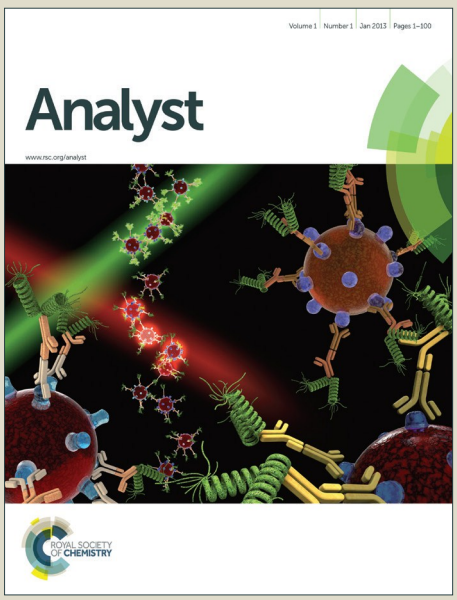
Analyst

Accepted Manuscript



ROYAL SOCIETY OF CHEMISTRY

www.rsc.org/analyst

Journal Name

ARTICLE

Gold Nanoparticle-based Colorimetric Probe for Rapid Detection of 1-Hydroxypyrene in Urine†

Received 00th January 20xx,
Accepted 00th January 20xx

DOI: 10.1039/x0xx00000x

www.rsc.org/

Yaqi Hu, Chunyan Du, Yunchao Li, Louzhen Fan, and Xiaohong Li*

Direct and rapid detection of 1-hydroxypyrene (1-OHP) is of great importance owing to its high carcinogenicity, teratogenicity and toxicity. In this study, a simple and colorimetric assay for rapid determination of 1-OHP was reported, which was based on non-crosslinking aggregation of gold nanoparticles (Au NPs) induced by 1-OHP in the presence of formic acid (FA). Initially, Au NPs was synthesized with citrate as capping agent and exhibited red color. Subsequently, the addition of FA did not cause aggregation, but a proton transfer process occurred from FA to carboxylic anions on the surface of Au NPs with a decreased zeta potential. The addition of 1-OHP resulted in further decreased zeta potential and intensely hydrophobic environment, which led to a strong and rapid non-crosslinking aggregation of Au NPs within 5 min with the color changing from red to violet blue. Based on this principle, a sensitive and selective detection of 1-OHP was achieved. The detection limit was 3.3 nM. Finally, the colorimetric assay was successfully applied to detect 1-OHP in urine sample. This strategy provides new insights into developing colorimetric methods for on-site and real-time detection of polycyclic aromatic hydrocarbons.

Introduction

Polycyclic aromatic hydrocarbons (PAHs) are known contaminants mainly from kinds of industrial and household sources.[1] Owing to high mutagenicity, teratogenicity and carcinogenicity,[2] PAHs have been identified as priority pollutants.[3] Upon entering the cell, PAHs were metabolized into diol epoxides, diones, and other reactive intermediates that react with DNA to form PAH-DNA covalent adducts or cause other forms of DNA damage.[4] The remained other metabolites (mainly hydroxyl polycyclic aromatic hydrocarbons, OH-PAHs) were excreted.[5] For example, OH-PAHs has been found in the urine of human and laboratory animals exposed to PAHs.[6] In particular, level of 1-hydroxypyrene (1-OHP) in urine had been widely identified as a reliable marker and indicator for evaluating PAHs exposure,[7] which could provide evidence for environmental health risk warning and occupational safety evaluation.[8] Thus, developing a simple and sensitive assay for monitoring 1-OHP was meaningful and of considerable significance.

Currently, the techniques for 1-OHP determination included high-performance liquid chromatography (HPLC), mass spectrometry (MS), gas chromatography-mass spectrometry (GC-MS), liquid chromatography-mass spectrometry (LC-MS) and liquid chromatography-fluorescence.[9] Although these methods offered high selectivity and sensitivity, complex sample treatments (such as pre-concentration and separation procedures) and huge instruments presented a great challenge to satisfy the increasing demands of practical applications in real-time and on-site determination. Therefore, the development of simple and miniaturized analytical assays for 1-OHP detection has drawn considerable attentions. Several assays had been developed for direct and effective quantification of 1-OHP.[10-12] For example, fluorescence spectroelectrochemical sensor was reported for the direct determination of 1-OHP in complex samples.[9] Immunological assay was developed for specifically recognizing 1-OHP with the monoclonal antibody as a probe.[11] Those methods made a great improvements in detection techniques and sample treatments. However, it still remains a challenge to achieve simple, rapid and visual determination of 1-OHP, which could really meet the requirements for on-site and real-time environmental monitoring.

Recently, colorimetric approaches with gold/silver nanoparticles (Au/Ag NPs) as a probe for multiple detections were greatly promising. Until now, various colorimetric sensors were designed for analytes, such as inorganic ions, small molecules, protein, andaminoacid.[13] Interestingly, several groups reported the detection of hydroxyl-compounds through colorimetric method.[14] For example, Zou and co-workers developed a colorimetric sensor for the detection of o-, m-, p-benzenediol with water-soluble β-cyclodextrin functionalized Ag NPs as a probe.[14a] However, to the best of our knowledge, the colorimetric assay for detection of 1-OHP has rarely been reported.

Key Laboratory of Theoretical and Computational Photochemistry, Ministry of Education, College of Chemistry, Beijing Normal University, Beijing 100875, China. Tel: +86-10-58802741; E-mail: lxhxiao@bnu.edu.cn

† Electronic Supplementary Information (ESI) available: Supporting table and figures. See DOI:10.1039/x0xx00000x

In this paper, a colorimetric assay for simple, rapid and visual determination of 1-OHP was reported, which was based on Au NPs aggregation induced by 1-OHP in the presence of formic acid. Initially, negatively charged Au NPs were prepared with citrate as a capping agent. The addition of formic acid partially neutralized the negatively charged Au NPs with a decreased zeta potential due to a weak proton transfer process, but couldn't induce the aggregation of Au NPs. When 1-OHP was finally added, a non-crosslinking aggregation of Au NPs within 5 min occurred, and the color changed from red to violet blue, which was due to decreased electrostatic repulsion interaction and an intensely hydrophobic environment around Au NPs caused by pyrene of 1-OHP deriving from the formed hydrogen bonds between 1-OHP and carboxylic anions on the surfaces of Au NPs. Based on this principle, a colorimetric sensor for sensitive and selective detection of 1-OHP was constructed. The detection limit was as low as 3.3 nM with a wide linear range from 0 nM to 1 μM. Most importantly, this sensor was successfully applied for detection of 1-OHP in urine sample.

Experimental

Chemicals and reagents

Gold (III) chloride trihydrate ($HAuCl_4 \cdot 3H_2O$) was purchased from Accela ChemBio Co., Ltd (Shanghai, China). Trisodium citrate, phenol (PN), hydroquinone (HQ), catechol (CC), resorcinol (RC), $Pb(CH_3COO)_2 \cdot H_2O$, $Hg(ClO_4)_2 \cdot H_2O$, $FeCl_3$, CH_3COOK, CH_3COONa, $CaCl_2$, creatinine (CREA) and urea were purchased from Sinopharm Chemical Reagent Co., Ltd (Shanghai, China). Uric acid (UA) was purchased from Aladdin Industrial Corporation (Shanghai, China). Formic acid (FA) was purchased from Beijing Chemical Works (Beijing, China). 1-hydroxypyrene (1-OHP), 9-hydroxyfluorene (9-OHF), 2-hydroxyfluorene (2-OHF), 1-hydroxynaphthalene (1-OHN), 2-hydroxynaphthalene (2-OHN), 6-hydroxychrysene (6-OHC), and 9-hydroxyphenanthrene (9-OHP) were purchased from Sigma-Aldrich Chemical (Sigma-Aldrich, USA). All chemicals were of analytical reagent grade and used without further purification. Stock solutions of aromatic compounds were prepared in acetonitrile with a concentration of 1 mM. Other solutions were prepared with deionized water (18.2 MΩ cm) from a Millipore system. Urine samples were prepared according to the previous reports,[15] and urine samples diluted by 40 times were spiked with 1-OHP applied for testing selectivity experiment.

Apparatus and instruments

UV/Vis spectra were recorded by UV/Vis spectrophotometer (UV-2450, Shimadzu, Japan) using 1 cm path length quartz cuvettes. Spectra responses were collected from 400 to 800 nm at room temperature. Photographs for color changes were taken with a Samsung (EOS 450D, Korea) digital camera. The morphology of Au NPs was characterized using transmission electron microscopy (HRTEM, JEOL 2100, Japan). Specimens were prepared by placing of the colloidal suspension onto carbon film, and allow the solvent evaporate. The Zeta potential was obtained using zeta potential analyzer (ZetaPlus, Brookhaven Instrument Co., Holtsville, NY). HPLC experiments were conducted by a Waters Acquity Ultra Performance Liquid Chromatography with ACQUITY UPLC BEH C18 (1.7 μm, 2.1×50 mm) column. The mobile phase was water–acetonitrile (v/v, 50/50) at a flow-rate of 0.3 mL/min. The column temperature was set at 35℃. The excitation and emission wavelengths were 240 nm and 277 nm, respectively.

Synthesis of Au NPs

All glassware was thoroughly cleaned with freshly prepared aqua regia solution of V_{HCl}:V_{HNO_3}= 3:1 for 20 min, then rinsed thoroughly in water and dried in air. The Au NPs were prepared as reported previously with minor modifications.[16] Briefly, 5 mL of 38.8 mM trisodium citrate was rapidly added into the boiling solution 100 mL of 0.4 mM $HAuCl_4$ with vigorous stirring, and the resulting solution was kept continuously boiling for 30 min until a red solution was obtained. The solution was cooled to room temperature and then filtrated through a filter membrane (0.22 μm) to remove the precipitate, and the filtrate was stored in a refrigerator at 4℃ for use. The diameter of synthetic Au NPs was about 13 nm as reported previously, which was confirmed by TEM image. The concentration of the Au NPs solution was estimated to be 4 nM according to the absorbance data and the average size of the particles as previously reported.[17]

Colorimetric detection of 1-OHP

For colorimetric detection of 1-OHP, the solutions of 1-OHP with different concentrations were prepared by diluting fresh stock solutions with deionized water. Firstly, 2 mM FA solution was added into 0.5 mL of Au NPs suspension to mix completely for 30 s. Then, different concentrations of 1-OHP were added into the solution. The color changes were photographed with a digital camera and recorded by the UV/Vis absorption spectra. The sensor responses (A_{670}/A_{518}) were calculated by dividing the absorption of the Au NP suspension at 670 nm by that at 518 nm. Au NPs suspension to be analyzed was allowed to react for 5 min before analysis unless special instructions and each reaction was monitored by UV/Vis to correlate the aggregation results.

Results and discussion

The spherical and well-dispersed Au NPs with the mean diameter of 13 nm were synthesized with citrate as the stabilizer (Fig. 1A). As shown in Fig. 2 (curve 1, vial 1), the as-prepared Au NPs exhibit an absorption peak at 518 nm, which is ascribed to the surface plasmon resonance of the Au NPs.[16] Owing to abundant carboxylic anions on the Au NPs surfaces, Au NPs remained highly stable with a ζ (zeta potential) of -41.3 mV (Fig. 1D).[18] Upon 2 mM FA being added into the Au NPs suspension (pH = 6.5), no obvious aggregation was observed in Fig. 1B, and the absorption at 518 nm was kept unchanged as shown in Fig. 2 (curve 2, vial 2). With such small change in pH (pH = 6.2), the value of ζ was decreased to -28.2 mV (Fig. 1D). The result suggested that the addition of FA couldn't change the acidity of the Au NPs, but the H^+ (partly dissociated from FA) further protonated the negatively-charged carboxylic anions on the Au NPs surfaces, which led to the decreased ζ.[19,20]

When 1 μM 1-OHP was finally added into the FA-Au NPs aqueous

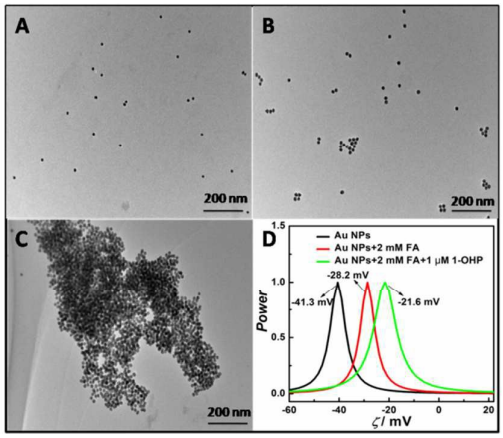


Fig. 1 TEM images of 2 nM Au NPs. (A) without any addition. (B) with the addition of 2 mM FA. (C) with the addition of 1 μM 1-OHP in the presence of 2 mM FA. (D) corresponding zeta potential measurements of Au NPs.

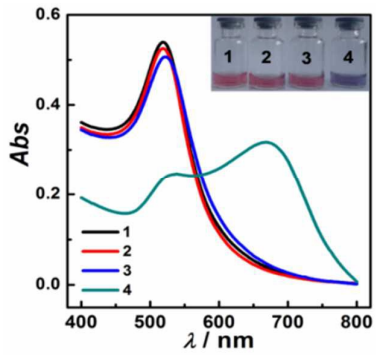
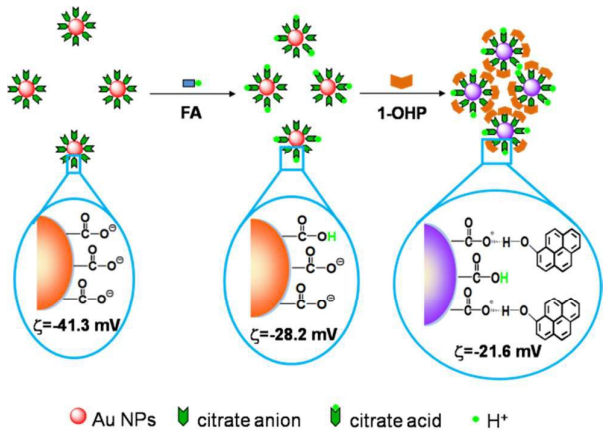


Fig. 2 UV/Vis absorption spectra of 2 nM Au NPs: 1) without any addition; 2) with the addition of 2 mM FA; 3) with the addition of 1 μM 1-OHP; 4) with the addition of 1 μM 1-OHP in the presence of 2 mM FA. Inset: images of corresponding color changes of Au NPs.



Scheme 1 Scheme of colorimetric sensing of 1-OHP.

suspension, the colour rapidly changed from red to purple within 5 min (Video S1, ESI†). The absorption at 518 nm greatly decreased and a new absorption peak at 670 nm appeared (curve 4, vial 4 in Fig. 2), which was attributed to the number of mono-dispersed Au NPs reduced and Au NPs aggregated.[13e] Meanwhile, the value of ζ was further decreased to -21.6 mV. Hydroxyl (–OH) in 1-OHP could possibly form hydrogen bond (–OH···OOC) with carboxylic anions on the Au NPs surface,[21] and led to the decreased ζ. Alternatively, if 1 μM 1-OHP was directly added into the Au NPs suspension without 2 mM FA, the absorption peak at 518 nm exhibited a slight decrease and red-shift (curve 3, vial 3 in Fig. 2). The results show: (1) FA plays an essential role in the process of Au NPs aggregation; (2) 1-OHP can trigger the aggregation of Au NPs in the presence of FA (Fig. 1C).

To explore the possible aggregation mechanism, a series of experiments were carried out. Firstly, in the presence of bases and acids instead of FA, the addition of 1-OHP could cause Au NPs aggregations with different extents. Compared with FA, bases (such as sodium acetate and sodium hydroxide) failed to provide H^+ for carboxylic anions on the Au NPs surfaces, the addition of 1-OHP couldn't induce the Au NPs aggregation (Fig. S1, ESI†); acids (such as sulfuric acid) provided abundant H^+ for carboxylic anions on the Au NPs surfaces, and directly triggered the Au NPs aggregation (Table S1). Alternatively, sulfuric acid was applied for mediated the acidity of the Au NPs to 6.2, the addition of 1-OHP induced a rapid aggregation within 5 min, which was similar to that of 2 mM FA (Fig. S2, ESI†). Based on the results, it was concluded that H^+ dissociated from FA played an important role in the process of Au NPs aggregation induced by 1-OHP. Secondly, in the presence of FA, pyrene instead of 1-OHP was added into the Au NPs suspension, no aggregation was observed (Fig. S3, ESI†), which indicated that –OH in 1-OHP played a key role to induce the Au NPs aggregations. If phenol instead of 1-OHP was added into the Au NPs suspension, also no aggregation was observed (Fig. S3, ESI†), which indicated the pyrene in 1-OHP was essential in the process of Au NPs aggregation. It could be reasoned that hydroxyl group (–OH) in 1-OHP could form p-π conjugation with pyrene ring,[22,14b] which was possibly beneficial to the formation of hydrogen bond between –OH and carboxylic anion on the Au NPs surfaces.[21] In addition, pyrene in 1-OHP could provide intensively hydrophobic environment around the Au NPs.[23] As a result, non-crosslinking aggregations of Au NPs occurred.[24]

On the basis of discussions above, the FA-Au NPs was selected as a colorimetric probe for the detection of 1-OHP as shown in Scheme 1. Initially, citrate-capped Au NPs was negatively charged with ζ of -41.3 mV. The electrostatic repulsion interactions between the Au NPs kept it stable. Upon FA being added, H^+ partly dissociated from FA could transfer to carboxylic anions on the Au NPs surface, and led to a decreased ζ (-28.2 mV). When 1-OHP was finally added, -OH in 1-OHP could form hydrogen bond (-OH···OOC) with carboxylic anions on the Au NPs surface with the further decreased ζ (-21.6 mV). The decreased electrostatic repulsion interaction between Au NPs and hydrophobic environment around Au NPs caused the rapid aggregations within 5 min. To obtain the best aggregation response for 1-OHP, 2 nM Au NPs and 2 mM FA were selected, respectively (Fig. S4 and Fig. S5, ESI†).

As shown in Fig. 3, when the concentration of 1-OHP was gradually increased from 0 nM to 4 μM, the absorption peak at 518 nm gradually decreased, and a new absorption peak at 670 nm appeared and further increased, followed by the color changed from

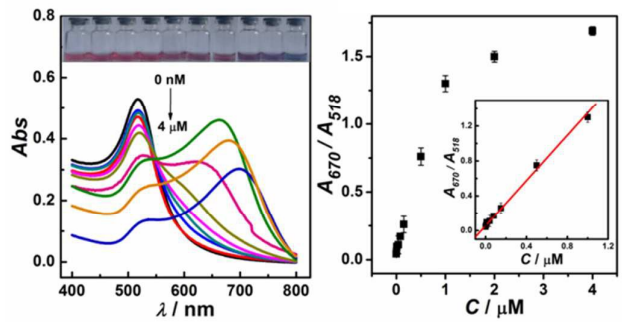


Fig. 3 (A) UV/Vis absorption spectra of FA-Au NPs probe with 1-OHP concentrations containing 0 nM, 5 nM, 10 nM, 40 nM, 80 nM, 150 nM, 500 nM, 1 μM, 2 μM and 4 μM. Inset: colorimetric images of FA-Au NPs probe with related 1-OHP concentrations (from left to right). (B) Dependences of the absorption ratio (A_{670}/A_{518}) on the concentrations of 1-OHP. Inset: Linear plot of the absorption ratio (A_{670}/A_{518}) vs. different 1-OHP concentrations from 0 nM to 1 μM.

red to purple and finally to violet blue (inset in Fig. 3A). When the 1-OHP concentration was increased from 0 nM to 1 μM, the corresponding A_{670}/A_{518} value gradually increased. Further increasing the concentration of 1-OHP up to 4 μM produced a slightly increased A_{670}/A_{518} (Fig. 3B). It was found that the value of A_{670}/A_{518} showed a linear relationship with the 1-OHP concentration ranged from 0 nM to 1 μM (R^2=0.997) (inset of Fig. 3B). The detection limit was calculated to be 3.3 nM (S/N=3).

To evaluate the selectivity of the assay, some hydroxyl aromatic hydrocarbons, metal ions and main urine ingredients (Crea, Urea, UA) were selected. The colorimetric responses of these interferents to the sensing system at a concentration of 1 μM except Crea (0.1 μM) were investigated, respectively. Hydroxyl polycyclic aromatic hydrocarbons included phenols (HQ, PN, CC, RC) and OH-PAHs (1-OHN, 2-OHN, 2-OHF, 9-OHF, 9-OHP, 6-OHC) as shown in Table S2.[5,25] OH-PAHs were common interferences in urine sample from those human and laboratory animals exposed to PAHs. It was reported that 3-hydroxy benzo[a]pyrene was not detected in metabolites[26] but exists combining glucosiduronide.[27] Therefore, 3-hydroxy benzo[a]pyrene was not included as one of interferences. Metal ions included Ca^{2+}, Fe^{3+}, Hg^{2+}, K^{+}, Mg^{2+}, Na^{+}, and Pb^{2+}, and they couldn't effectively decrease the electrostatic repulsion interactions between Au NPs at lower concentration (1 μM), and no obvious aggregation was observed within 5 min. For some phenols (PN, HQ, CC, and RC), they couldn't produce interference signal due to unsuccessful satisfaction for hydrophobic environment around the Au NPs. Based on the discussed results above, 1-OHP owned preferable conjugacy which was beneficial to form the p-π conjugation between –OH and pyrene ring, and further beneficial to the formation of hydrogen bond between –OH in 1-OHP and carboxylic anion at Au NPs surface. As a result, pyrene in 1-OHP accordingly provided a hydrophobic environment around the Au NPs. As shown in Fig. 4, other OH-PAHs produced a relative smaller aggregation response (A_{670}/A_{518}) compared with 1-OHP, only 1-OHP gave a larger value of A_{670}/A_{518}. In addition, the response against 1-OHP in the presence of the mixture of interferents was also investigated, which was only slightly reduced. The results indicated the high selectivity of FA-Au NPs probe for 1-OHP.

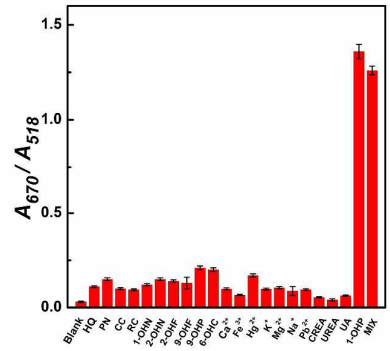


Fig. 4 Selectivity of the colorimetric assay for 1-OHP. Response (A_{670}/A_{518}) of the colorimetric sensor against the competing interferents from left to right were corresponding to blank, HQ, PN, CC, RC, 1-OHN, 2-OHN, 2-OHF, 9-OHF, 9-OHP, 6-OHC, Ca^{2+}, Fe^{3+}, Hg^{2+}, K^{+}, Mg^{2+}, Na^{+}, Pb^{2+}, Crea, Urea, UA and the mixture of interferents, respectively.

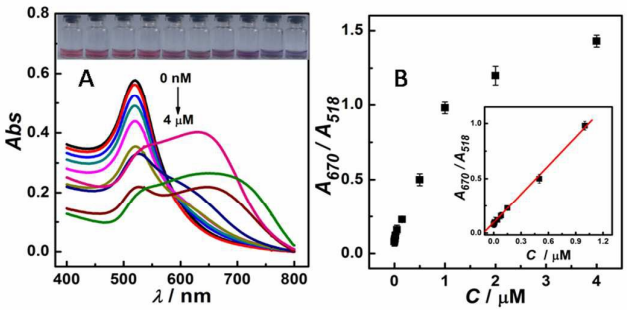


Fig. 5 (A) UV/Vis absorption spectra of FA-Au NPs probe for 1-OHP in spiked urine samples containing 0 nM, 5 nM, 10 nM, 40 nM, 80 nM, 150 nM, 500 nM, 1 μM, 2 μM and 4 μM. Inset: colorimetric images of FA-Au NPs probe for 1-OHP in spiked urine samples with related concentrations (from left to right). (B) Dependences of the absorption ratio (A_{670}/A_{518}) on the concentrations of 1-OHP. Inset: Linear plot of the absorption ratio (A_{670}/A_{518}) vs. different 1-OHP concentrations from 0 nM to 1 μM.

Finally, the potential application of the developed colorimetric method in urine sample was investigated. With the increased concentration of 1-OHP spiked in urine sample, the absorption peak at 518 nm decreased, and a new absorption peak at 670 nm appeared and further increased. Accordingly, the colour of Au NPs changed from red to violet blue (inset in Fig. 5A). It was found that the value of A_{670}/A_{518} showed a linear relationship with the concentration of 1-OHP from 0 nM to 1 μM (R^2=0.986), and the detection limit was 4.9 nM (inset in Fig. 5B). The results indicated that the colorimetric assay could be applied for 1-OHP detection in the urine sample. In addition, to further demonstrate the feasibility of the assay, the recovery experiments were performed, and obtained the average recovery of 100.4±4.0% by this probe for 0.5 μM 1-OHP, which was well consistent with the value (96.4±2.1%) obtained by HPLC.

Conclusions

In this paper, a simple colorimetric assay for rapid detection of 1-OHP has been developed, which was based on non-crosslinking aggregations of Au NPs triggered by 1-OHP. The

negatively charged Au NPs with citrate as capping agent was partly neutralized by FA, and kept metastable. The addition of 1-OHP induced strong and rapid aggregations of the Au NPs within 5 min, which was due to the further decreased electrostatic repulsion and intense hydrophobic environment derived from the formed hydrogen bonds between 1-OHP and carboxylic anions on the Au NPs surface. Based on the results, 1-OHP was sensitively and selectively detected with a linear range from 0 nM to 1 μM. The detection limit was 3.3 nM. Importantly, the colorimetric assay was successfully applied for the detection of 1-OHP in urine sample. This strategy opens a new way to develop colorimetric methods for on-site and real-time detection of polycyclic aromatic hydrocarbons.

Acknowledgements

This work is supported by the National Nature Science Foundation of China (Grant No. 21073019) and the Major Research Plan of NSFC (21233003).

Notes and references

1 (a) S. Stanley, C. J. Percival, M. Auer, A. Braithwaite, M. I. Newton, G. McHale and W. Hayes, *Anal. Chem.,* 2003, **75**, 1573; (b) J. V. Goodpaster and V. L. McGuffin, *Anal. Chem.*, 2000, **72**, 1072.

2 (a) I. J. Keyte, R. M. Harrison and G. Lammel, *Chem. Soc. Rev.*, 2013, **42**, 9333; (b) C. Achten and T. Hofmann, *Sci. Total Environ.*, 2009, **407**, 2461.

3 M. Schedl, G. Wilharm, S. Achatz, A. Kettrup, R. Niessner and D. Knopp, *Anal. Chem.*, 2001, **73**, 5669.

4 T. M. Penning, M. E. Burczynski, C.-F. Hung, K. D. McCoull, N. T. Palackal and L. S. Tsuruda, *Chem. Res. Toxicol.*, 1998, **12**, 1.

5 Y. Guo, K. Senthilkumar, H. Alomirah, H.-B. Moon, T. B. Minh, M. A. Mohd, H. Nakata and K. Kannan, *Environ. Sci. Technol.,* 2013, **47**, 2932.

6 (a) F. J. Jongeneelen, *Toxicol. Lett.*, 1994, **72**, 205; (b) F. Dor, W. Dab, P. Empereur-Bissonnet and D. Zmirou, *Crit. Rev. Toxicol.*, 1999, **29**, 129.

7 (a) T. Chetiyanukornkul, A. Toriba, R. Kizu, T. Makino, H. Nakazawa and K. Hayakawa, *J. Chromatogr. A*, 2002, **961**, 107; (b) J. O. Levin, *Sci. Total Environ.*, 1995, **163**, 165.

8 G. J. Stroomberg, F. Ariese, C. A. M. van Gestel, B. van Hattum, N. H. Velthorst and N. M. van Straalen, *Environ. Toxicol. Chem.*, 2003, **22**, 224.

9 (a) A. Chahin, Y. P. Guiavarc'h, M.-A. Dziurla, H. Toussaint, C. Feidt and G. Rychen, *J. Agric. Food Chem.*, 2008, **56**, 1780; (b) X. Li, X. Fang, Z. Yu, G. Sheng, M. Wu, J. Fu and H. Chen, *Anal. Methods*, 2013, **5**, 2816; (c) H.-H. Lim and H.-S. Shin, *Food Chem.*, 2013, **138**, 791; (d) P. Jacob, M. Wilson and N. L. Benowitz, *Anal. Chem.*, 2006, **79**, 587; (e) C.-T. Kuo, H.-W. Chen and J.-L. Chen, *J. Chromatogr. B*, 2004, **805**, 187.

10 (a) R. A. Wilson, C. J. Seliskar, G. Talaska and W. R. Heineman, *Anal. Chem.*, 2011, **83**, 3725; (b) T. S. Pinyayev, C. J. Seliskar and W. R. Heineman, *Anal. Chem.*, 2010, **82**, 9743.

11 K. Li, L. A. Woodward, A. E. Karu and Q. X. Li, *Analytica Chimica Acta*, 2000, **419**, 1.

12 (a) X. Shen, Y. Cui, Y. Pang and H. Qian, *Electrochimica Acta*, 2012, **59**, 91; (b) N. Kirsch, J. P. Hart, D. J. Bird, R. W. Luxton and D. V. McCalley, *Analyst*, 2001, **126**, 1936.

13 (a) Y. Guo, Y. Zhang, H. Shao, Z. Wang, X. Wang and X. Jiang, *Anal. Chem.*, 2014, **86**, 8530; (b) G .-H. Chen, W.-Y. Chen, Y.-C. Yen, C.-W. Wang, H.-T. Chang and C.-F. Chen, *Anal. Chem.*, 2014, **86**, 6843; (c) J. Deng, P. Yu, L. Yang and L. Mao, *Anal. Chem.*, 2013, **85**, 2516; (d) W. J. Qi, D. Wu, J. Ling and C. Z. Huang, *Chem. Commun.*, 2010, **46**, 4893; (e) B. Kong, A. Zhu, Y. Luo, Y. Tian, Y. Yu and G. Shi, *Angew. Chem.*, 2011, **123**, 1877; (f) J. You, H. Hu, J. Zhou, L. Zhang, Y. Zhang and T. Kondo, *Langmuir*, 2013, **29**, 5085; (g) R. Chandrawati and M. M. Stevens, *Chem. Commun.*, 2014, **50**, 5431; (h) Y. Jiang, H. Zhao, Y. Lin, N. Zhu, Y. Ma and L. Mao, *Angew. Chem., Int. Ed.,* 2010, **49**, 4800; (i) H. Su, Q. Zheng and H. Li, *J. Mater. Chem.*, 2012, **22**, 6546.

14 (a) X. Chen, S. G. Parker, G. Zou, W. Su and Q. Zhang, *ACS Nano*, 2010, **4**, 6387; (b) Z. Chen, X. Zhang, H. Cao and Y. Huang, *Analyst*, 2013, **138**, 2343.

15 C. J. Haglock-Adler, A. Hurley and F. G. Strathmann, *Clin Biochem.*, 2014, **47**, 80.

16 K. C. Grabar, R. G. Freeman, M. B. Hommer and M. J. Natan, *Anal. Chem.*, 1995, **67**, 735.

17 X. Liu, M. Atwater, J. Wang and Q. Huo, *Colloids Surf., B*, 2007, **58**, 3.

18 C. H. Munro, W. E. Smith, M. Garner, J. Clarkson and P. C. White, *Langmuir*, 1995, **11**, 3712.

19 J. Yu and P. E. Savage, *Ind. Eng. Chem. Res.*, 1998, **37**, 2.

20 J. Tan, R. Liu, W. Wang, W. Liu, Y. Tian, M. Wu and Y. Huang, *Langmuir*, 2010, **26**, 2093.

21 G. R. Desiraju, *Acc. Chem. Res.*, 1996, **29**, 441.

22 Z. Cai, J. Gao, X. Li and B. Xiang, *Opt Commun.*, 2007, **272**, 503.

23 E. J. Cho, H. Holback, K. C. Liu, S. A. Abouelmagd, J. Park and Y. Yeo, *Mol. Pharmaceutics.*, 2013, **10**, 2093.

24 (a) L.-Q. Zheng, X.-D. Yu, J.-J. Xu and H.-Y. Chen, *Anal. Methods*, 2014, **6**, 2031; (b) L.-Q. Zheng, X.-D. Yu, J.-J. Xu and H.-Y. Chen, *Talanta*, 2014, **118**, 90.

25 S. Lutz, C. Feidt, F. Monteau, G. Rychen, B. Le Bizec and S. Jurjanz, *J. Agric. Food Chem.*, 2006, **54**, 263.

26 X. Li and R. Zenobi, *Anal. Chem.*, 2013, **85**, 3526.

27 K. Bal and L. Larsson, *J Chromatogr B Biomed Appl.*, 2000, **738**, 57.