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Highly reactive (<1 min) ratiometric probe for selective 'naked-eye' detection of cyanide in aqueous media

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ABSTRACT

We have designed and synthesized a triphenyl aminebenzothiazole coupled receptor (TBH) that exhibits a selective, sensitive, colorimetric, and ratiometric rapid response toward cyanide anion in aqueous media. The sensing event is explained by spectroscopy along with DFT calculation and CV diagram. Sensor displays a very fast response (<1 min) toward cyanide at room temperature with a 'naked-eye' change over F^- and AcO^- in aqueous media.

The development of optical chemosensors for anions of biological, environmental, and clinical concerns is currently under active investigation.[1] Among the toxic anions acting as severe environmental pollutants and consequently having adverse health effects, cyanide is one of the most-concerning anions. It can directly lead to the death of human beings[2] as well as aquatic life,[3] even at low concentration, by binding to a 3 cytochromes, inhibiting the electron transport chain in mitochondria and by depressing the central nervous system.[4] Due to this, it is lethal to human at concentrations of 0.5–3.5 mg/kg of body weight.[5] Despite its toxicity, its application in various areas as raw materials for synthetic fibers, resins, herbicides, and the gold extraction process is inevitable, which release cyanide into the environment as a toxic contaminant[6,7] and it can lead to serious contamination of the ground and/or drinking water.[8] Thus, there is a need for an efficient sensing system for cyanide to monitor cyanide concentration from contaminant sources.

In past few years, a variety of colorimetric and fluorescent probes for cyanide have been reported. One of the common approaches is utilizing cyanide complexes or addition with Zn^{2+}–porphyrin,[9a] Ru^{2+}–pyridine,[9b] boronic acid derivatives,[9c] and CdSe quantum dots.[9d] Other strategies were also involved, such as hydrogen bonding interactions,[10] copper–cyanide affinity,[11] and single-electron transfer reaction.[12] Recently, nucleophilic addition of cyanide has also been adopted for sensing cyanide. Based on this idea, nucleophilic addition of cyanide to oxazine, pyrylium, squarane, trifluoroacetophenone, acyltrazene, acridinium, salicylaldehyde, and carboxamide has been reported.[13]

In spite of these developments, there are still relatively few examples of selective and sensitive probe for cyanide anion especially those that display limited inference in the presence of other anions particularly with F^-, AcO^-, and $H_2PO_4^-$. Moreover, the receptors based on these approaches have very complex structures. This requires multiple step synthesis with relatively low overall yields. As a result, developed chemosensors cannot be prepared on a large scale. Furthermore, most of the sensors/receptors have limitations in analytical and bio analytical applications due to poor sensing of cyanide in aqueous media and most of the chemo dosimeter type sensors for CN^- are time consuming, that is, the neucleophilic attack of cyanide to the sensor is really slow. Therefore, it is highly desirable to develop sensitive, selective, and easy-to-prepare chemical sensor for cyanide even in water medium with a rapid response.

With these considerations in mind, we report here the design and synthesis of a simple receptor, triphenylamine benzothiazole hybrid (TBH) that exhibits a selective, sensitive, colorimetric, and ratiometric response toward cyanide anion in aqueous acetonitrile solution. Importantly, TBH displays a very fast response (<1 min) to cyanide at room temperature, and 'naked-eye' detection is possible in the presence of only 1 equiv of cyanide.

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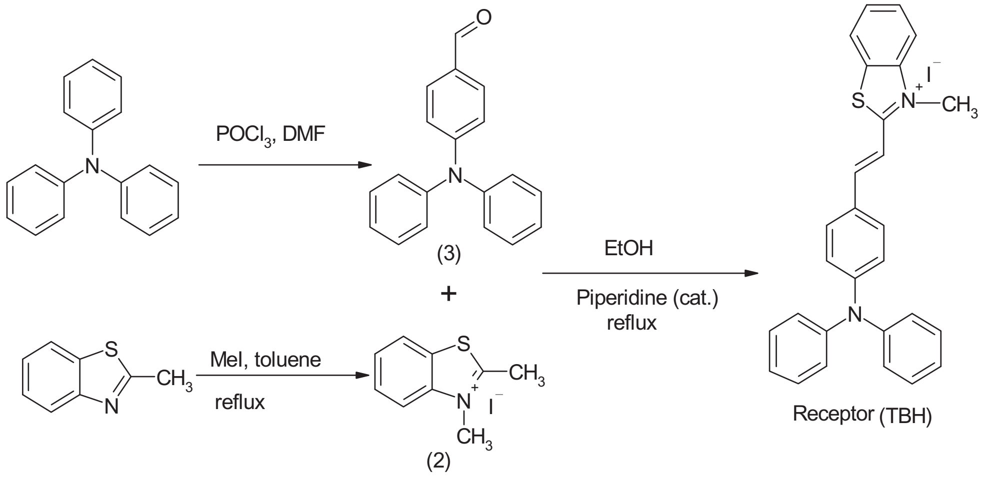


Scheme 1. Synthesis of the receptor (TBH).

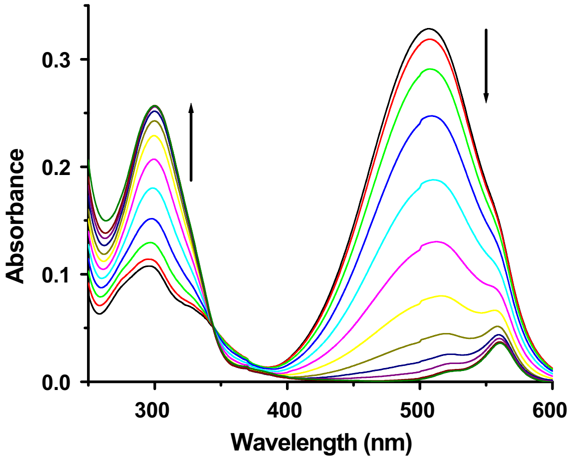


Figure 1. UV–vis absorption titration spectra of TBH ($c = 2.0 \times 10^{-6}$ M) in the presence of CN^- ($c = 2.0 \times 10^{-5}$ M) at pH 7.1 in CH_3CN/H_2O = 1:1.

The synthesis of the sensor is shown in Scheme 1. The precursor mono aldehyde of triphenylamine (**3**) is prepared from the corresponding amine maintaining the Vilsmeier–Haack condition according to the literature procedure.[14] When benzothiazole is treated with MeI in toluene as a solvent corresponding salt (**2**) is obtained. In the presence of piperidine, **2** and **3** are coupled in absolute ethanol to form the desired receptor (i.e., TBH) in 90% yield. The purity of TBH was confirmed by ^{1}H NMR, ^{13}C NMR, and ESI-MS spectra (Supplementary data).

The behavior of TBH toward a variety of anions was explored with UV–vis absorption spectrometry. The various anions tested are AcO^-, Cl^-, Br^-, I^-, F^-, and PhO^- as their tetra butyl salts; SH^-, $H_2PO_4^-$, PO_4^{3-}, S^{2-}, N_3^-, $P_2O_7^{4-}$, and SCN^- as their sodium salts; CN^- and ADP as their potassium salts in solution. In UV–vis absorption spectrometry, only CN^- was found to perturb the electronic behavior of TBH to a significant extent. The absorption spectrum of TBH (2×10^{-6} M, in CH_3CN/H_2O as 1:1) is characterized by an intense absorption band (a twin band) centered at 507 nm attributed to intramolecular charge-transfer (ICT) transition, in combination with the less intense $\pi \rightarrow \pi*$ transitions at 300 nm. The ICT band is responsible for the reddish pink color of TBH. Upon incremental addition of CN^- solution (2×10^{-5} M, in HEPES solution), a complete reduction in the intensity of 507 nm bands accompanied by ratiometric (isosbestic point at 343 nm) increase of intensity at 300 nm was observed which achieved saturation after the addition of 1 equiv solution of CN^- ions (Figs. 1 and 3). The visual color change is shown in Figure 2. In emission spectroscopy there is a negligible change observed in 440 nm range upon addition of 1 equiv cyanide ion (Supplementary data).

This indicated the minimum required amount of CN^- which was used at this point of saturation for the formation of the visual colorless solution. The large hypsochromic shift in the ICT band resulted in the observed complete bleaching of the original reddish pink color of the receptor.

We envisaged that the observed bleaching of the color in the presence of CN^- may arise from the nucleophilic addition reaction of CN^- at the benzothiazole ring carbon adjacent to the quaternary nitrogen atom to give a neutral structure and thus rupturing the electronic delocalization with the concurrent disappearance of the low energy band, resulting in the formation of colorless species (Scheme 2).

This was confirmed by ^{1}H NMR spectra which show the δ value downfield shift (0.61 ppm) from 1.45 to 2.06 ppm of methyl protons adjacent to quaternary 'N' to tertiary 'N' (Supplementary data). From the IR data the phenomenon is also well explained by the appearance of a new peak at 2250 cm^{-1} due to the insertion of the cyano group in TBH (Supplementary data). The mass spec-

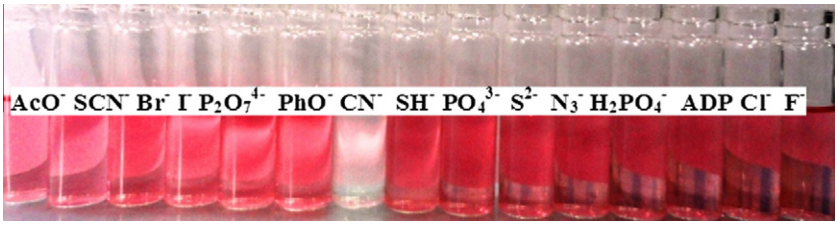


Figure 2. Visual changes of TBH ($c = 2.0 \times 10^{-6}$ M) with addition of 1.0 equiv of each anion ($c = 2.0 \times 10^{-5}$ M) at pH 7.1 in CH_3CN/H_2O (1:1, V/V).

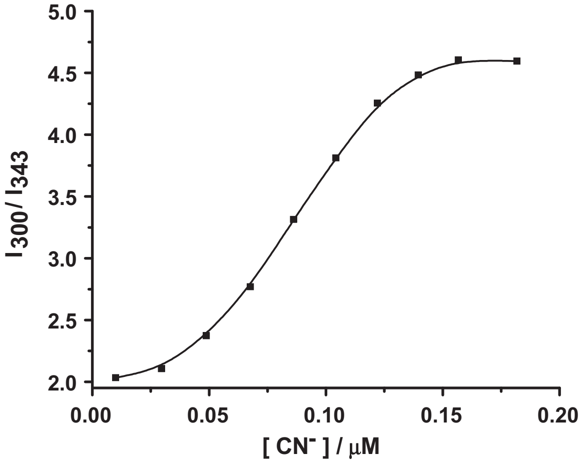
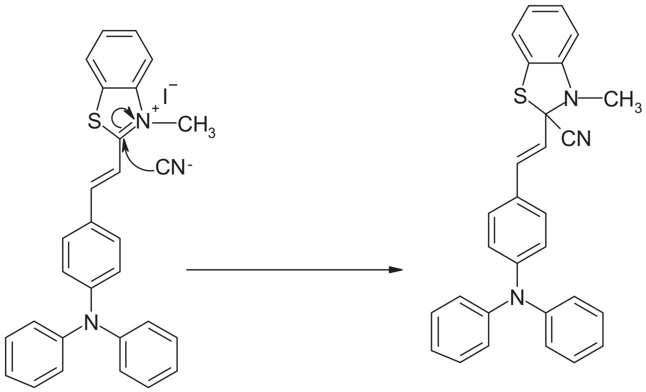


Figure 3. Normalized absorbance (I_{300}/I_{343}) versus [CN⁻]/µM diagram of TBH with gradual addition of cyanide (from the data of Fig. 1).



Scheme 2.

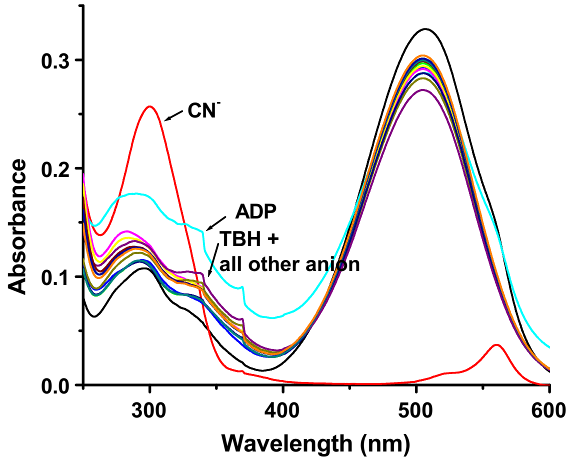


Figure 4. The absorption spectra of TBH ($c = 2.0 \times 10^{-6}$ M) and TBH with all other anions ($c = 2.0 \times 10^{-5}$ M) in CH_3CN/H_2O (1:1, V/V) at pH 7.1.

trum (ESI-MS) of the cyano adduct shows the highest peak at *m*/*z* 446.0 possibly for $(M+CN)^+$ ions, which also proves a single mononuclear addition of cyanide to the receptor TBH, *m*/*z* 418.99 (Supplementary data).

However, when titrations of other anions such as AcO^-, Cl^-, Br^-, I^-, F^-, PhO^-, SH^-, $H_2PO_4^-$, PO_4^{3-}, S^{2-}, N_3^-, $P_2O_7^{4-}$, and ADP were

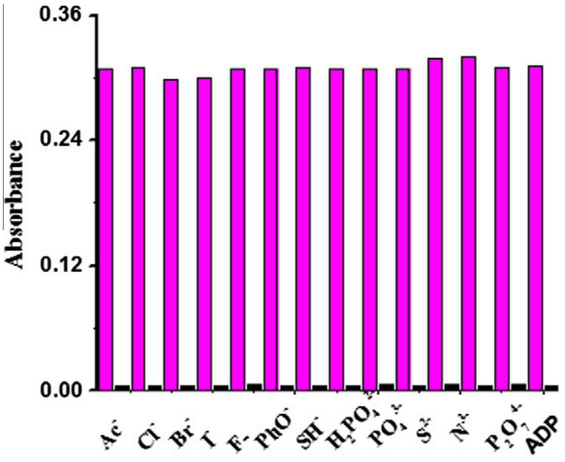


Figure 5. Absorption response of TBH with addition of CN⁻ (1.0 equiv) (black bar) in the presence of all other tested anions (5 equiv) (pink bar) at Λ_{max} = 507 nm.

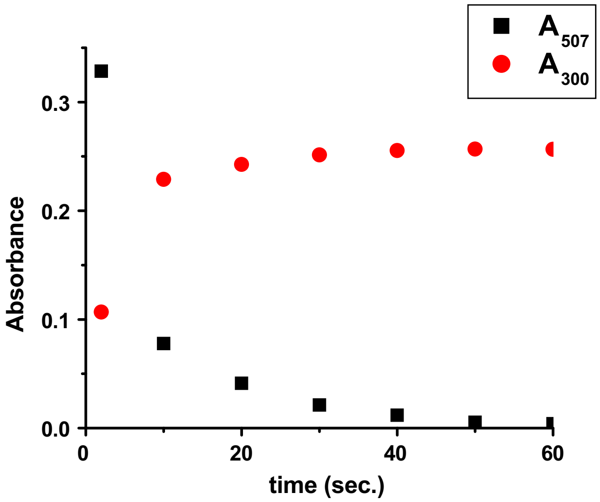


Figure 6. Time-dependent absorption intensity of TBH at 300 nm (in red) and 507 nm (in black) in the presence of CN⁻ (1.0 equiv).

performed under a similar experimental condition, no significant change in the absorption spectrum (Fig. 4) as well as in color of the solution was noticed (Fig. 2).

Interestingly, the anions, F⁻ and AcO⁻, which have been reported[15] to be the most interfering anions in the detection of CN⁻, also did not affect the sensing process.

Further, competition experiments have also been performed by adding CN⁻ (1.0 equiv) to the sensor in the presence of commonly employed interfering anions (5.0 equiv). The selectivity profile diagram (Fig. 5) reveals that cyanide-induced quenching of absorbance (Λ_{max} = 507 nm) remains unperturbed and does not get any interference by the coexisting anions. This indicates that TBH can be used potentially to quantitatively detect CN⁻ concentration with a high selectivity.

We then investigated the time-dependent changes in the absorption spectra upon incubation of TBH (10 µM) with CN⁻ (1.0 equiv) for 1 min we see that 1 equiv of cyanide is sufficient to drive the reaction to completion within 1 min, re-enforcing the high reactivity feature of the probe (Fig. 6). The calculated detection limit 0.037 µM (Supplementary data) suggests that the receptor is very sensitive toward CN⁻ ion.

In order to investigate the structural change occurred for the colorimetric response of TBH–CN⁻, DFT calculations were carried

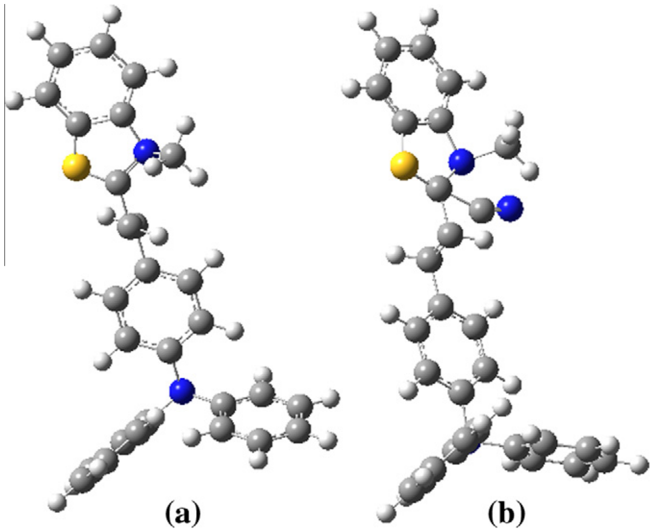


Figure 7. Optimized structure of TBH (a) and TBH–CN (b).

out for TBH and the TBH–CN using the DFT/B3LYP/6-31G$*$ basis set (Gaussian 03 program).[16] The significant difference in the π-conjunction between TBH and TBH–CN is observed in the optimized structures of TBH and TBH–CN, shown in Figure 7. It clearly indicates the high degree of conjugation between the two coplanar aromatic rings, that is, the phenyl ring and the benzothiazole ring via a 'C=C' bond in TBH (Fig. 7a). The hampered conjugation in TBH–CN (Fig. 7b) results from the addition of CN^- at the methine carbon of the benzothiazole ring which is responsible for observed hypsochromic shift in the lower wavelength absorbance (ICT) of TBH on forming the $TBH–CN^-$ adduct. The HOMO–LUMO energy gap (Supplementary data) in the calculated structures also supports the phenomenon.

In order to see if the results obtained in the solution studies could be visualized on TLC plate strips so that it can be used as ready to use 'dip sticks', strips coated with TBH were immersed in the aqueous solutions of KCN in different concentrations and an instant bleaching of the reddish pink color was observed (Fig. 8). Development of such dipsticks is useful as instant qualitative information without resorting to the instrumental analysis.

The nucleophilic addition of CN^- at the methine carbon of TBH is further supported by the cyclic voltammogram of $TBH–CN^-$ adduct. The two reversible one-electron reduction processes observed in the cyclic voltammogram of TBH (formally carrying one positive charge) with $E_{1/2} = -0.19$ and -1.13 V versus $Hg/HgCl_2$, attributed to the reduction processes[17] which disappear upon the addition of CN^- at the electrophilic methine carbon of the benzothiazole ring (Fig. 9).

In conclusion, we have designed and synthesized a simple receptor triphenylamine benzothiazole hybrid (TBH) that exhibits a selective, sensitive, colorimetric, and ratiometric rapid response toward cyanide anion in aqueous acetonitrile solution. The recognition events of the sensor toward CN^- are demonstrated nicely by absorbance spectroscopy and explained by other spectroscopic data with DFT calculation and CV diagram. From the competition experiment it is clear that sensor can be used potentially to quantitatively detect CN^- with a high selectivity over F^-, AcO^-, and other anions. Importantly, TBH displays a very fast response (<1 min) to cyanide at room temperature, and 'naked-eye' detection is possible in the presence of only 1 equiv of cyanide both in aqueous solution and in TLC plate strips which are very useful tools for the detection of cyanide without resorting to the instrumental analysis.

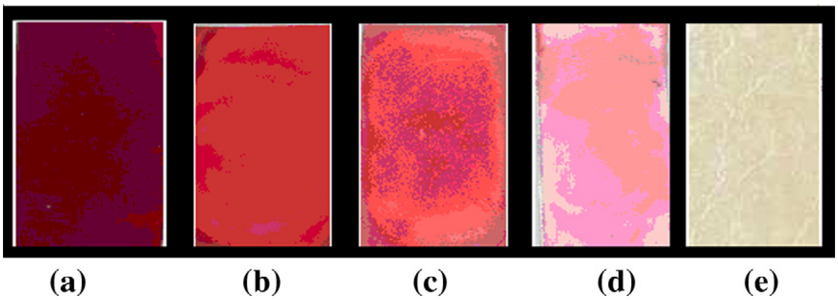


Figure 8. Color changes visualized on TLC plate strips of (a) TBH ($c = 2.0 \times 10^{-3}$ M) and during addition of KCN at (b) 2.0×10^{-6} M; (c) 2.0×10^{-5} M; (d) 2.0×10^{-4} M and (e) 2.0×10^{-2} M in $CH_3CN/H_2O = 1:1.4$

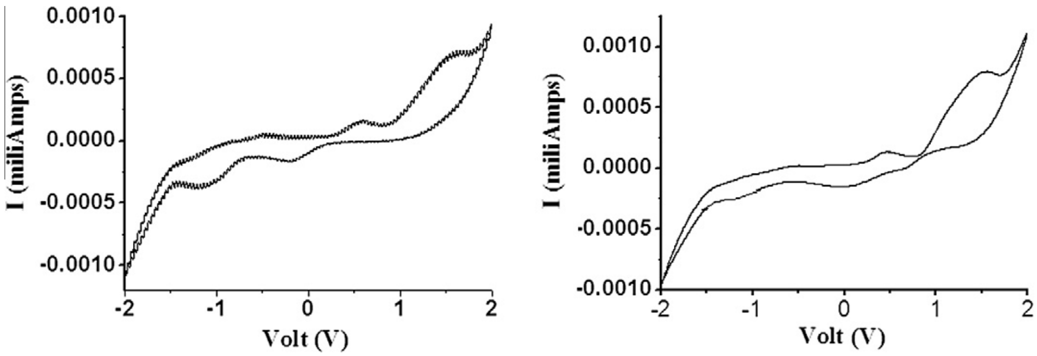


Figure 9. Cyclic voltammograms of TBH (1×10^{-3} M, in CH_3CN) before (left) and after addition of CN^- solution (1×10^{-2} M, in HEPES buffered H_2O) (right).

Acknowledgments

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