilayer film of P3/PSS; d) Absorbance changes at 408 (red) and 800 nm (blue) of a P3/PSS film upon ramping the voltage between 1.5 and -1.25 V at a 50 mV · s⁻¹ rate (black).

![Figure 3](image2.png) a) Fluorescence intensity changes of solutions of P4 in water (formate buffer, pH 3.6) in the presence of electron-donating bioanalytes (100 µM concentrations, $\lambda_{ex}=406$ nm, $\lambda_{em}=536$ nm); b) Stern-Volmer plots displaying fluorescence intensity and lifetime of P4 as a function of indole concentration. The line corresponds to a linear fit with $K_{SV} = 9.5(0.6) \cdot 10^3$ M⁻¹; c) Emission intensity changes upon titration of P4 with caffeine under the same conditions. All displayed data are averages of three independent measurements.
polymers can act as optical probes for various analytes of biological interest in aqueous solutions, such as indole and caffeine. Further studies to elucidate the interaction mechanisms behind the fluorescence responses are required in order to fine-tune the sensitivity of these compounds.

ASSOCIATED CONTENT

Supporting Information
Synthesis, characterization and properties of the investigated compounds, and structures of the tested bioanalytes. This material is available free of charge via the Internet at http://pubs.acs.org.

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Notes
The authors declare no competing financial interests.

ACKNOWLEDGMENT

This work was supported by the Swiss National Science Foundation (fellowships PBELP2-135845 and PA00P2-145389) and the Army Research Office through the Institute for Soldier Nanotechnologies.

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(39) A series of other catalysts commonly employed for this type of reaction was screened (e.g., [Ir(co2Cl)2], CpRu[Ph2]C, RhCl(CO)3, CoCl2, CoCo(CO)4, or CpZrCl2 under various conditions), and only Wilkinson's catalyst was found to afford the desired product in significant amount.
(44) Difficulties in processing polymer P4 made it impossible to reliably determine conductivity by in situ measurements.