Colorimetric anion chemosensors based on anthraquinone: naked-eye detection of isomeric dicarboxylate and tricarboxylate anions†

Yi-Shan Lin, Guan-Min Tu, Chi-Yung Lin, Yen-Tzu Chang and Yao-Pin Yen*

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Three new colorimetric anion receptors **1–3** were synthesized and characterized. Among them, both **1** and **3** showed good sensitivity and selectivity for discrimination of maleate *vs*. fumarate or malate *vs*. tartrate by dramatic colour changes in DMSO or DMSO–H_2O (95 : 5). Thus, both **1** and **3** can be used as optical chemosensors for recognition of maleate *vs*. fumarate or malate *vs*. tartrate anion. Besides that, the receptor **1** has also a unique colour change for recognition of either *cis*-aconitate or *trans*-aconitate in DMSO, accordingly it can be used for detection of each isomer and discrimination of *cis*-aconitate from *trans*-aconitate anion.

Introduction

Anions, especially dicarboxylates or tricarboxylates, play an important role in chemical and biochemical processes and their recognition and sensing by artificial chemo-sensors has been a focus of interest for chemists in the past decades.[1] The selective recognition of specific anionic species is generally based on electrochemical, visible and optical response.[2] Colour changes, as signaling an event detected by the naked eye, are widely used owing to the low cost or the lack of required equipment. The strategy to prepare colorimetric anion sensors is the binding site-signaling unit approach in which an appropriate chromophore is attached to a specific anion receptor.[3] These chromophores may contain electron-withdrawing groups that can enhance the acidity of the anion binding subunit. Urea and thiourea subunits are currently used in the design of neutral receptors for anions, owing to their ability to act as H-bond donors,[4] and many ligands containing either one or two of these groups have been reported to be excellent sensors for dicarboxylate anions.[5] During recent years, we have been studying the synthesis of colorimetric chemosensors for dicarboxylate anions and their possible application in sensing.[6] Now we wish to report the preparation of new chromogenic receptors **1–3** and their utility in the selective colorimetric discrimination between certain organic isomers (*cis*/*trans* dicarboxylates and *cis*/*trans* tricarboxylates) and structurally similar dicarboxylates (malate/tartrate) (Chart 1). Differentiation of geometric isomers is, in general, a difficult task because of their rather similar chemical and physical properties. To the best of our knowledge, only a few examples have been published.[6,7]

The interest in selective sensors that are able to distinguish maleate *vs*. fumarate is not only related to π-diastereoisomer recognition but is also due to the different biological behaviour

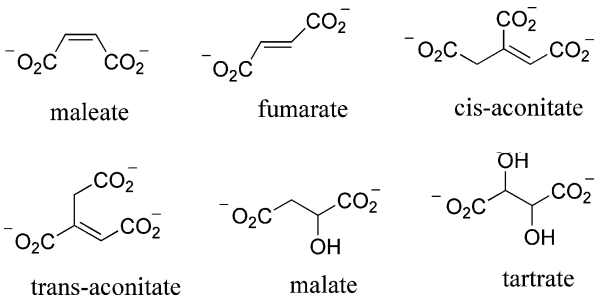

Chart 1

of these anions. In fact, whereas fumarate is generated in the Krebs cycle, maleate is a well known inhibitor of this cycle and its implication in different kidney diseases has been widely described.[8] On the other hand, the *cis*-aconitate is generated in the citric acid cycle, however, the *trans*-aconitate is an effective inhibitor of both aconitase and fumarase.[9] Moreover, the interest to selective differentiation between the structurally similar analytes, malate and tartrate, is due to the malate being an essential metabolic intermediate, the abnormal levels of its concentration being closely related to some diseases.[10]

In this work, a chromogenic unit, an anthraquinone was chosen as a scaffold to link the recognition units (Scheme 1). The introduction of binding sites at 1- and 8-positions of 1,8-diaminoanthraquinone through a propylene spacer would form a flexible convergent binding site for a feasible complexation with target species. The 4-nitrophenyl or 4-trifluoromethylphenyl fragment which is linked to the thiourea moiety was chosen as a chromophore to provide spectral sensing character upon complexation with anions. In spite of lacking electronic conjugation between the thiourea and anthraquinone moiety, the receptors **1–3** showed UV-vis spectral changes on complexation with anions.

Results and discussion

Preparation of receptors **1–3** is depicted in Scheme 1. A synthetic intermediate, 1,8-di-(3-aminopropylamino) anthraquinone (**4**) was prepared from 1,8-dichloroanthraquinone.[11]

Department of Applied Chemistry, Providence University, 200 Chungchi Road, Sha-Lu, Taichung Hsien, 433, Taiwan. E-mail: ypyen@pu.edu.tw; Fax: +886-4-2632-7554; Tel: +886-4-2632-8001 ext 15218

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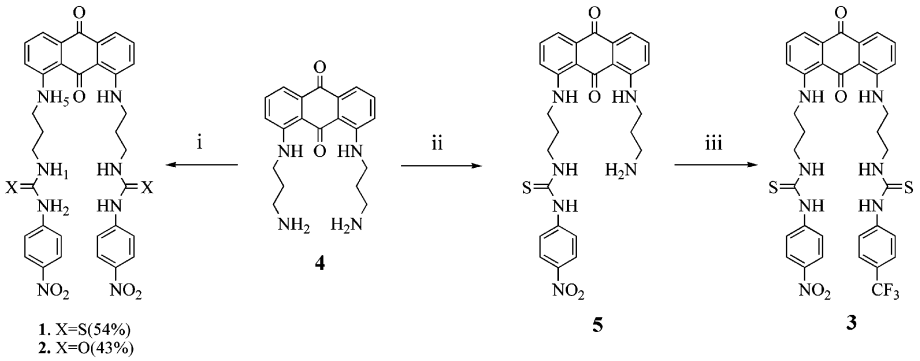

Scheme 1 *Reagents and conditions*: (i) 4-nitrophenyl isothiocyanate or 4-nitrophenyl isocyanate, THF, reflux, 18 h; (ii) 4-nitrophenyl isothiocyanate, $CHCl_3$, reflux, 46 h; (iii) 4-trifluoromethylphenyl isothiocyanate, THF, reflux, 30 h.

Reactions of **4** with 4-nitrophenylisothiocyanate and 4-nitrophenyl isocyanate afforded the corresponding receptors **1** and **2**, respectively, in moderate yields.[12] Reaction of **4** with 0.8 equivalents of 4-nitrophenyl isothiocyanate in $CHCl_3$ gave **5** in 43% yield. Subsequently, reaction of **5** with 4-trifluoromethylphenyl isothiocyanate afforded the receptor **3**. All of these compounds were characterized by ^{1}H NMR, ^{13}C NMR, IR and HRMS.

Anion binding studies

The colorimetric selective sensing ability of the receptors **1–3** with maleate and fumarate anions in DMSO was monitored by UV-Vis absorption and by the naked eye observation. The anions were added as tetrabutylammonium salts to the DMSO solutions of the receptors **1–3** (5×10^{-5} M). The receptor **1** itself displays two absorption bands at 353 and 554 nm, respectively, in DMSO. The interaction of receptor **1** with maleate anion was investigated in detail through the UV-Vis spectroscopic titration, and spectral behaviours were observed (Fig. 1). Upon addition of maleate to receptor **1** in DMSO, the intensity of the absorption peak at 353 nm was gradually decreased, while the band at 493 nm evolved and reached its limiting value after the addition of 2.0 equivalents of maleate

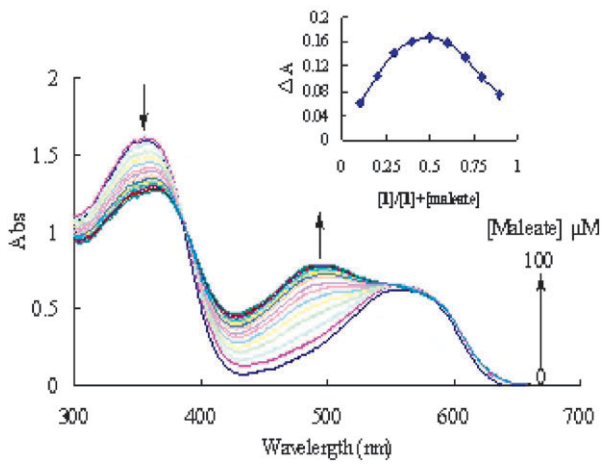

Fig. 1 Family of spectra taken in the course of the titration of a 5×10^{-5} M DMSO solution in **1** with a standard solution of maleate at 25 °C. Titration profile (inset) indicates the formation of a 1 : 1 complex.

Fig. 2 Effect of anions (as $(C_4H_9)_4N^+$ salt) on colour changes of **1** in DMSO after the addition of various anions: (a) **1** only; (b) **1** + 0.1 equiv. of maleate; (c) **1** + 2.0 equiv. of maleate; (d) **1** + 2.0 equiv. of fumarate.

(Fig. 1). Interestingly, the colour of the solution of receptor **1** was changed from its initial purple colour, *via* medium violet–red, to red, visible to the naked eye (Fig. 2). A clear isosbestic point at 386 nm indicates the presence of a complex in equilibrium with the free ligand. The changes in the absorbance as a function of the concentration of maleate added can be fitted to a 1 : 1 binding equilibrium model, with the association constant given in Table 1.[12] In fact, the 1 : 1 ligand-to-anion complex implicated that the two thiourea functionalities of the receptor **1** can act as cooperative binding sites.

The initial purple to medium violet–red colour change was observed at low maleate concentrations. This is suggestive of the formation of a charge-transfer complex of the anion through a hydrogen bonding interaction with receptor **1**. At high guest concentrations, the medium violet–red colour eventually changed to red. This may be ascribed to the deprotonation of the N–H proton of the thiourea moiety of the receptor **1**, resulting in the formation of the monodeprotonated receptor L_1^- (**1** = L_1H). The new band that develops at 493 nm pertains to the monodeprotonated receptor L_1^- which was confirmed by the Brønsted acid–base reaction of adding 1.0 equivalent of strong base [*n*-Bu_4N]OH (*cf.* Fig. SI-1, ESI†). The negative charge causes an increase in the intensity of the electrical dipole along which the optical transition takes place, which accounts for the substantial red-shift of the band (140 nm). Such a deprotonation was related to the acidity of the H-bond donor site.[13] The process of the combination of hydrogen bonding interaction and deprotonation of receptor **1** with maleate was corroborated by ^{1}H NMR titration experiments carried out in DMSO-d_6 (Fig. 3). It was found that the proton signal of N–H_2 (δ = 10.12 ppm) which is close to the 4-nitrophenyl group (signals of N–H protons were assigned by referring to the 2D

Table 1 Association constants K_a/M of receptors **1**, **2** and **3** with guest anions[a]

Anion	**1**	R^b	**2**	R^b	**3**	R^b
Maleate[c]	$(8.74 \pm 0.05) \times 10^3$	0.9963	$(5.29 \pm 0.14) \times 10^2$	0.9958	$(3.72 \pm 0.12) \times 10^3$	0.9923
Fumarate[c]	$(8.31 \pm 0.12) \times 10^2$	0.9966	$(3.82 \pm 0.47) \times 10^2$	0.9935	$(4.21 \pm 0.07) \times 10^2$	0.9979
cis-Aconitate[c]	$(8.88 \pm 0.10) \times 10^3$	0.9941	$(5.31 \pm 0.64) \times 10^2$	0.9974	$(1.92 \pm 0.26) \times 10^3$	0.9922
trans-Aconitate[c]	$(3.85 \pm 0.03) \times 10^3$	0.9955	$(2.63 \pm 0.02) \times 10^2$	0.9913	$(1.82 \pm 0.06) \times 10^3$	0.9939
Maleate[c]	$(3.83 \pm 0.16) \times 10^3$	0.9978	$(4.58 \pm 0.36) \times 10^2$	0.9982	$(1.85 \pm 0.31) \times 10^3$	0.9979
Tartrate[c]	$(6.66 \pm 0.31) \times 10^2$	0.9939	$(2.29 \pm 0.15) \times 10^2$	0.9911	$(2.18 \pm 0.07) \times 10^2$	0.9946

[a] The data were calculated from UV-Visible titration in DMSO. [b] The data values of R were obtained by the results of nonlinear curve fitting. [c] The anions were used as their tetrabutylammonium salts.

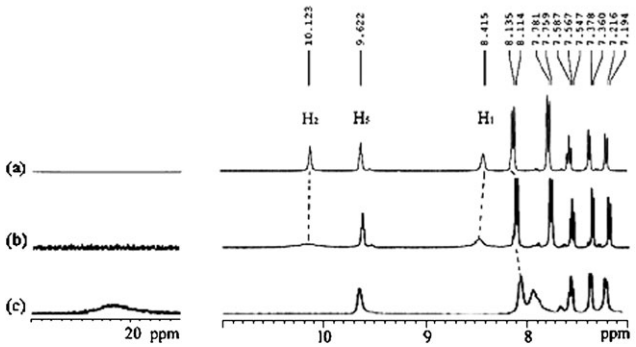

Fig. 3 ^{1}H NMR (400 MHz) spectra of sensor **1** (10 mM) in DMSO-d_6 upon addition of various quantities of maleate: (a) 0 equiv.; (b) 0.1 equiv.; (c) 1.0 equiv.

NOESY spectrum of **1**) (*cf.* Fig. SI-2, ESI†), broadened significantly early in the titration and underwent downfield shifts with increasing maleate concentration. The N–H_2 peak disappeared after addition of 1.0 equivalent of maleate, whilst a new signal was observed at δ = 20.16 ppm. This confirms the formation of a $[\mathbf{HM}]^-$ (**M** = maleate anion) species.[14] The monodeprotonation is also signaled by the significant upfield shift of the protons of the phenyl group.[15] Such an effect derives from the through-bond propagation onto the phenyl framework of the electronic charge generated on N–H deprotonation. In addition, the other signal of thiourea (N–H_1, δ = 8.42 ppm) was also found to disappear when 1.0 equivalent of maleate was added. The results implied that at low concentration of maleate, the initial complex is formed by the receptor **1** with maleate anion through hydrogen bonding interaction, followed by the deprotonation at high concentration of the guest. To further provide support for the supposition of the deprotonation, the intermolecular N–H···O hydrogen bonded distances were calculated at the HF/6-31G(d) level using *ab initio* calculations (Fig. 4). Four protons of thioureas are directed toward anion ligands but each hydrogen-bond distance is different as shown in Table 2 of ESI.† Among them, only the proton (H_2) which is connected to the 4-nitrophenyl group has a much shorter distance to the carboxylic group than a typical hydrogen-bond distance, which ranges between 1.86 and 2.16 Å.[16]

In contrast, a similar experiment with fumarate anion was carried out and no significant changes in spectra were observed in the UV-Vis absorption. In this process, no noticeable colour change was observed and the solution remained a purple colour (Fig. 2). This indicates that the receptor **1** is weakly binding or not interacting significantly with fumarate in this solvent medium. The interaction of receptor **1** with fumarate was corroborated by ^{1}H NMR titration experiments. It was found that when receptor **1** formed a complex with fumarate, the proton signal of the N–H_2 underwent downfield shifts with increasing fumarate concentration from 10.13 to 11.89 ppm and the chemical shift of N–H_1 changed from 8.42 to 10.32 ppm (Fig. 5). The relatively small downfield shifts indicate that the complex is formed solely through weak hydrogen bonding interactions and is inconsistent with a deprotonation process between fumarate and the receptor. This rationale was also supported by the *ab initio* calculations (see Table 2, ESI†). The comparison of the UV-Vis absorption spectra of the complex **1** upon addition of either maleate or fumarate is shown in the ESI (Fig. SI-3, ESI†).

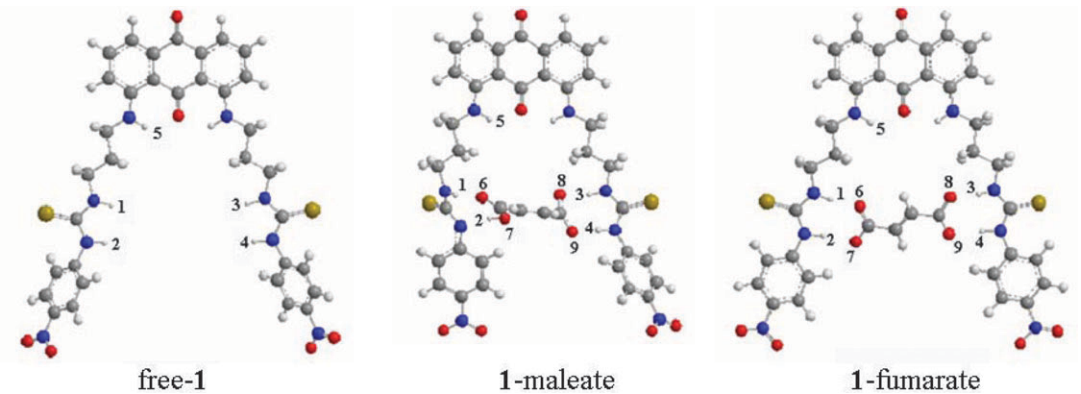

Fig. 4 Optimized geometries from *ab initio* HF/6-31G(D) calculations.

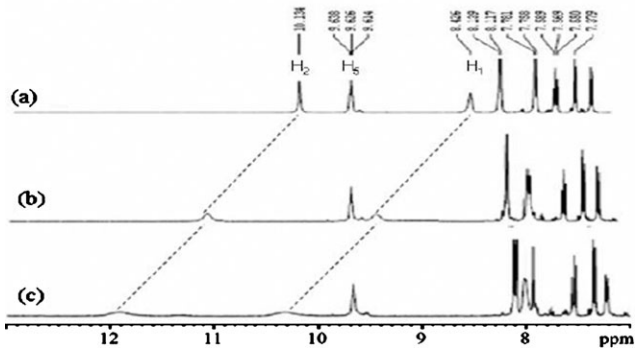

Fig. 5 ^{1}H NMR (400 MHz) spectra of sensor **1** (10 mM) in DMSO-d_6 upon addition of various quantities of fumarate: (a) 0 equiv.; (b) 0.5 equiv.; (c) 1.0 equiv.

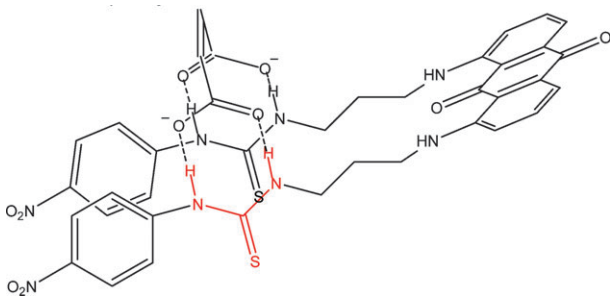

Fig. 6 Possible binding model of **1** with maleate anion.

Apparently, the receptor **1** has a unique colour change and higher sensitivity and selectivity recognition for maleate than fumarate, and can act as an optical chemosensor for recognition of maleate *vs*. fumarate. The different sensitivity and selectivity with maleate and fumarate can be related to the receptor stereochemistry that gives rise to different geometries depending on the anion stereochemistry. Thus, the maleate anion with its *cis* configuration perfectly fits into the complex inducing a conformation change in the receptor. By contrast, the fumarate anion with a *trans* disposition of carboxylate moiety which does not induce changes in the ligand conformation results in a negligible change of the UV-Vis absorption. The proposed conformational structure for the complex formed between receptor **1** and maleate dianion is shown in Fig. 6. Besides that, the basicity of the anion may also play an important role for recognition. Since the maleate dianion (pK_{a_2} = 6.23 in H_2O, 18.8 in DMSO) is more basic than the fumarate dianion (pK_{a_2} = 4.46 in H_2O, 11.0 in DMSO, respectively),[17] deprotonation of N–H_2 will occur preferentially for the maleate anion.

The strong selectivity of receptor **1** for maleate compared to that of fumarate prompted us to investigate the geometric tricarboxylates, *cis*-aconitate and *trans*-aconitate anions. A similar phenomenon of UV-Vis absorption is observed in Fig. 7. Spectrum (a) was measured in the absence of anion. As shown in spectrum (b) and (c), the CT absorption bands appear at 489 nm and the solution colour changes from purple to red for *cis*-aconitate and from purple to medium violet–red for *trans*-aconitate, respectively (Fig. 8). It is apparent that receptor **1** has a selective colour change for *cis*-aconitate

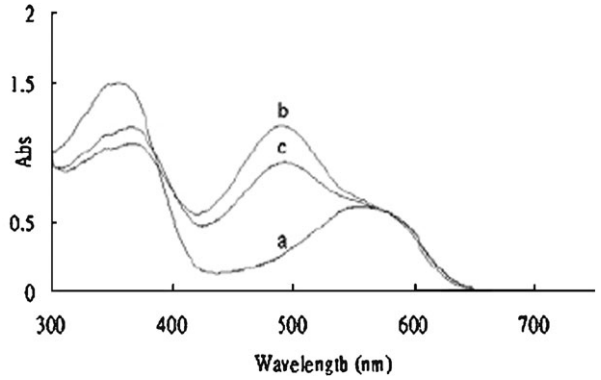

Fig. 7 UV-Vis spectra change of **1** in DMSO (5×10^{-5} M) after the addition of 2.0 equivalents of anions: (a) **1** only; (b) **1** + *cis*-aconitate; (c) **1** + *trans*-aconitate.

Fig. 8 Effect of anions (as $(C_4H_9)_4N^+$ salts) on colour changes of **1** in DMSO after the addition of 2.0 equivalents of anions: (a) **1** only; (b) **1** + *cis*-aconitate; (c) **1** + *trans*-aconitate.

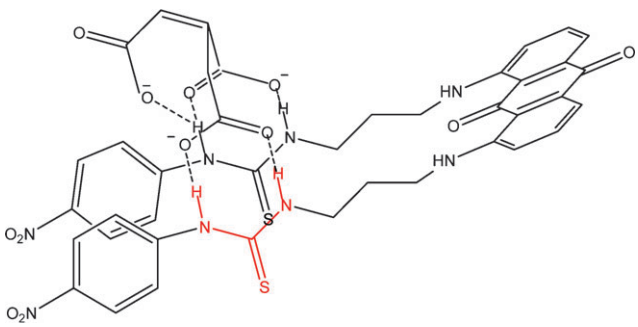

Fig. 9 Possible binding model of **1** with *cis*-aconitate anion.

vs. *trans*-aconitate. The selectivity of **1** for recognition of these anions can also be rationalized on the basis of the receptor geometry that gives rise to different geometries depending on the anion stereochemistry and the basicity of the anionic species (pK_{a_3} values of the *cis*-aconitic and the *trans*-aconitic are 6.21 and 6.16 in H_2O, respectively).[17] The *cis*-aconitate can fit more perfectly into the complex inducing a conformation change in the receptor. The additional carboxylate group can enhance the deprotonation effect of N–H_2 and resulted in a higher absorbance in the UV-Vis spectra. The proposed conformational structure for the complex formed between receptor **1** and *cis*-aconitate is shown in Fig. 9. The dramatic colour changes can be attributed to the occurrence of the combination of hydrogen bonding interaction and deprotonation of the thiourea proton with the anion, similar to that mentioned above. The monodeprotonated receptor is responsible for the absorption at 489 nm. This was similarly confirmed by ^{1}H NMR titration experiments with *cis*-aconitate in which the peak of $[\mathbf{HM}]^-$ (**M** = *cis*-aconitate anion) appeared

at 20.20 ppm (Fig. SI-4, ESI†). However, when *trans*-aconitate was titrated against receptor **1** significant broadening of N–H_1 and N–H_2 peaks were observed and indeed after the addition of 2.0 equivalents the resonances assigned to both N–H_1 and N–H_2 completely disappeared but no $[\mathbf{HM}]^-$ (**M** = *trans*-aconitate anion) peak was observed in the range of 17–21 ppm (*cf*. SI-4). This result implied that the receptor **1** may strongly bind with *trans*-aconitate through multiple hydrogen bonds. To further discriminate whether the process is a hydrogen bond complexation or a proton transfer of a Brønsted-type acid–base equilibrium, a ^{1}H NMR dilution experiment of a 1 : 1 mixture of **1** and *trans*-aconitate was performed (*cf*. SI-5). If the process is a hydrogen bonding interaction, the equilibrium is shifted to the dissociation direction; therefore, spectral shifts should be observed by dilution. On the other hand, if the process is a proton transfer, the equilibrium is independent of the concentration of host and guest because the equilibrium constant is dimensionless.[18] The CH protons of the phenyl groups showed a shift to the direction of dissociation by dilution. Therefore, this process is clearly hydrogen bond complexation rather than proton transfer.

Judging from the UV-Vis titrations, the Job plot method showed the formation of a 1 : 1 stoichiometry complex of **1** with either *cis*-aconitate or *trans*-aconitate (Fig. SI-6, ESI†). The association constants were calculated and listed in Table 1. To further elucidate the interaction between *cis*-aconitate or *trans*-aconitate with receptor **1**, *ab initio* calculations of the [**1**·*cis*-aconitate] complex and the [**1**·*trans*-aconitate] complex were undertaken. These calculations clearly shows only the proton (H_2) of the *cis*-aconitate has a much shorter distance to the carboxylic group than a typical H-bond distance (see Table 2, ESI†).

In order to investigate whether the similar structural dicarboxylates can be differentiated by colour change, the binding of receptor **1** with malate and tartrate were studied. Consistent with the above results of the titration of maleate and fumarate, the titration of **1** with malate and tartrate gave similar phenomena in their UV-Vis absorption spectra (Fig. 10). As shown in spectrum (b) the CT absorption band appears at 492 nm and the solution colour changes from purple to purple–red (Fig. 11). On the contrary, spectrum (c)

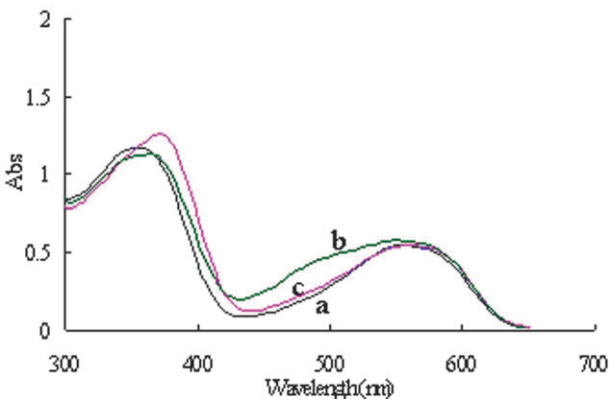

Fig. 10 UV-Vis spectra change of **1** in DMSO (5×10^{-5} M) after the addition of 2.0 equivalents of anions: (a) **1** only; (b) **1** + malate; (c) **1** + tartrate.

Fig. 11 Effect of anions (as $(C_4H_9)_4N^+$ salts) on colour changes of **1** in DMSO after the addition of 2.0 equivalents of anions: (a) **1** only; (b) **1** + malate; (c) **1** + tartrate.

exhibits negligible perturbation upon addition of 2.0 equivalents of tartrate and the solution still retains a purple colour (Fig. 11). Apparently, the receptor **1** has a unique colour change and higher selectivity for malate than tartrate. That the receptor **1** preferentially binds malate over tartrate anion is also interpreted in terms of the receptor geometry and the higher basicity of the malate (pK_{a_2} values of malic acid and tartaric acid are 5.20 and 4.40 in H_2O, respectively).[19] The tartrate with an additional hydroxyl group that would reduce the binding ability between the carboxyl group and the N–H of the thiourea moiety, will result in weak or insignificant interaction with the receptor. The proposed conformational structure for the complex formed between receptor **1** and tartrate is shown in Fig. 12. From ^{1}H NMR titration of receptor **1** with malate, the signal of N–H_2 disappeared and the N–H_1 signal underwent a downfield shift from 8.42 to 11.35 ppm (Fig. 13). However, no $[\mathbf{HM}]^-$ (**M** = malate anion) peak was observed. To discriminate whether the process is a hydrogen bond complexation or a proton transfer, a ^{1}H NMR dilution experiment of a 1 : 1 mixture of **1** and malate was performed (Fig. SI-7, ESI†). The CH protons of the phenyl groups also showed a shift to the direction of dissociation by dilution. Therefore, the process is demonstrated to be hydrogen bond complexation.[18]

On the other hand, for titration with tartrate anion, the chemical shift of the N–H_1 changed from 8.42 to 11.05 ppm and the signal of the N–H_2 changed from 10.12 to 13.28 ppm, respectively (Fig. 14). The relatively small downfield shifts indicate the formation of a complex through intermolecular hydrogen bonds between the receptor **1** and tartrate anion. The Job plots show each anion and receptor **1** formed the complexes in 1 : 1 binding stoichiometry (Fig. SI-8, ESI†). The binding constants were determined and listed in Table 1.

In order to gain a clear picture of how the urea unit can affect the binding property of **1**, a UV-Vis study was conducted on the control compound **2**. Upon progressive increase

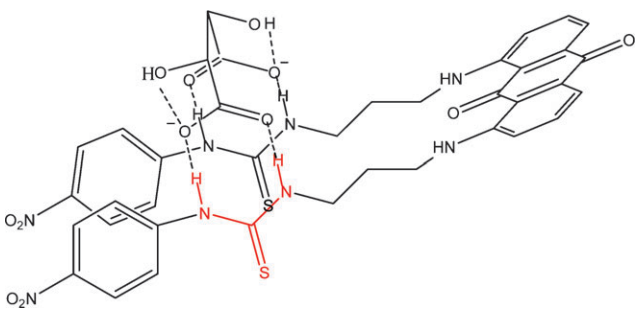

Fig. 12 Possible binding model of **1** with tartrate anion.

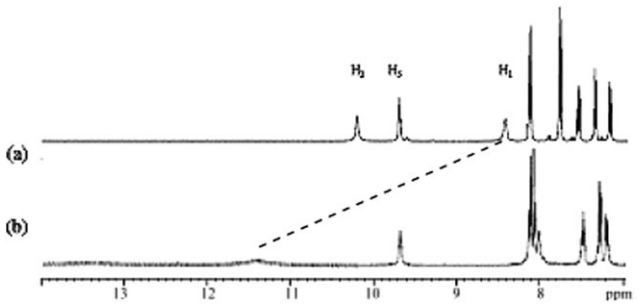

Fig. 13 ^{1}H NMR (400 MHz) spectra of sensor **1** (10 mM) in DMSO-d_6 upon addition of various quantities of malate: (a) 0 equiv.; (b) 1.0 equiv.

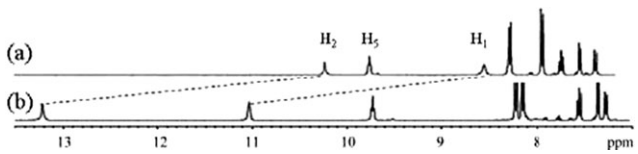

Fig. 14 ^{1}H NMR (400 MHz) spectra of sensor **1** (10 mM) in DMSO-d_6 upon addition of various quantities of tartrate: (a) 0 equiv.; (b) 1.0 equiv.

of the concentrations of different anions such as maleate, *cis*-aconitate, malate and other isomeric anions, no significant change in the UV-Vis spectra or colour changes were observed. This weak binding could be explained by the strongly electronegative oxygen atom of the urea subunit which poorly contributes to the charge transfer transition. Thiourea is a much stronger protonic acid than urea (pK_a = 21.1 and 26.9, respectively, in DMSO).[20]

Furthermore, in order to check how the different substituent on the one of the two thiourea groups would influence the anion binding and sensing property, a 4-nitrophenyl group was replaced by a weaker electron-withdrawing group, 4-trifluoromethylphenyl group, in receptor **3**. The UV-Vis absorption spectral profiles of **3** with addition of either maleate or malate are similar to those of **1** with these two anions. It appeared that the receptor **3** has the same propensity; combination of hydrogen bonding interaction and deprotonation of the N–H_2 group occurred upon addition of the increasing concentration of maleate whereas a strong hydrogen bonding complexation occurred upon addition of the increasing concentration of malate anion. This is similarly proved by ^{1}H NMR titration experiments (Fig. SI-9, ESI†).

Consistent with the result of receptor **1**, titration of **3** with either fumarate or tartrate anion also gave no apparent colour change. The colour of the solution still remains the original purple (Fig. SI-10, ESI†). The weak hydrogen-bonding between **3** and fumarate or tartrate was corroborated by the ^{1}H NMR titration experiments and the hydrogen-bonded distances were also reflected in the *ab initio* calculations (Table 3, ESI†). Due to the fact that receptor **3** has the unique colour change and higher selectivity for maleate than fumarate anion or malate than tartrate, it can be used as an optical chemosensor for recognition of maleate *vs.* fumarate or malate *vs.* tartrate. The binding of receptor **3** with isomeric tricarboxylate anions (*cis*-aconitate and *trans*-aconitate) were also studied. Unfortunately, no distinct colour change was observed (Fig. SI-11, ESI†).

To explore potential and analytical applications of the sensor **1** for anions tested, UV-Vis titrations were carried out in DMSO–H_2O (95 : 5) mixtures (Fig. SI-12, ESI†). As we know, protic solvent such as H_2O and ethanol would compete with the anion for binding sites of the host and, therefore, could disturb the hydrogen-bonding interactions between host and guest. However, in the case of the sensor **1**, the distinct colour changes for the recognition of maleate and malate anion in DMSO–water (95 : 5) solution were also observed (Fig. SI-13, ESI†). The results revealed that the spectrum changed similarly as that of dry DMSO solution. Likewise, there was significant increase in the intensity of the band at 493 nm upon addition of maleate or malate, which corresponded to light to dark colour changes. This result indicated that the addition of small amounts of water had little effect on maleate or malate anion sensing property of **1**. On the other hand, a distinct colour change was also observed for the recognition of tricarboxylate anions (*cis*-aconitate and *trans*-aconitate) with sensor **1** in DMSO–water (97 : 3) solution. Thus, the addition of water to DMSO up to 3% did not interfere in the anion sensing (Fig. SI-13, ESI†). This probably is due to that receptor **1** bears two thiourea groups which have been proven to be good hydrogen bonding acceptors that could make strong hydrogen bonds with anions, which water molecules could not break.[21] Additionally, DMSO is a very good hydrogen-bond accepting solvent and in this situation it can interact strongly with the water molecules at the concentration utilized. Consequently, the possibility of the interaction of anions with the sensor was improved greatly.

Conclusion

In conclusion, the new colorimetric anion receptors **1–3** were synthesized. Among them, both **1** and **3** show good sensitivity and selectivity for discrimination of maleate *vs.* fumarate or malate *vs.* tartrate by dramatic colour changes in DMSO or DMSO–H_2O (95 : 5). Thus, both **1** and **3** can be used as optical chemosensors for recognition of maleate *vs.* fumarate or malate *vs.* tartrate anion. Besides that, the receptor **1** has also a unique colour change for recognition of either *cis*-aconitate or *trans*-aconitate in DMSO or DMSO–H_2O (97 : 3), accordingly it can be used for detection of either *cis*-aconitate or *trans*-aconitate anion. To the best of our knowledge, this is the first synthetic host that can selectively recognize either *cis*-aconitate or *trans*-aconitate anion by colour changes. Future work will continue to develop the practical colorimetric sensors for recognition of chiral dicarboxylates.

Experimental

General

The chemical reagents were purchased from Acros or Aldrich Corporation and utilized as received, unless indicated otherwise. All solvents were purified by standard procedures.

Melting points were measured on a Yanaco MP-S3 melting-point apparatus. The infrared spectra were performed on a Perkin Elmer System 2000 FT-IR spectrophotometer. UV–Vis spectra were measured on a Cary 300 spectrometer. All NMR spectra were measured on a Bruker spectrometer at 400 (^{1}H) and 100 MHz (^{13}C) and Varian Unity Inova-600 spectrometers at 600 (^{1}H) and 150 MHz (^{13}C) with DMSO-d_6 as solvent. High-resolution mass spectra were measured with a Finnigan/Thermo Quest MAT 95XL instrument.

Preparation of tetrabutylammonium salts

To a stirred solution of a di- or tricarboxylic acid (2.5 or 1.0 mmol) in dry methanol (5 mL), 2.0 or 3.0 equiv. of a 1.0 M solution of tetrabutylammonium hydroxide in methanol (5 mL) was added. The resulting mixture was stirred for 2 h at room temperature. The solvent was evaporated *in vacuo* and dried over P_2O_5. The resulting tetrabutylammonium salt was stored under anhydrous condition before use.

Synthesis of 1,8-di(3-aminopropylamino)anthraquinone (4). A solution of 1,8-dichloroanthraquinone (1.00 g, 3.60 mmol), K_2CO_3 (1.49 g), 1,3-diaminopropane (1.03 g, 13.64 mmol) and tetrabutylammonium hydrogensulfate (20 mg) (catalyst) in CH_3CN (30 mL) was stirred and heated to reflux for 12 h, the solid residue was filtered off. After cooling, the reaction mixture was treated with crushed ice. The resulting precipitate was collected by filtration, washed well with water and further purified by recrystallization from ethyl acetate–*n*-hexane to afford the product as red needles. Yield: 1.01 g (80%), mp 162–163 °C. ^{1}H NMR ($CDCl_3$): δ 1.94–1.99 (m, 4H), 2.82–2.84 (m, 4H), 2.97–2.99 (m, 4H), 3.42–3.46 (m, 4H), 7.07–7.10 (m, 2H), 7.48–7.51 (m, 2H), 7.57–7.60 (m, 2H), 9.67 (br s, 2H). HRMS (FAB) calc. for $C_{20}H_{24}O_2N_4$ [M + 1] 353.1980; found 353.1974.

Synthesis of 1-(3-aminopropylamino)-8-(4-nitrophenylthiourelyenepropeneamino)anthraquinone (5). To a stirred solution of **4** (0.30 g, 0.85 mmol) in $CHCl_3$ (50 mL), 4-nitrophenyl isothiocyanate (0.12 g, 0.67 mmol) in $CHCl_3$ (30 mL) was added at room temperature. The resulting mixture was stirred and heated to reflux for 46 h. After cooling to room temperature, the solution was concentrated in vacuum. The crude product was washed with $CHCl_3$ several times to afford pure **5**. Yield: 0.42 g (43%), mp 187–189 °C. ^{1}H NMR (400 MHz, DMSO-d_6): δ 1.83–2.08 (m, 4H), 3.33 (br s, 2H), 3.39–3.48 (m, 4H), 3.52–3.75 (m, 4H), 7.20 (d, 2H, J = 8.4 Hz), 7.36 (d, 2H, J = 7.2 Hz), 7.59 (dd, 2H, J = 7.6 Hz, J = 8.0 Hz), 7.79 (d, 2H, J = 9.2 Hz), 8.12 (d, 2H, J = 8.8 Hz), 8.52 (br s, 1H), 9.62 (br s, 2H), 10.24 (br s, 1H). ^{13}C NMR (DMSO-d_6): δ 27.9, 31.5, 40.6, 42.0, 113.6, 114.5, 118.6, 120.5, 124.7, 133.8, 134.7, 146.6, 150.9, 180.3, 183.7, 188.1. FT-IR (KBr): 3446, 2929, 2867, 2346, 1741, 1614, 1511, 1326, 1217 cm^{-1}. UV-Vis (DMSO): 333 nm (ε = 19 661), 543 (14 425). HRMS (FAB) calc. for $C_{27}H_{28}O_4N_6S$ [M + 1] 533.1895; found 533.1964.

Synthesis of 1,8-bis(4-nitrophenylthiourelyenepropeneamino)-anthraquinone (1). To a stirred solution of **4** (0.20 g, 0.34 mmol) in THF (40 mL), 4-nitrophenyl isothiocyanate (0.18 g, 1.03 mmol) in THF (40 mL) was added at room temperature. The resulting mixture was stirred and heated to reflux for 18 h. After cooling to room temperature, the solution was concentrated in vacuum. The crude product was washed with CH_2Cl_2 several times to afford pure **1**. Yield 54%, mp 202–203 °C. ^{1}H NMR (600 MHz, DMSO-d_6): δ 1.94–2.04 (m, 4H), 3.36–3.46 (m, 4H), 3.60–3.72 (m, 4H), 7.21 (d, 2H, J = 8.4 Hz), 7.38 (d, 2H, J = 7.2 Hz), 7.58 (dd, 2H, J = 7.8 Hz, J = 8.4 Hz), 7.79 (m, 4H), 8.13 (m, 4H), 8.42 (br s, 2H), 9.63 (br s, 2H), 10.12 (br s, 2H). ^{13}C NMR (DMSO-d_6): δ 27.7, 40.0, 41.8, 113.4, 114.3, 118.4, 120.3, 124.4, 133.5, 134.5, 141.7, 146.3, 150.7, 180.1, 183.4, 187.9. FT-IR (KBr): 3278, 2925, 2853, 1614, 1511, 1322, 1214 cm^{-1}. UV-Vis (DMSO): 353 nm (ε = 35 454), 554 (14 188). HRMS (FAB) calc. for $C_{34}H_{32}O_6N_8S_2$ [M + 1] 713.1890; found 713.1968.

Synthesis of 1,8-bis(4-nitrophenylurelyenepropeneamino)-anthraquinone (2). A similar procedure to synthesis of **1** was carried out using 4-nitrophenyl isocyanate in place of 4-nitrophenyl isothiocyanate. Yield 43%, mp 251–252 °C. ^{1}H NMR (600 MHz, DMSO-d_6): δ 1.81–1.90 (m, 4H), 3.23–3.31 (m, 4H), 3.34-3.43 (m, 4H), 6.61 (br s, 2H), 7.17 (d, 2H, J = 8.4 Hz), 7.35 (d, 2H, J = 7.2 Hz), 7.55 (dd, 2H, J = 7.8 Hz, J = 8.4 Hz), 7.59 (m, 4H), 8.08 (m, 4H), 9.27 (br s, 2 H), 9.60 (br s, 2H). ^{13}C NMR (DMSO-d_6): δ 29.0, 37.2, 40.0, 113.4, 114.2, 116.7, 118.2, 125.0, 133.5, 134.4, 140.3, 147.2, 150.7, 154.5, 183.4, 187.9. FT-IR (KBr): 3304, 3088, 2919, 2853, 1660, 1614, 1562, 1491, 1393, 1322, 1230 cm^{-1}. UV-Vis (DMSO): 344 nm (ε = 38 460), 552 (11 484). HRMS (FAB) calc. for $C_{34}H_{32}O_8N_8$ [M + 1] 681.2346; found 681.6412.

Synthesis of 1-(4-nitrophenylthiourelyenepropeneamino)-8-(4-trifluoromethylphenylthiourelyenepropeneamino)anthraquinone (3). To a stirred solution of **5** (0.26 g, 0.48 mmol) in THF (80 mL), 4-trifluoromethylphenyl isothiocyanate (0.15 g, 0.72 mmol) in THF (40 mL) was added at room temperature. The resulting mixture was stirred and heated to reflux for 30 h. After cooling to room temperature, the solution was concentrated in vacuum. The crude product was washed with CH_2Cl_2 several times to afford pure **3**. Yield 41%, mp 200–201 °C. ^{1}H NMR (400 MHz, DMSO-d_6): δ 1.87–2.13 (m, 4H), 3.38–3.48 (m, 4H), 3.52–3.79 (m, 4H), 7.13–7.25 (m, 4H), 7.36–7.41 (m, 2H), 7.52–7.65 (m, 4H), 7.69 (br s, 1H), 7.75–7.81 (m, 2H), 7.95 (br s, 1H), 8.08–8.18 (m, 2H), 8.53 (br s, 1H), 9.59 (br s, 1H), 9.65 (br s, 1H), 10.30 (br s, 1H). ^{13}C NMR (DMSO-d_6): δ 22.9, 25.3, 27.9, 28.9, 36.6, 42.0, 67.2, 113.5, 113.6, 113.7, 114.4, 114.5, 118.6, 120.4, 124.7, 133.8, 134.7, 150.9, 169.4, 183.6, 188.1. FT-IR (KBr): 3291, 2931, 2864, 2348, 1614, 1512, 1327, 1303, 1215 cm^{-1}. UV-Vis (DMSO): 345 nm (ε = 19 089), 360 (18 316), 559 (12 648). HRMS (FAB) calc. for $C_{35}H_{32}O_4N_7F_3S_2$ [M + 1] 735.1936; found 735.2004.

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