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Efficient detection of polycyclic aromatic hydrocarbons and polychlorinated biphenyls via three-component energy transfer

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Reported herein is the detection of highly toxic polycyclic aromatic hydrocarbons (PAHs) and polychlorinated biphenyls (PCBs) via proximity-induced non-covalent energy transfer. This energy transfer occurs in the cavity of γ-cyclodextrin, and is efficient even with the most toxic PAHs and least fluorescent PCBs. The low limits of detection and potential for selective detection using array-based systems, combined with the straightforward experimental setup, make this new detection method particularly promising.

Polycyclic aromatic hydrocarbons (PAHs) and polychlorinated biphenyls (PCBs) are two of the ten most toxic classes of compounds according to the Center for Disease Control’s ranking in 2011; as such, the development of sensitive and selective detection methods remains a top priority. PAHs are formed from the incomplete combustion of petroleum, and their presence has been detected in human blood and breast milk, and in Gulf water seafood following the Gulf of Mexico oil spill. Some examples of PAHs and the FDA-recommended concentration limits of PAHs in seafood are shown in Figure 1.

PCBs were historically used as refrigerator coolants and in a variety of manufacturing products. Although the use of PCBs was banned in the United States in 1979, their atmospheric stability means that PCBs still persist in the environment. Some examples of PCBs are shown in Figure 1; the FDA-recommended concentration limits for PCBs in food ranges from 0.2-3.0 parts per million (ppm).

Current methods for the detection of PAHs and PCBs generally rely on separation using chromatography, followed by detection via mass spectrometry (for PAHs) or fluorescence spectroscopy (for PAHs). The development of new methods for the detection of these compounds remains a high priority, especially if such methods have improved sensitivity and/or selectivity.

We previously reported that energy transfer occurs between anthracene and a squaraine fluorophore inside the cavity of γ-cyclodextrin, with up to 35% energy transfer observed from anthracene excitation compared to direct squaraine excitation. The energy transfer efficiency is defined as:

\[
\text{Efficiency} = \left( \frac{I_{\text{DA}}}{I_{\text{D}}} \right) \times 100\%
\]

where \(I_{\text{DA}}\) is the integrated emission of the fluorophore from PAH excitation and \(I_{\text{D}}\) is the integrated fluorophore emission from direct excitation.

Although examples of energy transfer with covalently-modified cyclodextrins have been reported, non-covalent energy transfer inside cyclodextrin cavities is much less developed, even though such energy transfer is substantially easier to tune and optimize.

\[
\begin{align*}
\text{anthracene} & \quad 1846 \text{ ppm} \\
\text{pyrene} & \quad 185 \text{ ppm} \\
\text{benzo[ghi]pyrene} & \quad 0.132 \text{ ppm} \\
\text{fluorene} & \quad 246 \text{ ppm} \\
\text{4,4'-dichlorobiphenyl} & \quad \text{conc. limit not determined} \\
\text{phenantrene} & \quad \text{246 ppm} \\
\text{PCB29} & \quad \text{246 ppm}
\end{align*}
\]

Figure 1: PAHs and PCBs used as energy donors, together with the FDA-recommended concentration limits for PAHs in parts per million (ppm)

Reported herein is the development of a widely applicable non-covalent energy transfer system between PAH and PCB energy donors and fluorophore acceptors. These fluorophores (Figure 2) were chosen because of their high quantum yields, and established use in a variety of sensing schemes. Compound 8 is commercially available, and compounds 9 and 10 were synthesized following known procedures.

Energy transfer from the analytes to the fluorophores in the presence of cyclodextrin was measured by mixing the analyte and fluorophore in phosphate-buffered saline (PBS) to generate a ternary complex. The complex was then excited near the absorbance maximum of the analyte and near the maximum of the fluorophore, and energy transfer efficiencies were calculated.

Control experiments were also done in which the fluorophore was excited at the analyte’s excitation wavelength in the absence of any analyte, to determine whether peaks previously identified as energy transfer peaks might be due to fluorophore emission from excitation at a wavelength where it has non-zero absorbance.
The results of these experiments were quantified as “fluorophore emission ratios,” defined as the integrated fluorophore emission in the absence of an analyte divided by the integrated fluorophore emission in the presence of the analyte (Table 1) (full results are in the Supporting Information).

Table 1 Fluorophore emission ratios at 10 mM γ-cyclodextrin

<table>
<thead>
<tr>
<th>compound</th>
<th>compound 8</th>
<th>compound 9</th>
<th>compound 10</th>
</tr>
</thead>
<tbody>
<tr>
<td>compound 1</td>
<td>0.99</td>
<td>0.98</td>
<td>1.09</td>
</tr>
<tr>
<td>compound 2</td>
<td>0.20</td>
<td>0.27</td>
<td>0.73</td>
</tr>
<tr>
<td>compound 3</td>
<td>0.05</td>
<td>0.09</td>
<td>0.91</td>
</tr>
<tr>
<td>compound 4</td>
<td>1.48</td>
<td>0.95</td>
<td>0.34</td>
</tr>
<tr>
<td>compound 5</td>
<td>1.73</td>
<td>0.60</td>
<td>0.97</td>
</tr>
<tr>
<td>compound 6</td>
<td>1.99</td>
<td>1.63</td>
<td>0.99</td>
</tr>
<tr>
<td>compound 7</td>
<td>1.89</td>
<td>1.78</td>
<td>0.87</td>
</tr>
</tbody>
</table>

Table 2 Energy transfer efficiencies for each analyte-fluorophore combination

<table>
<thead>
<tr>
<th>compound</th>
<th>compound 8</th>
<th>compound 9</th>
<th>compound 10</th>
</tr>
</thead>
<tbody>
<tr>
<td>compound 1</td>
<td>c</td>
<td>c</td>
<td>55.2%</td>
</tr>
<tr>
<td>compound 2</td>
<td>6.0%</td>
<td>a</td>
<td>19.0%</td>
</tr>
<tr>
<td>compound 3</td>
<td>10.1%</td>
<td>a</td>
<td>27.4%</td>
</tr>
<tr>
<td>compound 4</td>
<td>b</td>
<td>c</td>
<td>b</td>
</tr>
<tr>
<td>compound 5</td>
<td>b</td>
<td>18.7%</td>
<td>c</td>
</tr>
<tr>
<td>compound 6</td>
<td>7.8%</td>
<td>9.2%</td>
<td>c</td>
</tr>
<tr>
<td>compound 7</td>
<td>b</td>
<td>8.6%</td>
<td>b</td>
</tr>
</tbody>
</table>

- Excessive overlap between the analyte and fluorophore prevented accurate integration.
- No fluorophore peak was observed from analyte excitation.
- Fluorophore emission ratios indicate no real energy transfer is occurring (emission ratios between 0.95 and 1.05).

Although anthracene (1) does not undergo significant energy transfer with fluorophores 8 and 9 (as measured by the fluorophore emission ratios), the highly toxic PAHs 2 and 3 demonstrate significant energy transfer.

Benzo[a]pyrene 3 acted as an energy donor with fluorophores 8 and 9 (and to a limited extent with squaraine 10). The energy transfer peaks with compounds 8 and 10 are clearly visible at 558 nm and 659 nm, respectively (Figure 3). Control experiments also demonstrated the necessity of γ-cyclodextrin for energy transfer, as in the absence of cyclodextrin only 3% energy transfer was observed for benzo[a]pyrene with compound 8 (compared to 10% in the presence of 10 mM γ-cyclodextrin). The detection of benzo[a]pyrene is particularly crucial, due to its low recommended concentration limit (0.132 ppm) and high carcinogenicity.

The formation of ternary complexes with compound 2 as an analyte can be measured by a decrease in the excimer emission in the presence of increasing amounts of fluorophore (Figure 4). Using pyrene 2 as an energy donor with compound 9 as an energy acceptor resulted in the sequential displacement of one molecule of pyrene from the γ-cyclodextrin cavity and a concomitant decrease in the pyrene excimer emission to 41% of its initial value (Figure 4). Both compounds 8 and 10 also acted as competent energy acceptors, with 6% and 19% energy transfer observed, respectively.

Although the interaction is not fully elucidated at this point, but nonetheless has the potential to contribute to array-based detection of toxic
analytes (see below).

In order for this energy transfer to be practical for the detection of toxic analytes, it needs to be both sensitive and selective. The sensitivity of this method was determined by quantifying the limits of detection for all analyte-fluorophore combinations, and the results are shown in Table 3. The limits of detection are defined as the amount of analyte necessary to observe a signal that is distinguishable from the baseline (see SI for details). The limits of detection for compounds 2 and 5 are below the FDA-recommended concentration limits, thus providing a useful mechanism for the detection of these highly toxic analytes.

Table 3 Limits of detection for all analytes with fluorophores 8-10 (all values given in parts per million (ppm))

<table>
<thead>
<tr>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
</tr>
</thead>
<tbody>
<tr>
<td>8</td>
<td>a</td>
<td>5.9</td>
<td>104</td>
<td>83</td>
<td>32</td>
<td>12</td>
</tr>
<tr>
<td>9</td>
<td>a</td>
<td>a</td>
<td>61</td>
<td>55</td>
<td>32</td>
<td>9.8</td>
</tr>
<tr>
<td>10</td>
<td>a</td>
<td>a</td>
<td>31</td>
<td>43</td>
<td>b</td>
<td>b</td>
</tr>
</tbody>
</table>

* Efforts to calculate limits of detection led to nonsensical values in these cases. Current efforts are focused on solving this problem.

In summary, reported herein is the development of highly efficient non-covalent energy transfer in γ-cyclodextrin cavities between toxic energy donors and fluorescent energy acceptors. This energy transfer has a number of advantages compared to previously-developed systems, including: (a) high sensitivity (as low as 5.9 ppm for compound 2); (b) ease of tunability; and (c) widespread applicability to two classes of highly toxic compounds. The development of a full array-based detection system, and a detailed investigation of the energy transfer mechanism, are underway and the results will be reported in due course.

Notes and references