Showcasing research from Professor Xia Wu’s group at the school of Chemistry and Chemical Engineering, Shandong University, Key Laboratory of Colloid and Interface Chemistry (Shandong University), Ministry of Education, Jinan, P.R. China and the research group of Bo Tang at the college of Chemistry, Chemical Engineering and Materials Science, Collaborative Innovation Center of Functionalized Probes for Chemical Imaging in Universities of Shandong, Shandong Normal University, Jinan, P.R. China.

A highly selective and sensitive fluorescent nanosensor for dopamine based on formate bridged Tb(III) complex and silver nanoparticles

A new fluorescence nanosensor was constructed based on a formate-bridged Tb(III)-complex and silver nanoparticles, which could successfully distinguish dopamine from epinephrine. Herein, HCOO⁻ played a pivotal role in improving the sensitivity and selectivity of the nanosensor for the detection of dopamine.

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A highly selective and sensitive fluorescent nanosensor for dopamine based on formate bridged Tb(III) complex and silver nanoparticles

Huihui Li,†‡ Jin Shen,†‡ Rongwei Cui,‡ Chongmei Sun,‡ Yanyan Zhao,‡ Xia Wu,*‡ Na Li‡ and Bo Tang‡†

Highly selective determination of dopamine (DA) over other catecholamines is an urgent need for the precise diagnosis and therapy of DA related diseases. Herein, a new formate-bridged Tb(III)-complex and silver nanoparticles (AgNPs) enhanced fluorescent nanosensor was constructed. HCOO− acted as a co-ligand of Tb(III) and also as a linker between the Tb(III) complex and AgNPs and more readily combined with the primary amine of DA than with epinephrine (EP). The formate-bridged action strengthened AgNPs-based surface enhanced fluorescence of the Tb5+-DA complex and improved the selectivity towards DA. Under neutral buffer conditions, the detection limit for the assay of DA was down to 0.15 nM (S/N = 3) with a linear range from 0.5 nM to 100 nM (R2 = 0.9978). Furthermore, the nanosensor could successfully distinguish DA from EP.

Introduction

Dopamine (4-(2-aminoethyl)-benzen-1,2-diol, DA), one of the crucial catecholamines (CAs), possesses unique physiological functions. Much evidence has shown that abnormality in the amount of DA in biofluids is associated with several serious neurological diseases such as anorexia, Parkinson’s and Alzheimer’s.1–3 To obtain superior therapeutic effects for DA related diseases, the development of a highly selective and sensitive detection method for DA is of great significance. Therefore, considerable research efforts have been devoted to this field.4–6 Multiple techniques such as LC-MS/MS,7 capillary electrophoresis (CE),8 electrochemical and electrochemiluminescence,9,10 and UV-Vis and fluorescence spectroscopies11,12 have been utilized for separation or selective determination of CAs. In addition to these traditional techniques, spectrofluorimetric methods based on nanoprobes have been developed and have increasingly drawn attention due to their advantages such as sensitivity, selectivity and visibility.13,14

Fluorescein/Nile Blue modified gold nanoparticles,11 silicon nanoparticles (SiNPs) rich with amidogens,15 and mesoporous SiNPs with β-cyclodextrin (β-CD) barricades16 were used as selective sensors to sense DA over other CAs (epinephrine (EP), norepinephrine (NE)). However, since the molecular structures and physicochemical properties of CAs are quite similar, the selective detection of DA from EP and NE is still a challenge.

Rare earth (RE) luminescent ions (Tb3+, Eu3+ etc.) have excellent intrinsic fluorescence properties such as narrow emission bands, large Stokes shifts and long fluorescence lifetimes. They have been widely used as luminescent probes for the detection of various target analytes. The employment of RE co-luminescence ions and co-ligands is an effective way to significantly improve the sensitivity of RE-based analytical methods.17,18 To date, metal nanoparticles enhanced RE luminescence/co-luminescence has received widespread attention.19 One of the important means for raising the efficiency of metal surface enhanced fluorescence (SEF) is to adjust an appropriate spacing distance between fluorophores and metal nanoparticles.20,21 HCOO−, a special small molecule with a carboxyl group and a formyl group, has small steric hindrance and excellent capability of coordination with metal ions.22 Formate can combine with metal ions and further connect other molecules to form metal organic frameworks.23,24 Herein, we propose a new strategy of applying HCOO−-assisted AgNPs-based SEF on Tb(III) luminescence for DA detection. This novel method exhibited higher sensitivity and could be implemented for the discriminative determination of DA from EP. On one hand, HCOO−...
provided a suitable distance for the AgNPs-based SEF via bridge-linking Tb(III) and the primary amine of DA to AgNPs. On the other hand, it also served as a second ligand of the Tb³⁺-DA complex. Under the same conditions, the fluorescence intensity increment of DA with the proposed Tb³⁺-HCOO⁻-AgNPs composite sensor was about 14 times higher than that of EP with the sensor. This method was successfully applied for the determination of DA in real samples with outstanding accuracy and satisfactory recoveries. The mechanisms of HCOO⁻ bridged AgNPs enhancing fluorescence of the Tb³⁺-DA complexes and the selectivity for DA are also discussed.

**Experimental**

**Materials**

Stock solution of terbium chloride (TbCl₃, 10 mM) was prepared by dissolving Tb₂O₃ (99.9%, Shanghai Sinopharm Chemical Reagent Co., Ltd, China) in hydrochloric acid. Dopamine hydrochloride and EP (99.7%) were obtained from the National Institutes for Food and Drug Control (Beijing, China). Sodium formate was obtained from Tianjin Damao Chemical Co., China. 2-[4-(Hydroxyethyl)-1-piperazinyl]ethanesulfonic acid (HEPES) was purchased from Aladdin Industrial, Inc. (Shanghai, China). Silver nitrate (99.8%) and the other chemicals and reagents were obtained from Sinopharm Chemical Reagent (Shanghai, China).

All reagents used in this study were of analytical grade and all the solutions were prepared using ultrapure water (18.25 MΩ cm).

**Apparatus**

Fluorescence spectra and the corresponding intensities were recorded on an F-7000 spectrophotometer (Hitachi, Japan). Fluorescence polarizations were conducted on a LS-55 fluorescence spectrometer (PerkinElmer). Fluorescence decay curves were obtained using an FLS-920 fluorometer (Edinburgh). Absorption spectra were measured using a U-4100 spectrophotometer (Hitachi, Japan). Transmission electron microscopy (TEM) measurements were taken at 100 kV on a JEOL JEM-1011 (Japan) transmission electron microscope. Raman spectra were measured with LabRam HR800 Raman spectrometer (Horiba Jobin Yvon, France). Infrared spectra were recorded with an FT-IR spectrophotometer (Bruker Alpha-T). Freeze drying was conducted on an Eyela FDU-1200 freeze dryer. All pH measurements were made using a Delta 320-S acidity meter (Mettler Toledo, Shanghai).

**Preparation of silver nanoparticles**

A stock solution of AgNPs was prepared by the sodium citrate reduction method with some modifications. Briefly, 50 mL of 2.0 mM AgNO₃ solution was vigorously stirred and brought to 86 °C. Sodium citrate solution (4 mL of 1%) was then added dropwise to the abovementioned solution. Heating was continued for an additional 5 min until the colour of the solution changed to light yellow. Then, the solution was stirred continu-
Fluorescence lifetime

The excitation and emission wavelengths were set at 308 nm and 546 nm. The decay curves were fitted by a double exponential function. The average lifetimes were calculated using \( \tau_{\text{ave}} = \sum \tau_i R_i \), where \( \tau_{\text{ave}} \) is the average lifetime, \( \tau_i \) is the lifetime of each part and \( R_i \) is the relative proportion of the corresponding component.

Results and discussion

Fluorescence enhancement

Fig. 1 shows that AgNPs can enhance the characteristic fluorescence of Tb\(^{3+}\)-DA complex at 490 nm (\( ^{5}D_4 \rightarrow ^{7}F_6 \), electric dipole transition) and 546 nm (\( ^{5}D_4 \rightarrow ^{7}F_5 \), magnetic dipole transition).\(^{26}\) Notably, in the presence of HCOO\(^{-}\), the fluorescence signal of the Tb\(^{3+}\)-DA-AgNPs system achieved the strongest enhancement. The fluorescence intensity (at 546 nm) of Tb\(^{3+}\)-DA-HCOO\(^{-}\)-AgNPs increased about 5.4 times compared with that of Tb\(^{3+}\)-DA-AgNPs. Moreover, HCOO\(^{-}\) also reduced the fluorescence intensities of Tb\(^{3+}\)-AgNPs. The results indicated that HCOO\(^{-}\) could assist AgNPs-based SEF for Tb\(^{3+}\)-DA complexes.

To confirm the HCOO\(^{-}\)-assisted functions, a series of tests was carried out (see Fig. 2). Raman spectra (Fig. 2A) showed the peaks of Tb\(^{3+}\)-HCOO\(^{-}\)-AgNPs at 1628 cm\(^{-1}\) and 1501 cm\(^{-1}\), which were assigned to the anti-symmetric and symmetric stretching vibrations of –O=C=O, respectively. Compared with that of Tb\(^{3+}\)-HCOO\(^{-}\)-AgNPs, the peak of Tb\(^{3+}\)-DA-HCOO\(^{-}\)-AgNPs at 1628 cm\(^{-1}\) shifted to a low wavenumber, while the peak at 1501 cm\(^{-1}\) showed only minor changes. Moreover, the band at 1045 cm\(^{-1}\), corresponding to the C–N stretching vibration, disappeared in the Raman spectrum of Tb\(^{3+}\)-DA-HCOO\(^{-}\)-AgNPs composite. In addition, the peak at 1321 cm\(^{-1}\) related to the adsorption of HCOO\(^{-}\) was significantly enhanced. These results confirmed that HCOO\(^{-}\) could directly connect amino group of DA to AgNPs. Some previous studies have verified that the metal–ligand sensitive Raman bands of Ln–O are located in the range of 400–500 cm\(^{-1}\).\(^{27}\) Herein, in the presence of HCOO\(^{-}\), Raman peak positions of the sensitive metal-ligands of Tb\(^{3+}\)-DA-AgNPs shifted from 465 cm\(^{-1}\) to 447 cm\(^{-1}\), suggesting that HCOO\(^{-}\) could form metal–oxo clusters with Tb\(^{3+}\).

FT-IR spectra of the complexes of Tb\(^{3+}\)-DA-AgNPs with and without HCOO\(^{-}\) were monitored and are shown in Fig. 2B. In comparison with the IR spectrum of Tb\(^{3+}\)-DA-AgNP composites, a new absorption peak of Tb\(^{3+}\)-DA-HCOO\(^{-}\)-AgNPs emerged at 3278 cm\(^{-1}\) (ν\(_{C=O}\)), the prominent differences of vibration frequencies in C–N stretch vibrations (1048 cm\(^{-1}\) and 1040 cm\(^{-1}\)) and N–H bending vibrations in the range of 900–770 cm\(^{-1}\) were observed. They all proved that the interaction existed between HCOO\(^{-}\) and the primary amine group of DA. The IR absorption peak intensity at 2828 cm\(^{-1}\) weakened and the 2716 cm\(^{-1}\) (aldehyde group ν\(_{C=H}\)) peak disappeared, while the C–O stretching vibration bands at 1453 cm\(^{-1}\) and 1364 cm\(^{-1}\) shifted to lower wavenumber. It indicated that HCOO\(^{-}\) combined with Tb\(^{3+}\) and also connected Tb\(^{3+}\)-DA complexes to AgNPs by the bonding configuration of –O=C=O– in the composite of Tb\(^{3+}\)-DA-HCOO\(^{-}\)-AgNPs. The vibration frequency of the aromatic C–O stretching vibration shifted from 1167 cm\(^{-1}\) to 1215 cm\(^{-1}\), demonstrating that the coordination–chelation interaction of Tb\(^{3+}\) with catechol group of DA was also affected by HCOO\(^{-}\).

Furthermore, the UV-visible absorption spectra were also testified to confirm the indispensability of HCOO\(^{-}\) (Fig. 2C). The absorption peak position of DA-HCOO\(^{-}\)-AgNPs blue shifted from 455 nm to 404 nm and the peak intensity decreased in comparison to that of DA-AgNPs, which indicated that the aggregation of DA-AgNPs collapsed owing to HCOO\(^{-}\). TEM images (Fig. 2D1 and 2D2) showed that the average diameter of the DA-HCOO\(^{-}\)-AgNP composites was smaller than those of DA-AgNPs and AgNPs. The blue-shift in the absorption peak position accompanied with the decrease in the absorbance and the average particle sizes of composites reducing verified the etching of HCOO\(^{-}\) on AgNPs and the inhibition of the aggregation between AgNPs and DA by HCOO\(^{-}\).\(^{28}\)

In the presence of HCOO\(^{-}\), the average particle diameter of Tb\(^{3+}\)-DA-AgNP composites was also reduced (Fig. 2D3 and 2D4). The abovementioned results demonstrated that HCOO\(^{-}\) could directly bond to AgNPs and then could connect AgNPs with DA or Tb\(^{3+}\)-DA complexes. The schematic of the composite nanosensor of Tb\(^{3+}\)-DA-HCOO\(^{-}\)-AgNPs is proposed in Scheme 1. Tb\(^{3+}\) coordinated with the catechol group of DA. HCOO\(^{-}\) could coordinate with Tb(III), combine with the primary amine group of DA and connect DA-Tb\(^{3+}\) complexes to AgNPs. Therefore, HCOO\(^{-}\) assisted the AgNPs-based Tb(III) SEF sensor formation. Herein, HCOO\(^{-}\) was used as a suitable spacer benefiting from its special molecular structure.

Moreover, Fig. 2C also shows that in the presence of HCOO\(^{-}\), the absorption peaks of Tb\(^{3+}\)-DA-AgNPs red shifted from 490 nm to 528 nm. There were increases in the spectral overlap proportion between the absorption and the emission of Tb(III). As is known, a higher overlap efficiency between the
emission spectrum of a fluorophore and a LSPR absorption spectrum of metal nanoparticle resulted in a stronger fluorescence enhancement.\(^{29,30}\) In addition, HCOO\(^-\) could coordinate with Tb\(^{3+}\) to replace the coordinated water molecules around Tb\(^{3+}\), resulting in a decrease in the non-radiation decay rate owing to –OH vibration of H\(_2\)O\(^+\) molecule around Tb\(^{3+}\), which also led to a large enhancement of the fluorescence signal.

**Selectivity for DA**

UA and AA coexist with DA in extracellular fluids of the human central nervous system, and EP is one of the neurotransmitters with a molecular structure similar to that of DA. They usually interfere with the determination of DA. The selective detection of DA is important for precise diagnoses and therapies of related diseases. In order to evaluate the selectivity of the system towards DA, the influences of some potential bio-competitors and interfering ions that may coexist in the pharmaceutical injection and biofluids were tested (Table 1). The results showed that most of the metal ions, citric acid, boric acid, amino acids, AA and UA caused minor changes in the fluorescence intensity within the relative error range of ±5%. EP and 5-hydroxytryptamine (5-HT) (the same concentration of DA) also had little effect on the fluorescence intensity (<5%). Herein, HCOO\(^-\) played a significant role in improving the selectivity of DA over EP and other co-existing substances in biofluids.
Table 1 Interference from foreign substances

<table>
<thead>
<tr>
<th>Interferents</th>
<th>Tolerable concentration (μM)</th>
<th>Change of ( f(%) \pm \text{RSD}(%) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mg(^{2+}), Cl(^-)</td>
<td>100</td>
<td>+3.2 ± 1.69</td>
</tr>
<tr>
<td>Al(^{3+}), Cl(^-)</td>
<td>22</td>
<td>-3.0 ± 2.32</td>
</tr>
<tr>
<td>Ca(^{2+}), Cl(^-)</td>
<td>50</td>
<td>-1.3 ± 3.48</td>
</tr>
<tr>
<td>Ba(^{2+}), Cl(^-)</td>
<td>50</td>
<td>-1.8 ± 2.69</td>
</tr>
<tr>
<td>K(^+), Cl(^-)</td>
<td>20</td>
<td>+1.5 ± 1.37</td>
</tr>
<tr>
<td>Zn(^{2+}), SO(_4^{2-})</td>
<td>10</td>
<td>+2.2 ± 0.59</td>
</tr>
<tr>
<td>Cu(^{2+}), SO(_4^{2-})</td>
<td>30</td>
<td>-4.5 ± 2.58</td>
</tr>
<tr>
<td>Na(^+), CO(_3^{2-})</td>
<td>100</td>
<td>+3.4 ± 1.36</td>
</tr>
<tr>
<td>Na(^+), CO(_3^{2-})</td>
<td>100</td>
<td>+2.0 ± 0.57</td>
</tr>
<tr>
<td>Uric acid</td>
<td>10</td>
<td>-3.2 ± 1.96</td>
</tr>
<tr>
<td>Ascorbic acid</td>
<td>8.0</td>
<td>+4.8 ± 1.08</td>
</tr>
<tr>
<td>Citric acid</td>
<td>10</td>
<td>+4.1 ± 2.69</td>
</tr>
<tr>
<td>Boric acid</td>
<td>10</td>
<td>-4.6 ± 2.04</td>
</tr>
<tr>
<td>Alanine</td>
<td>50</td>
<td>-2.1 ± 2.96</td>
</tr>
<tr>
<td>Glycine</td>
<td>30</td>
<td>+4.1 ± 0.94</td>
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<tr>
<td>Tyrosine</td>
<td>50</td>
<td>-2.7 ± 3.86</td>
</tr>
<tr>
<td>Cysteine</td>
<td>10</td>
<td>+5.2 ± 3.07</td>
</tr>
<tr>
<td>Aspartic acid</td>
<td>10</td>
<td>-2.5 ± 3.41</td>
</tr>
<tr>
<td>EP</td>
<td>1.0</td>
<td>+4.9 ± 0.16</td>
</tr>
<tr>
<td>5-HT</td>
<td>1.0</td>
<td>-4.0 ± 0.21</td>
</tr>
</tbody>
</table>

Conditions: 30 μM Tb\(^{3+}\); 7.0 μM AgNPs; 5.0 mM HCOO\(^-\); 0.10 μM DA; and 0.01 M, HEPES–NaOH, pH = 7.00 buffer solution.

To verify the selectivity in the detection of DA, the fluorescence intensity of Tb\(^{3+}\)-HCOO\(^-\)-AgNPs with DA or other different biocompetitors was investigated (Fig. 3). Interestingly, an excellent enhancement in the fluorescence intensity of the Tb\(^{3+}\)-HCOO\(^-\)-AgNPs was observed only with DA. Little changes in the fluorescence intensities of the Tb\(^{3+}\)-HCOO\(^-\)-AgNPs were observed in the presence of glucose (Glc), alanine (Ala), glycine (Gly), tyrosine (Tyr), cysteine (Cys), aspartic acid (Asp), glutathione (GSH), glutamic acid (Glu), adenosine monophosphate (AMP), AA and 5-HT (100-times concentrations of DA). The fluorescence intensity increment \((I - I_0)\) of the Tb\(^{3+}\)-DA-HCOO\(^-\)-AgNPs composite was 14 times larger than that of Tb\(^{3+}\)-EP-HCOO\(^-\)-AgNPs and 19 times higher than that of Tb\(^{3+}\)-UA-HCOO\(^-\)-AgNPs (EP, UA concentration same as DA), validating that the Tb\(^{3+}\)-HCOO\(^-\)-AgNPs composites have a selective response towards DA against other biocompetitors, including AA, UA and EP. The proposed probe has higher selectivity to DA against EP compared with some reported selective methods.

The selective fluorescence response of Tb\(^{3+}\)-HCOO\(^-\)-AgNPs to DA against EP could be mainly ascribed to the following reasons. First, HCOO\(^-\) showed high combining capacity with the primary amine group of DA and this enlarged the difference of the coordinating capabilities of DA and EP with Tb\(^{3+}\) ion. The interaction between HCOO\(^-\) and the secondary amine group of EP was negatively affected by the hydrogen bond between adjacent hydroxyl and amine group and the steric hindrance by methyl group. In addition, the smaller steric hindrance of DA was beneficial for HCOO\(^-\) to tune the space distance between Tb\(^{3+}\)-DA complexes and AgNPs. Afterwards, the fluorescence polarization ratios \((P)\) were also investigated to further prove the same. Upon the addition of HCOO\(^-\), the \(P\) values of Tb\(^{3+}\)-DA-AgNPs and Tb\(^{3+}\)-EP-AgNPs reduced from 0.935 to 0.557 and from 0.916 to 0.895, respectively. Moreover, the \(P\) value was inversely related to the rotational speed of the fluorophore molecules. In contrast to Tb\(^{3+}\)-EP-AgNPs, the rotational speed of the composite of Tb\(^{3+}\)-DA-AgNPs increased clearly due to the introduction of HCOO\(^-\), further confirming that HCOO\(^-\) was an ideal linkage between Tb\(^{3+}\)-DA and AgNPs. Second, upon the participation of HCOO\(^-\), the spectral overlap efficiency between the emission spectrum of Tb\((\text{III})\) and LSPR absorption spectra of Tb\(^{3+}\)-DA-AgNPs was larger than that of Tb\(^{3+}\)-EP-AgNPs (Fig. 2C). Third, with the addition of HCOO\(^-\), the ratio of the magnetic dipole transition to electric dipole transition \((I_{540}/I_{490})\) of Tb\(^{3+}\)-DA-AgNPs was raised from 1.2 to 1.8, but the ratios of \(I_{546}/I_{490}\) of Tb\(^{3+}\)-EP-AgNPs with and without HCOO\(^-\) were both approximately equal to 1.1. The results indicated that HCOO\(^-\) induced more prominent changes in Tb\((\text{III})\) magnetic dipole transition in the Tb\(^{3+}\)-DA-HCOO\(^-\)-AgNPs systems, leading to the higher fluorescence intensity increment.

Furthermore, in the presence of HCOO\(^-\), the fluorescence average lifetime \((\tau_{\text{ave}})\) of Tb\(^{3+}\)-DA-AgNPs and Tb\(^{3+}\)-EP-AgNPs lengthened from 642.4 μs to 682.3 μs and 545.8 μs to 583.6 μs, respectively. The \(\tau_{\text{ave}}\) of Tb\(^{3+}\)-DA-HCOO\(^-\)-AgNPs was significantly longer than that of Tb\(^{3+}\)-EP-HCOO\(^-\)-AgNPs (Table 2, Fig. S3†). All of the above results confirmed that HCOO\(^-\)-assisted SEF effect on Tb\(^{3+}\)-DA-AgNPs was superior than that of Tb\(^{3+}\)-EP-AgNPs.

Table 2 Fluorescence lifetime parameters

<table>
<thead>
<tr>
<th>(\tau_1) (μs)</th>
<th>(R_1) (%)</th>
<th>(\tau_2) (μs)</th>
<th>(R_2) (%)</th>
<th>(\tau_{\text{ave}}) (μs)</th>
<th>(\chi^2)</th>
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<tbody>
<tr>
<td>Tb(^{3+})-EP-AgNPs</td>
<td>26.6</td>
<td>2.89</td>
<td>561.2</td>
<td>97.11</td>
<td>545.8</td>
</tr>
<tr>
<td>Tb(^{3+})-EP-HCOO(^-)-AgNPs</td>
<td>42.6</td>
<td>7.64</td>
<td>628.4</td>
<td>92.36</td>
<td>583.6</td>
</tr>
<tr>
<td>Tb(^{3+})-DA-AgNPs</td>
<td>99.8</td>
<td>2.96</td>
<td>658.9</td>
<td>97.04</td>
<td>642.4</td>
</tr>
<tr>
<td>Tb(^{3+})-DA-HCOO(^-)-AgNPs</td>
<td>682.3</td>
<td>100</td>
<td>682.3</td>
<td>100</td>
<td>1.33</td>
</tr>
</tbody>
</table>

Condition: 30 μM Tb\(^{3+}\); 7.0 μM AgNPs; 5.0 mM HCOO\(^-\); 1.0 μM DA in 0.01 M, HEPES–NaOH, pH = 7.00 buffer solution.

Fig. 3 Selectivity of the assay. Experimental conditions: 30 μM Tb\(^{3+}\), 7.0 μM AgNPs, 5.0 mM HCOO\(^-\), 10 μM Glc, Ala, Gly, Tyr, Cys, Asp, GSH, GLu, AA, AMP and 5-HT, 0.10 μM DA, UA and EP in 0.01 M HEPES–NaOH, pH = 7.00 buffer solutions.
Development of DA detection strategy

Considering that DA can be easily oxidized in alkaline physiological conditions, the fluorescence signals were monitored over the pH range from 6.40 to 8.30. Fig. S2A† shows that when pH value was 7.00, the maximum ΔI was obtained.

Effects of various buffers on the fluorescence signals were tested at the same pH (7.00 ± 0.05). The measured relative value of ΔI (%) for HEPES–NaOH, tris(hydroxymethyl)aminomethane–HCl, barbital sodium–HCl, sodium citrate–citric acid and hexamethylenetetramine (HMTA)–HCl was 100, 43.6, 38.8, 2.3 and 0, respectively. Further test results indicated that the optimal buffer solution was 0.01 M HEPES–NaOH (pH 7.00).

The effects of the concentration of HCOONa, terbium chloride and AgNPs on the fluorescence signals were tested. The fluorescence intensities were plotted against HCOO⁻ concentration (Fig. S2B†). With an increase in HCOO⁻ concentration, the fluorescence intensities were sharply amplified till 2.0 mM, reached a maximum and then remained constant. Therefore, 5.0 mM HCOONa was employed in the subsequent tests. As shown in Fig. S2C and S2D, optimum concentrations of Tb³⁺ and AgNPs solutions were 30 μM and 7.0 μM, respectively.

The influences of the reagent adding sequence and reaction time on the fluorescence intensity were tested. The strongest fluorescence enhancement was obtained with the sequence of HEPES–NaOH buffer, HCOO⁻, DA, Tb³⁺ and AgNPs. After the sequential addition of all the reagents, the fluorescence increment reached a maximum after 30 min and became nearly constant for over 3 h.

Under optimal conditions, the sensitivity and linearity range of this proposed method were evaluated. As shown in Fig. 4, the fluorescence intensity increased with increasing concentration of DA. Fig. 4 inset shows that ΔI has a good linearity in DA concentration range of 0.5 nM–100 nM (R² = 0.9978) with a detection limit of 0.15 nM (S/N = 3). Compared with some reported analytical results, the LOD of DA obtained herein was apparently lower (Table S1†). Therefore, the proposed composite probe could improve the sensitivity of the DA assay.

Table 3 Recovery of the DA in serum samples

<table>
<thead>
<tr>
<th>Samples</th>
<th>Added (×10 nM)</th>
<th>Observed (×10 nM) ± RSD (%)</th>
<th>Recovery (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Human serum</td>
<td>1.00</td>
<td>0.97 ± 4.17</td>
<td>97.0</td>
</tr>
<tr>
<td></td>
<td>2.00</td>
<td>1.93 ± 2.44</td>
<td>96.5</td>
</tr>
<tr>
<td></td>
<td>3.00</td>
<td>3.10 ± 4.60</td>
<td>103.3</td>
</tr>
</tbody>
</table>

* Relative standard deviation for three replicate measurements.

Determination of DA

To examine the applicability of the method, our proposed method was applied for DA determination in pharmaceutical injection and serum samples. The DA hydrochloride injection samples were stepwise diluted to appropriate concentration with water for the DA assay. Then, the standard addition method was adopted. The detected average value of DA was measured to be 10.7 mg mL⁻¹ with a relative standard derivation of 3.3% (n = 5). The measured result depicting the amount of DA was in good agreement with the labelled amount of DA in DA hydrochloride injections.

This method was also used to detect DA in human serum samples (Table 3). The spiked samples were obtained using 100-folds dilution solutions of serum by adding appropriate amounts of standard solution of DA. The recoveries were within the range from 96.5% to 103.3%.

Conclusions

In conclusion, a new composite fluorescent nanosensor for the detection of DA was developed. AgNPs were enhancing substrates and HCOO⁻ connected the Tb³⁺ complex to AgNPs. The synergistic action of AgNPs-based SEF with formic-bridging/coordination could effectively improve the sensitivity and selectivity for DA determination. Particularly, the formate played a pivotal role in improving the selectivity of the nanosensor towards DA in the presence of EP. Therefore, the highly selective and sensitive nanosensor would be a promising candidate for future biological and chemical applications.

Conflicts of interest

There are no conflicts to declare.

Acknowledgements

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Notes and references