Non-ionic polythiophenes: a non-aggregating folded structure in water†

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The non-aggregating nature of a water-soluble π-conjugated polythiophene has been characterised by concentration independent thermal denaturing.

π-Conjugated polymers are highly interesting materials that have potential applications as sensors[1] for biological,[2,3] organic[4,5] and inorganic[6–8] materials. Sensing relies on the photophysical properties of π-conjugated polymers changing in a reliable and reproducible way on exposure to analytes. However, π-conjugated polymers often form aggregates in an ill-defined way causing irreproducible sensing results. The use of non-aggregating isolated chain polymers having a specific conformation therefore has appeal. It is of the utmost importance to be able to distinguish between an aggregated and a non-aggregated folded species. This is a non-trivial issue. While the folding structure of oligomers may often be determined by NMR[9] and X-ray crystallography, polymers present significant challenges to both these techniques. Polymers often show very broad NMR peaks and form amorphous films rather than crystallise.

Water-soluble π-conjugated polymers are of particular interest due to the ubiquity of water in biological contexts. In addition, these polymers should be non-ionic to maximise the chances of compatibility and minimise interference in sensing through non-specific ionic interactions. Non-ionic water soluble π-conjugated polymers have been synthesised and investigated.[1,2,10] However, there are only a few claims in which the polymers are present as a single species.[10] Herein we present the synthesis of a water soluble π-conjugated polythiophene having oligoethylene glycol side-chains (**1**) and its single chain conformation in aqueous solution, by investigating the concentration dependence of the thermal denaturation.
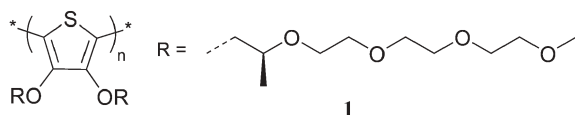
Polythiophene **1** was synthesised by oxidative coupling with iron(III) chloride followed by purification by size exclusion chromatography. The synthesis of the monomer is based on a transetherification with 3,4-dimethoxythiophene and a chirally substituted tetra-ethylene glycol.‡ The resulting purple polymer has been characterised, including by GPC and NMR.‡

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The optical properties of the polymer have been investigated in THF and water. Upon dissolution in THF red solutions are produced, which exhibit spectra (λ_{max} = 510 nm) similar to other polythiophenes having random coil conformations.[11,12] Fig. 1 shows the effect of varying the solvent from THF to pure water for solutions of polythiophene **1**. As much as 96% water may be present without affecting the random coil like nature of the spectrum. With less than 4% THF in the now mostly aqueous solution the spectrum starts to shift. When dissolved in pure water the solutions are purple at room temperature having absorption maxima at 508 nm, 550 nm and 602 nm, clearly indicating a non-random coil conformation. Fig. 2 shows the UV–visible and fluorescence spectra of polythiophene **1** in both pure THF and pure water (λ_{ex} = 502 nm). Not only does the aqueous UV–visible spectrum show additional red-shifted bands but the aqueous fluorescence ($\lambda_{max,em}$ = 612 nm, 662 nm) is also red-shifted in relation to that of the random coil conformation of the THF dissolved polymer ($\lambda_{max,em}$ = 590 nm). Upon heating an aqueous
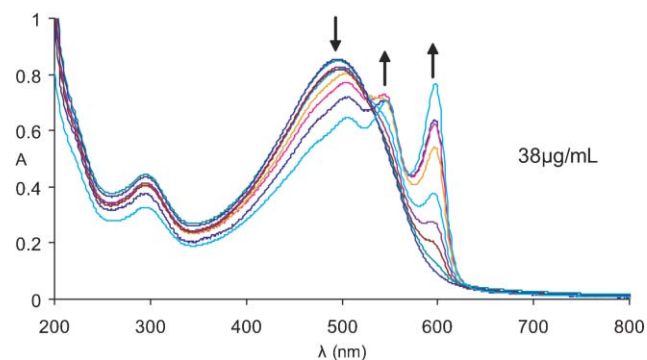

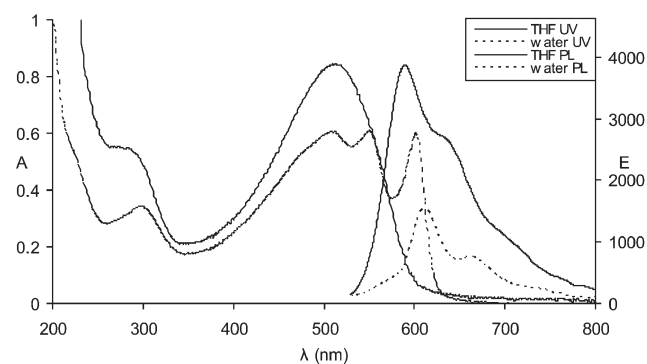**Fig. 1** UV–visible spectra of polythiophene **1** in THF/water mixtures, ranging from 96%–100% water.

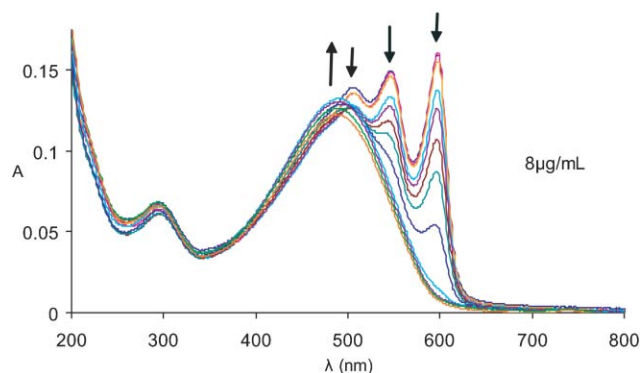**Fig. 2** UV–visible and fluorescence spectra of polythiophene **1** in THF and in water (λ_{ex} = 502 nm).

Fig. 3 UV–visible spectra of polythiophene **1** in water from 10 °C to 60 °C.

Fig. 5 Linear change in the peak absorbance of polythiophene **1** in water.

Fig. 6 Concentration independence of the thermal unfolding transition of polythiophene **1** in water.

solution of polythiophene **1** the UV–visible absorption and fluorescence emission spectra change to ones similar to that of a THF solution (Figs. 3 and 4). The interpretation of spectroscopic data for such materials is usually ascribed to either aggregation[13–15] or to non-aggregation processes involving the adoption of different conformers in solution.[11,16,17] Considerable debate exists on this subject because foldamers exhibit many of the photophysical properties of aggregates.

To investigate the issue of aggregation *vs.* conformation in detail concentration dependent UV–visible measurements were carried out. The intensity of the UV–visible absorption spectrum of polythiophene **1** changes linearly with concentration (Fig. 5). This is consistent with a non-aggregated behaviour. The linear change in absorption with concentration suggests that this is not an aggregate species in water. If, however, aggregation is very strong then dilution may not break up the aggregates to a significant enough extent. Additional proof is therefore required to rule out aggregation.

For an aggregated system the temperature at which the denaturation transition occurs should be dependent on the concentration of the solution. This has been shown to be the case for aggregated oligomeric systems,[18,19] where increasing the concentration raises the temperature of thermal deaggregation. In contrast, the thermal unfolding of a single chain species should be independent of concentration. The UV–visible absorption spectrum of an aqueous solution of polythiophene **1** was monitored over a range of temperatures from 10 °C to 60 °C at
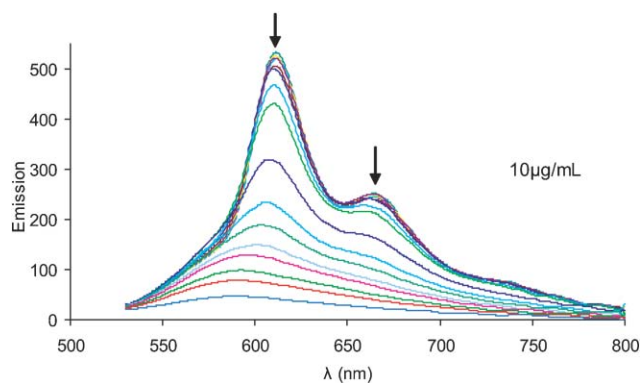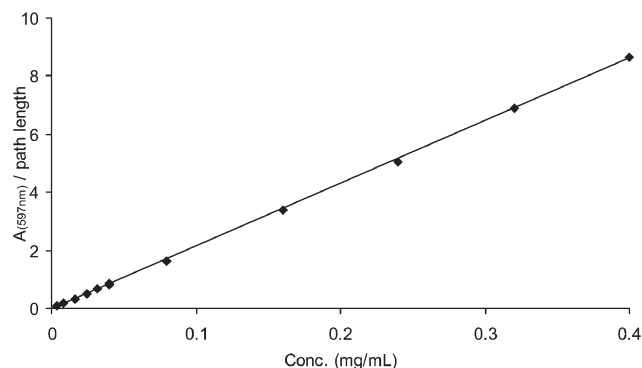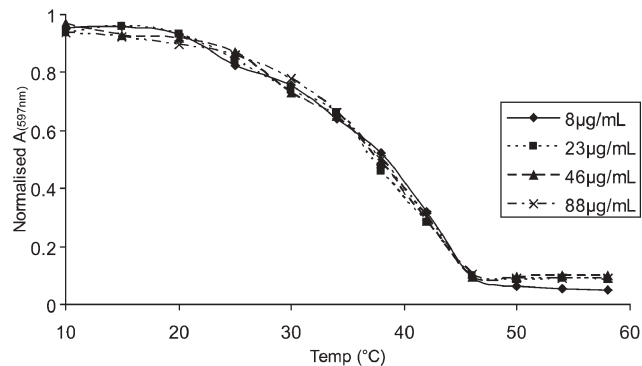
a variety of different concentrations. Fig. 6 shows one of the peak absorbances (597 nm) over the temperature range observed, scaled by solution concentration, for four different concentrations.[20] It can clearly be seen from the close congruence of the lines that the thermal transition is concentration independent, pointing to foldameric properties.[21]

Fig. 7 shows the concentration independence of the fluorescence of polythiophene **1** through the thermal transition between folded and unfolded states in water, revealing similar behaviour to that from the UV–visible spectra. However, the exact shape of the relative spectral intensities throughout the transition is slightly different from UV–visible spectra to fluorescence spectra.[22] It is
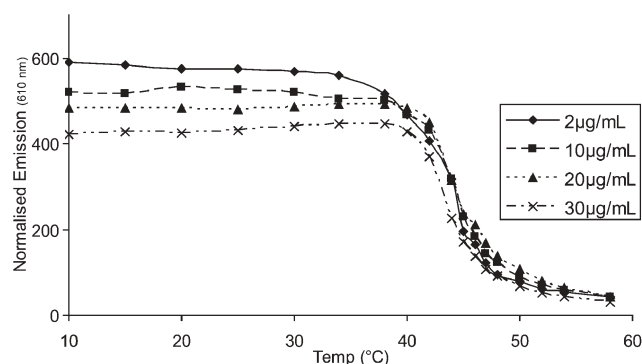

Fig. 4 Fluorescence spectra of polythiophene **1** in water from 10 °C to 60 °C (λ_{ex} = 502 nm).

Fig. 7 Fluorescence thermal unfolding transitions of polythiophene **1** in water (λ_{ex}=502 nm).

generally observed that as a solution of an aggregating polymer is cooled its fluorescence goes down due to quenching through inter-chain interactions. However, in the case of polythiophene **1** quite the reverse is seen. Fig. 7 shows a dramatic increase in fluorescence on cooling, revealing that this transition is more likely to be related to folding than to aggregation.

Aqueous GPC measurements have been made on polythiophene **1** with injection concentrations in the range 0.064–8 mg/mL.‡ In all cases the elution time was identical, indicating that no aggregation exists in aqueous solution.

Since polythiophene **1** has been shown here not to aggregate in aqueous solution one must consider what conformational structure it does adopt. Circular dichroism experiments showed no Cotton effect for polythiophene **1** in water, in contrast to earlier findings for aggregated polythiophenes.[15] The lack of a Cotton effect indicates that the chirality in the side-chains is not expressed in the main-chain and that in the case of a folded structure equal amounts of P and M helices exist. This is evidence for a structure that does not bring the side-chains into close proximity. The broad nature of the NMR signals for polythiophene **1** in D_2O makes NOE experiments to determine conformation in solution impossible. Dilution of the solutons in D_2O did not lead to significant changes in the shape or positions of the peaks. Interestingly, the spectrum is similar to that in deuterated chloroform, suggesting that the side-chains are not packed in water. Both Moore[23] and Hecht[10,24] have made oligoethylene glycol appended foldamers in aqueous solution and shown them to have a helical conformation. Calculations have shown that the helical form of an all *cis* polythiophene is a stable conformation.[25] Based on this we believe that polythiophene **1** adopts a helical conformation in water.

A new polythiophene has been synthesised that shows a non-aggregating folded structure in water. This behaviour was determined by new techniques for distinguishing between foldameric and aggregated polymeric systems.[26] The new π-conjugated polythiophene presented here provides a basis for the development of new and interesting materials with controlled electronic properties through control of their secondary structure, which will have applications in the field of organic electronics as well as biosensing.

Koen Pieterse is acknowledged for generating the artwork that is on the cover of this issue.

Notes and references

‡ Synthetic procedures and experimental details are included in the ESI.

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26 Experiments covering extension of the concentration dependent thermal denaturation technique to other polymers have been carried out but the material has yet to be published.