Inorganic Chemistry Communications 130 (2021) 108753

Contents lists available at ScienceDirect

Inorganic Chemistry Communications

journal homepage: www.elsevier.com/locate/inoche

Short communication

An anthraquinone-based "turn-on" fluorescence probe for Hg^{2+} detection and its application in cell imaging

Zhiwei Ma [a,b], Di Zhang [a,*], Jie Guo [a], Man Li [a], Tieliang Wang [a], Haiyan Yin [a], Hongqi Wang [a], Jihong Liu [a,*]

[a] Henan Cereal Quality and Safety Testing Key Laboratory, Institute of Quality Standards and Testing Technology for Agro-Products, Henan Academy of Agricultural Sciences, Zhengzhou 450002, China

[b] Faculty of Science, Henan University of Animal Husbandry and Economy, Zhengzhou 450046, China

ARTICLE INFO

Keywords:
Turn-on
Fluorescence
Desulfurization
Hg^{2+}

ABSTRACT

A new highly sensitive fluorescence "turn-on" probe (**HgP1**) based on anthraquinone derivatives for the detection of Hg^{2+} has been designed and developed. Based on desulfurization effect, probe **HgP1** shows high selectivity towards Hg^{2+} in CH_3OH/HEPES (10 mM, pH = 7.4, 1/1, v/v) solution over other analytes. The detection limit for Hg^{2+} is 8.2 nM. In addition, the probe shows good biocompatibility and has been successfully used in living cell imaging.

1. Introduction

Mercury is one of common pollutants in organisms and the environment. At room temperature, mercury exists in liquid form and is easy to volatile. Mercury vapor and mercury compounds are highly toxic, which cause serious pollution to the ecological environment [1]. Mercury ion (Hg^{2+}) pollution in the environment has caused serious harm to animals, plants and human health [2–3]. For example, some genetic in plants and animals will be changed with excess mercury ions. As a typical Lewis acid, mercury ions have a strong thiophilic property, and will react with proteins or enzymes that contain sulfur in living organisms, causing a range of diseases, including excessive mercury ions that can lead to irreversible DNA damage, pulmonary edema, kidney failure and many types of autism [4–9]. As the hypertoxicity of mercury ions, the rapid and real-time detection of the content of mercury ions in the environment is of great importance, and it is particularly urgent need in food safety and biomedical fields [10].

Because of its obvious advantages of low cost, simple instrument operation, low detection limit and real-time monitoring, fluorescence probe detection of metal ions has attracted widely attention in recent years [11–20]. Among various of fluorescent probes, reactive probes show high selectivity to target analytes due to the irreversible chemical reaction with the target analytes, which can reduce the detection error and improve the detection accuracy. Therefore, it has a good application value for heavy metal detection in complex systems [21–26]. For mercury ion recognition, the main strategy is based on its strong thiophilic property [27–29]. In the desulfurization progress between mercury ions and sulfur atoms, the fluorescence intensity will be changed as the structure of fluorescent probe changed. Anthraquinone derivatives have the advantages of easy synthesis, large stoke shift, good photostability, and can form excited intramolecular charge transfer (ICT), which are suitable precursors for designing new fluorescent probes. Based on the strong sthiophilic property of Hg^{2+}, a fluorescence "turn-on" probe which containing thioacetals as the reactive site for Hg^{2+} and anthraquinone derivatives as fluorophore was designed. Besides of good selectivity and sensitivity, the probe overcome the interference of common metal cations and anions, and can effectively identify Hg^{2+} in complex systems. In addition, the probe showed low biological toxicity and had been successfully applied to detect exogenous Hg^{2+} in living cells.

2. Experimental

2.1. Apparatus and materials

NMR data was collected by Bruker AVII-400 instrument. High resolution mass spectrometry data were recorded by an HPLC Q-Exactive HR-MS spectroscopy (Thermo). The fluorescence spectra were recorded by Hitachi F-7000 fluorescence spectrometer. Fluorescence images experiments were performed by an Olympus FV-3000 confocal

* Corresponding authors.
E-mail addresses: zhangdi@hnagri.org.cn (D. Zhang), ljha3100@163.com (J. Liu).

https://doi.org/10.1016/j.inoche.2021.108753
Received 21 April 2021; Received in revised form 9 June 2021; Accepted 13 June 2021
Available online 16 June 2021

microscope.

The solvents and reagents used in the experiment are analytically pure, purchased from commercial companies and used directly. The metal ions used in the analysis experiment are corresponding chloride or nitrate salts, dissolved in distilled water to prepare a 10 mM stock solution. The probe **HgP1** was dissolved in MeOH to prepare 1 mM stock solution.

2.2. Synthesis

Compound **QCHO** was synthesized by referring to the known literature [30]. The detail synthetic steps of probe **HgP1** are as follows:

Compound **QCHO** (352 mg, 1 mmol) and p-toluenesulfonic acid (17.2 mg, 0.10 mmol) were dissolved in 25 mL anhydrous dichloromethane solution, and ethyl mercaptan (497 mg, 8 mmol) was added to the above solution. And the reaction solution was stirred at room temperature for about 15 h under N_2 atmosphere. After the reaction is complete, 30 mL saturated NaCl solution was added to the above solution. Then the organic solvent was separated, and dried over anhydrous Na_2SO_4. The crude product was purified by silica gel chromatography (petroleum/ ethyl acetate = 15:1, v/v) to get probe **HgP1** as a brown solid (343.5 mg, 75%). ^{1}H NMR ($CDCl_3$, 400 MHz) δ 1.15 (t, J = 7.0 Hz, 6H), 2.62 (m, 4H), 5.01 (s, 1H), 7.67 (d, J = 7.6 Hz, 2H), 7.80 (s, 2H), 8.12 (t, J = 9.2 Hz, 3H), 8.23 (t, J = 7.8 Hz, 2H), 8.32 (s, 1H), 11.28 (s, 1H); ^{13}C NMR ($CDCl_3$, 100 MHz) δ 185.19, 182.61, 156.19, 149.51, 144.34, 134.48, 133.98, 133.81, 133.33, 133.18, 128.72, 128.67, 128.07, 127.62, 127.33, 126.52, 125.73, 122.06, 118.06, 52.16, 26.34, 14.32; HR-ESI-MS calcd for $[M + H^+]^+$ ($C_{26}H_{23}N_2O_2S_2$): 459.1201, found 459.1188 $[M + H^+]$.

3. Results and analysis

Probe **HgP1** was synthesized in a simple step, and its chemical structure was verified by ^{1}H NMR, ^{13}C NMR and HRMS (Fig. S1-S3). Probe **HgP1** showed good solubility in common organic solvents. By referring to the previous experimental methods [31], the best recognition system for Hg^{2+} is CH_3OH/HEPES(10 mM, pH = 7.4, 1/1, v/v) solution (Fig. S4).

3.1. Fluorescence spectra

Specific selectivity is an important factor to evaluate the efficiency of fluorescent probe molecules. Firstly, the selectivity of probe **HgP1** towards various metal ions was investigated by fluorescence spectrometer. As shown in Fig. 1, the fluorescence emission intensity of the single probe **HgP1** in CH_3OH/HEPES(10 mM, pH = 7.4, 1/1, v/v) solution system was weak between 400 nm and 700 nm, and the fluorescence emission of the solution system was significantly enhanced when Hg^{2+} (10 eq.) was added. However, when 10 eq. of various common metal ions (K^+, Na^+, Li^+, Ca^{2+}, Mg^{2+}, Ba^{2+}, Zn^{2+}, Sn^{2+}, Sn^{4+}, Fe^{2+}, Mn^{2+}, Pb^{2+}, Cu^{2+}, Co^{2+}, Fe^{3+}, Cr^{3+}, Ag^+, Ni^{2+}, Cd^{2+}) were added, the fluorescence emission of the solution system did not change significantly. The above experimental results showed that the probe has good selectivity to Hg^{2+}.

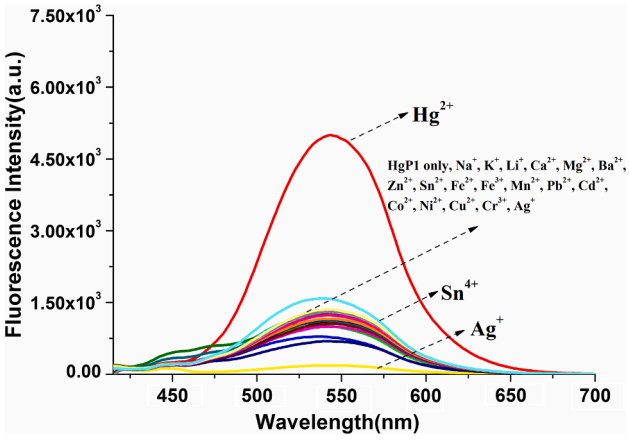


Fig. 1. The fluorescence emission spectra of probe **HgP1** (10 μM) towards different metal ions (100 μM) in CH_3OH/HEPES(10 mM, pH = 7.4, 1/1, v/v) solution (λ_{ex} = 390 nm).

In order to test potential competition of probe **HgP1** towards Hg^{2+} detection, the fluorescence emission spectra of the probe recognizes Hg^{2+} were measured in the presence of common metal ions and anions. As shown in Fig. 2, in the presence of other metal ions or anions, the fluorescence emission intensity (at 544 nm) of the probe for Hg^{2+} recognition is almost the same as that of Hg^{2+} recognition alone. The results showed that the probe can be used to identify Hg^{2+} under complex conditions, which improves the practical application value of the probe.

Good detection limit is one of the criteria to check whether a probe molecule has application value. Fluorescence spectrometer was used to determine the Hg^{2+} detection limit in CH_3OH/HEPES (10 mM, pH = 7.4, 1/1, v/v) solution. As shown in Fig. 3A, the single probe (10 μM) exhibits weak fluorescence emission in the CH_3OH/HEPES (10 mM, pH = 7.4, 1/1, v/v) solution. With the continuous addition of Hg^{2+}, the fluorescence emission intensity of the solution system increases continuously, indicating that probe **HgP1** is a fluorescence "turn-on" probe for the detection of Hg^{2+}. It should be noted that the fluorescence emission intensity (at 544 nm) of the solution system has a good linear relationship (R^2 = 0.990) with the concentration of Hg^{2+} in the range of 0–1.0 μM (Fig. 3B). According to the calculation of IUPAC (3sd/k), the detection limit of Hg^{2+} by this probe is estimated to 8.2 nM [32], which can meet the national requirement of limiting the content of Hg^{2+} in food and water, indicating that this probe **HgP1** has great application value in the quality and safety of agricultural products [33].

In order to further evaluate the effect of different pH of buffer solution on the detection of Hg^{2+} by probe **HgP1**, fluorescence titration experiments of buffer solutions with different pH values were carried out. As shown in the Fig. 4, the fluorescence emission intensity (at 544 nm) of the single probe (10 μM) is very low and stable between pH 4 and 9. In the presence of Hg^{2+} (100 μM), the solution system exhibits strong fluorescence emission at pH 4–8, indicating that the probe can be used to identify Hg^{2+} under physiological conditions. The result of kinetic experiments shows that the fluorescence emission of the solution reaches the maximum value in about 400 s (Fig. S5), which further indicates that the probe has a rapid recognition effect on Hg^{2+}. Comparing with the fluorescent probes based on desulfurization reaction mechanism for the detection of Hg^{2+} listed in Table S1, the probe **HgP1** demonstrates moderate advantages in the aspects of detection limit, recognition time, recognition system and application field, which provides a new choice for the detection of Hg^{2+}.

3.2. Mechanism

The above results showed that the probe **HgP1** has good recognition performance for Hg^{2+}, and we further studied the mechanism of detection. Based on the addition of EDTA, the reversible recognition experiment of Hg^{2+} was investigated (Fig. S6). When excess EDTA was added to the **HgP1**-Hg^{2+} solution, the fluorescence emission spectrum was almost the same as the **HgP1**-Hg^{2+} solution, which indicates that the coordination of **HgP1** with Hg^{2+} is chemically nonreversible. ^{1}H NMR titration experiment was conducted on probe **HgP1** with different amounts of Hg^{2+} in DMSO-d_6 (shown in Fig. S7). A new peak at 9.65 ppm ($H_{1'}$) which assigned to the proton on the –CHO signal appeared and increased, along with the amounts of Hg^{2+} increasing. Meanwhile, the peak at 5.30 ppm (H_1), assigned to methine proton of the thioacetal group in probe **HgP1** were gradually decreased and finally disappeared.

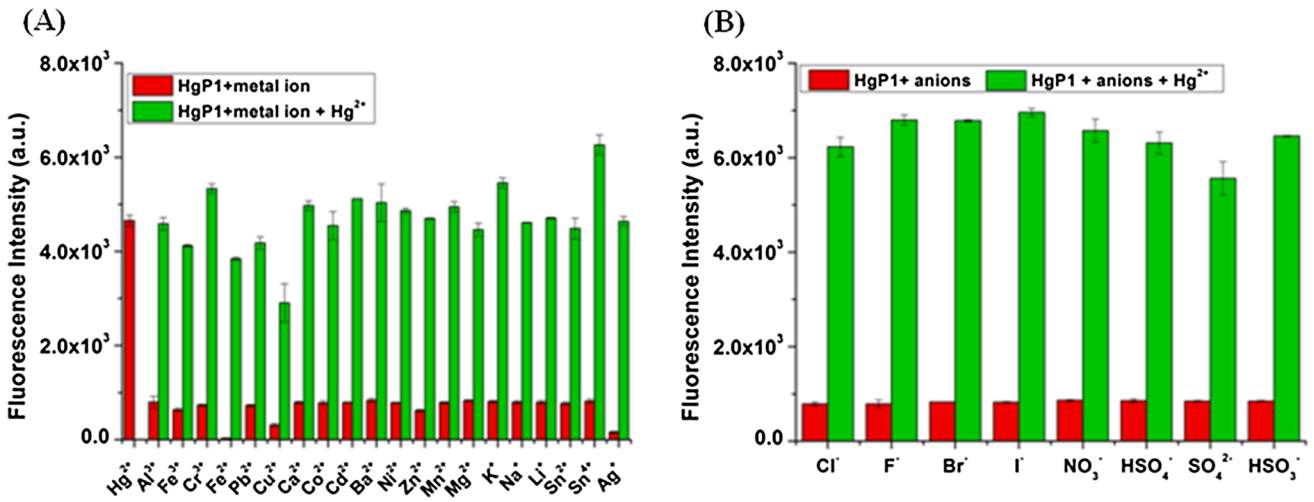


Fig. 2. Fluorescence emission (at 544 nm) of Hg^{2+} (100 μM) recognized by the probe **HgP1** (10 μM) in the presence of metal ions (100 μM, A) and anions (100 μM, B) (λ_{ex} = 390 nm).

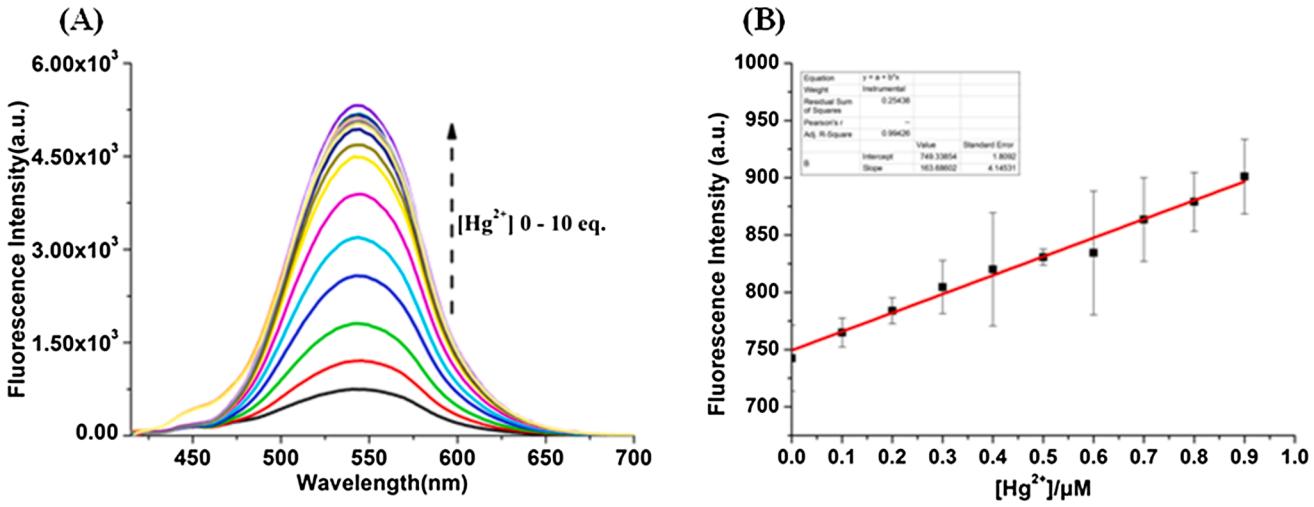


Fig. 3. (A) The fluorescence emission spectra of probe **HgP1** (10 μM) with different concentrations of Hg^{2+} (0–10 eq.), (B) the linear fluorescence emission responses (at 544 nm) of Hg^{2+} (0–1.0 μM) (λ_{ex} = 390 nm).

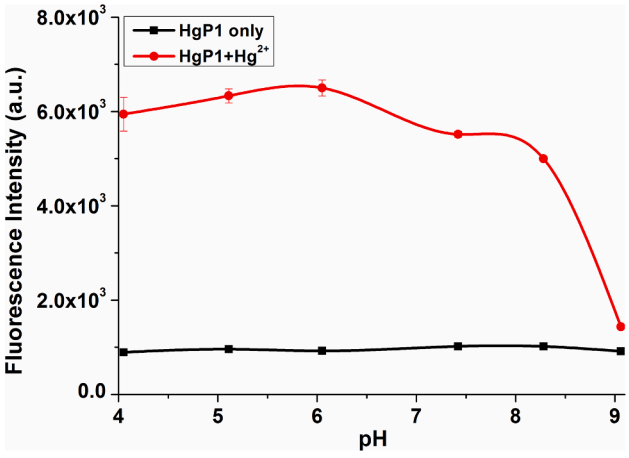
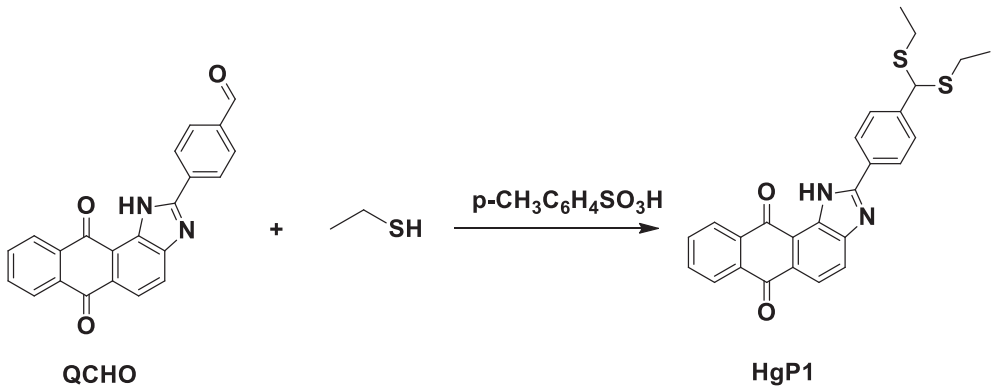


Fig. 4. Fluorescence response responses (at 544 nm) of probe **HgP1** (10 μM) with/without Hg^{2+} (100 μM) under different pH values in CH_3OH/HEPES (10 mM, 1/1, v/v) solution (λ_{ex} = 390 nm).

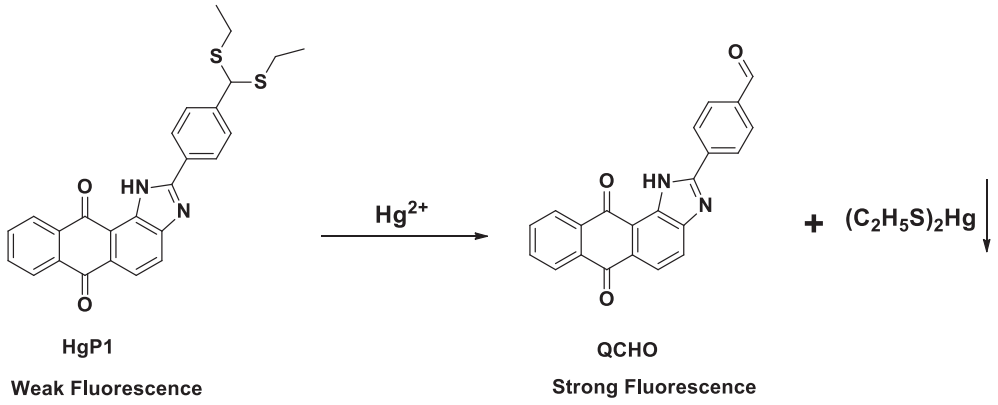
Based on the above experimental results of fluorescence spectra and previous work [34–40], we proposed a receivable mechanism. As shown in Scheme 2, based on the strong thiophilic affinity of Hg^{2+}, Hg^{2+} can react with dithioacetal in the probe structure to release aldehyde group, and then the intramolecular charge transfer (ICT) of the anthraquinone was enhanced, resulting in fluorescence recovery. The high resolution mass spectrometry (HRMS) results of the solution which contains probe **HgP1** and Hg^{2+} showed an obvious peak at m/z = 353.0856, which should be assigned to the species compound **QCHO** (calculated 353.0926) (Fig. S8). The HRMS data further confirmed the above recognition mechanism shown in Scheme 2.

3.3. *Biological imaging application experiment*

In order to further explore the practical application value of probe **HgP1**, we used fluorescence inverted microscope to conduct cell imaging experiment in biological living cells (human esophageal cancer cell, Kyse30) to recognize exogenous Hg^{2+} [41–43]. First, we investigated the cytotoxicity of the probe by MTT assay. MTT results showed that the probe **HgP1** has weak cytotoxicity and could be used in living samples (Fig. 5). Then, the imaging experiment of recognizing exogenous Hg^{2+} by probe **HgP1** in living Kyse30 cells was carried out. As shown in Fig. 6,



Scheme 1. The synthesis route of probe **HgP1**.



Scheme 2. Proposed recognition mechanism.

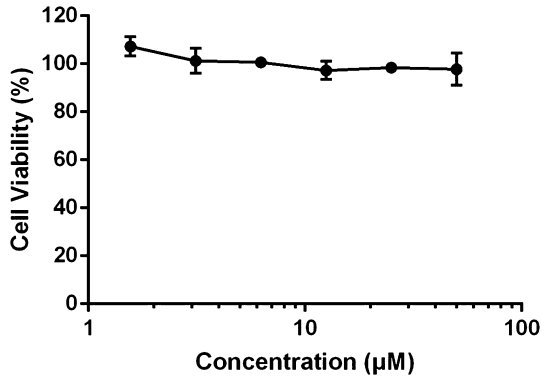


Fig. 5. Viability of living cells treated with various concentrations of **HgP1** (3.0, 6.0, 8.0, 20, 50, 70 μM) measured by MTT assay (24 h). The cell viability data were checked by three independent experiments.

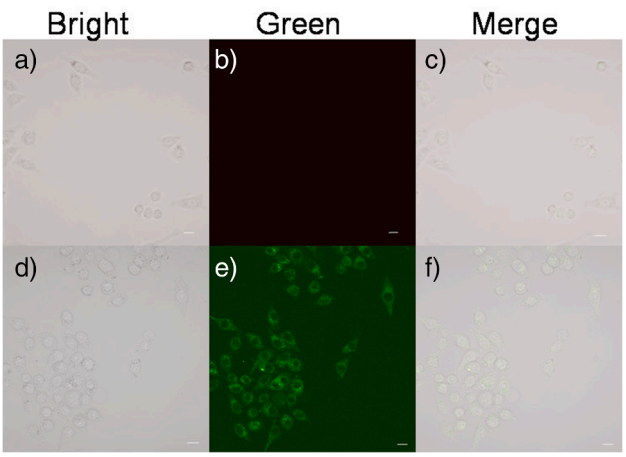


Fig. 6. The fluorescence imaging experiment of recognizing exogenous Hg^{2+} by **HgP1** in living cells. b) The images of **HgP1** (10 μM) under green light in kyse30 cells; e) images of **HgP1** (10 μM) and Hg^{2+} (10 μM) in kyse30 cells under green light; a) and d) are the corresponding images of b) and e) under white light; c) is the merge images of a) and b), f) is the merge images of d) and e). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

the single probe **HgP1** (10 μM) showed almost no fluorescence after being incubated in living cells for 30 min (Fig. 6b). When Hg^{2+} (10 μM) was added and incubated for another 30 min, the cells showed obvious green fluorescence (Fig. 6e). At the same time, the white light test results showed that the cells were in good condition during the above experiments (Fig. 6a and 6d). The results demonstrated that the probe **HgP1** can be used in biological detection of Hg^{2+}.

3.4. Direct detection of Hg^{2+} in real water samples

In order to further investigate the practical application value of probe **HgP1**, probe **HgP1** was applied to detect the content of Hg^{2+} in drinking water and tap water. The standard addition method of different concentrations of Hg^{2+} in drinking water and tap water was carried out. As shown in Table 1, by adding different concentrations of Hg^{2+}, the recovery results and recovery rates are satisfactory. The above experimental results further demonstrate the application value of probe **HgP1** in practical samples.

Table 1
Recovery experiments (n = 4) of target Hg^{2+} in real water samples.

Sample number	Water	Added c/ (μmol·L^{-1})	Found c/ (μmol·L^{-1})	Recovery R/%
1	Tap water	3.6	3.49 ± 0.25	96.9
2	Tap water	4	4.43 ± 0.07	110.7
3	Drinking water	3.6	3.83 ± 0.01	106.3
4	Drinking water	4	4.07 ± 0.06	101.7

4. Conclusions

In conclusion, a new "turn-on" fluorescent probe which contains a dithioacetal group for the detection of Hg^{2+} was constructed by a simple one-step reaction. Based on the strong thiophilic affinity, probe **HgP1** displayed high selectivity and sensitivity to Hg^{2+}. The minimum detection limit of the probe is 8.2 nM. The results of biological imaging experiments showed that the probe can be applied in living cells.

CRediT authorship contribution statement

Zhiwei Ma: Writing - review & editing, Methodology. **Di Zhang:** Writing - review & editing, Data curation, Funding acquisition, Resources. **Jie Guo:** Investigation, Methodology, Formal analysis. **Man Li:** Data curation, Methodology. **Tieliang Wang:** Data curation, Software. **Haiyan Yin:** Software. **Hongqi Wang:** Data curation. **Jihong Liu:** Supervision, Project administration.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

This work was financially supported by the National Natural Science Foundation of China (No. 21907025), Scientific and Technological Project of Henan Province of China (182102310670), Scientific and Technological Innovation Project of Henan Academy of Agricultural Sciences (2020CX05), and the Key Scientific Research Project of Colleges and Universities of Henan Province of China (20A150020).

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.inoche.2021.108753.

References

[1] M.F. Wolfe, S. Schwarzbach, R.A. Sulaiman, Effects of mercury on wildlife: A comprehensive review, Environ. Toxicol. Chem. 17 (1998) 146–160.
[2] E.M. Nolan, J.L. Stephen, Tools and tactics for the optical detection of mercuric ion, Chem. Rev. 108 (2008) 3443–3480.
[3] J. Vas, M. Monestier, Immunology of mercury, Ann. N. Y. Acad. Sci. 1143 (2008) 240–267.
[4] J. Du, M. Hu, J. Fan, X. Peng, Fluorescent chemodosimeters using "mild'' chemical events for the detection of small anions and cations in biological and environmental media, Chem. Soc. Rev. 41 (2012) 4511–4535.
[5] Y. Yang, R. Shen, Y.-Z. Wang, F.-Z. Qiu, Y. Feng, X.-L. Tang, D. Bai, G.-L. Zhang, W.-S. Liu, A selective turn-on fluorescent sensor for Hg (II) in living cells and tissues, Sens. Actuators, B 255 (2018) 3479–3487.
[6] C. Wang, D. Zhang, X. Huang, P. Ding, Z. Wang, Y. Zhao, Y. Ye, A ratiometric fluorescent chemosensor for Hg^{2+} based on FRET and its application in living cells, Sens. Actuators, B 198 (2014) 33–40.
[7] F.M.M. Morel, A.M.L. Kraepiel, M. Amyot, Thechemicalcycle and bioaccumulation of mercury, Annu. Rev. Ecol. Syst. 29 (1998) 543–566.
[8] J. Chen, H. Chen, X. Jin, H. Chen, Determination of ultra-trace amount methyl-, phenyl- and inorganic mercury in environmental and biological samples by liquid chromatography with inductively coupled plasma mass spectrometry after cloud point extraction pre-concentration, Talanta 77 (2009) 1381–1387.
[9] W. Crowe, P.J. Allsopp, G.E. Watson, P.J. Magee, J.J. Strain, D.J. Armstrong, E. Ball, E.M. McSorley, Mercury as an environmental stimulus in the development of autoimmunity-A systematic review, Autoimmun. Rev. 16 (2017) 72–80.
[10] Mercury Update: Impact of Fish Advisories. EPA Fact Sheet EPA-823-F-01-011; EPA, Office of Water: Washington, DC, 2001.
[11] D.T. Quang, J.S. Kim, Fluoro- and chromogenic-chemodosimeters for heavy metal ion detection in solution and biospecimens, Chem. Rev. 110 (2010) 6280–6301.
[12] J.F. Zhang, Y. Zhou, J. Yoon, J.S. Kim, Recent progress on fluorescent and colorimetric chemosensors for detection of precious metal ions (silver, gold and platinum ions), Chem. Soc. Rev. 40 (2011) 3416–3429.
[13] J. Yin, Y. Hu, J. Yoon, Fluorescent probes and bioimaging: alkali metals, alkaline earth metals and pH, Chem. Soc. Rev. 44 (2015) 4619–4644.
[14] P. Ravichandiran, D.S. Prabakaran, N. Maroli, A. Boguszewska-Czubara, M. Masłyk, A.R. Kim, P. Kolandaivel, P. Ramalingam, B.-H. Park, M.-K. Han, T. Ramesh, D.J. Yoo, Mitochondria-targeted dual-channel colorimetric and fluorescence chemosensor for detection of Sn^{2+} ions in aqueous solution based on aggregation-induced emission and its bioimaging applications, J. Hazard. Mater. 415 (2021), 125593.
[15] P. Ravichandiran, V.K. Kaliannagounder, A.P. Bella, A. Boguszewska-Czubara, M. Masłyk, C.S. Kim, C.H. Park, P.M. Johnson, B.-H. Park, M.-K. Han, A.R. Kim, D. J. Yoo, Simple Colorimetric and Fluorescence Chemosensing Probe for Selective Detection of Sn^{2+} Ions in an Aqueous Solution: Evaluation of the Novel Sensing Mechanism and Its Bioimaging Applications, Anal. Chem. 93 (2021) 801–811.
[16] P. Ravichandiran, D.S. Prabakaran, A.P. Bella, A. Boguszewska-Czubara, M. Masłyk, K. Dineshkumar, P.M. Johnson, B.-H. Park, M.-K. Han, H.G. Kim, D. J. Yoo, Naphthoquinone-Dopamine Linked Colorimetric and Fluorescence Chemosensor for Selective Detection of Sn^{2+} Ion in Aqueous Medium and Its Bio-Imaging Applications, ACS Sustainable Chem. Eng. 8 (2020) 10947–10958.
[17] P. Ravichandiran, V.K. Kaliannagounder, N. Maroli, A. Boguszewska-Czubara, M. Masłyk, A.R. Kim, B.-H. Park, M.-K. Han, C.S. Kim, C.H. Park, D.J. Yoo, A dual-channel colorimetric and ratiometric fluorescence chemosensor for detection of Hg^{2+} ion and its bioimaging applications, Spectrochim. Acta Part A Mol. Biomol. Spectrosc. 257 (2021), 119776.
[18] G. Sivaraman, T. Ananda, D. Chellappa, Development of a pyrene based "turn on" fluorescent chemosensor for Hg^{2+}, RSC Adv. 2 (2012) 10605–10609.
[19] G. Sivaraman, M. Iniy, T. Anand, N.G. Kotl, O. Sunnapu, S. Singaravadivel, A. Gulyani, D. Chellappa, Chemically diverse small molecule fluorescent chemosensors for copper ion, Coord. Chem. Rev. 357 (2018) 50–104.
[20] S.A.A. Vandarkuzhali, V. Jeyalakshmi, G. Sivaraman, S. Singaravadivel, K. R. Krishnamurthy, B. Viswanathan, Highly fluorescent carbon dots from Pseudo-stem of banana plant: Applications as nanosensor and bio-imaging agents, Sens. Actuators, B 252 (2017) 894–900.
[21] K.M. Vengaiana, C.D. Brittoa, K. Sekar, G. Sivaraman, S. Singaravadivel, Phenothiazine-diaminomalenonitrile based Colorimetric and Fluorescence "Turn-off-on" Sensing of Hg^{2+} and S^{2-}, Sens. Actuators, B 235 (2016) 232–240.
[22] P. Chinna, J. Ayya Swamy, S. Shanmugapriya, G. Singaravadivel, D. Chellappa Sivaraman, Anthracene-Based Highly Selective and Sensitive Fluorescent "Turn-on" Chemodosimeter for Hg^{2+}, ACS Omega 3 (2018) 12341–12348.
[23] G.G.V. Kumar, R.S. Kannan, T.C.-K. Yang, J. Rajesh, G. Sivaraman, An efficient "Ratiometric" fluorescent chemosensor for the selective detection of Hg^{2+} ions based on phosphonates: its live cell imaging and molecular keypad lock applications, Anal. Methods 11 (2019) 901–916.
[24] P. Sakthivel, K. Sekar, G. Sivaraman, S. Singaravadivel, Rhodamine–benzothiazole conjugate as an efficient multimodal sensor for Hg^{2+} ions and its application to imaging in living cells, New J. Chem. 42 (2018) 11665–11672.
[25] K.M. Vengaian, C.D. Britto, G. Sivaraman, K. Sekar, S. Singaravadivel, Phenothiazine based sensor for naked-eye detection and bioimaging of Hg(ii) and F^- ions, RSC Adv. 5 (2015) 94903–94908.
[26] G.G.V. Kumar, M.P. Kesavan, A. Tamilselvi, G. Rajagopal, J.D. Raja, K. Sakthipandi, J. Rajesh, G. Sivaraman, A reversible fluorescent chemosensor for the rapid detection of Hg^{2+} in an aqueous solution: Its logic gates behavior, Sens. Actuators, B 273 (2018) 305–315.
[27] D. Zhang, M. Li, M. Wang, J. Wang, X. Yang, Y. Ye, Y. Zhao, A rhodamine-phosphonate off-on fluorescent sensor for Hg^{2+} in natural water and its application in live cell imaging, Sens. Actuators, B 177 (2013) 997–1002.
[28] D. Zhang, M. Li, Y. Jiang, C. Wang, Z. Wang, Y. Ye, Y. Zhao, A new sensitive and selective chromogenic and fluorescent chemodosimeter for Hg(II) in aqueous media and its application in live cell imaging, Dyes Pigm. 99 (2013) 607–612.
[29] M. Wang, J. Wen, Z. Qin, H. Wang, A new coumarine-rhodamine FRET system as an efficient ratiometric fluorescent probe for Hg^{2+} in aqueous solution and in living cells, Dyes Pigm. 120 (2015) 208–212.
[30] P. Das, A.K. Mandal, N.B. Chandar, M. Baidya, H.B. Bhatt, B. Ganguly, S.K. Ghosh, A. Das, New Chemodosimetric Reagents as Ratiometric Probes for Cysteine and Homocysteine and Possible Detection in Living Cells and in Blood Plasma, Chem. Eur. J. 18 (2012) 15382–15393.
[31] D. Zhang, M. Wang, M. Chai, X. Chen, Y. Ye, Y. Zhao, Three highly sensitive and selective colorimetric and off–on fluorescent chemosensors for Cu^{2+} in aqueous solution, Sens. Actuators, B 168 (2012) 200–206.
[32] J. Wang, Y. Ni, S. Shao, A reversible fluorescence probe for detection of ClO/AA redox cycle in aqueous solution and in living cells, Talanta 147 (2016) 468–472.
[33] Standardization administration of the People's Republic of China, Hygienic standard for drinking water, GB 5749-2006.
[34] J. Hu, Z. Hu, S. Liu, Q. Zhang, H.-W. Gao, K. Uvdal, A new ratiometric fluorescent chemodosimeter based on an ICT modulation for the detection of Hg^{2+}, Sens. Actuators, B 230 (2016) 639–644.

[35] X. Cheng, S. Li, A. Zhong, J. Qin, Z. Li, New fluorescent probes for mercury(II) with simple structure, Sens. Actuators, B 157 (2011) 57–63.
[36] Y. Zhou, X. He, H. Chen, Y. Wang, S. Xiao, N. Zhang, D. Li, K. Zheng, An ESIPT/ICT modulation based ratiometric fluorescent probe for sensitive and selective sensing Hg^{2+}, Sens. Actuators, B 247 (2017) 626–631.
[37] Y. Gao, T. Ma, Z. Ou, W. Cai, G. Yang, Y. Li, M. Xu, Q. Li, Highly sensitive and selective turn-on fluorescent chemosensors for Hg^{2+} based on thioacetal modified pyrene, Talanta 178 (2018) 663–669.
[38] A.S. Rao, D. Kim, T. Wang, K.H. Kim, S. Hwang, K.H. Ahn, Reaction-Based Two-Photon Probes for Mercury Ions: Fluorescence Imaging with Dual Optical Windows, Org. Lett. 14 (2012) 2598–2601.
[39] D. Xu, L. Tang, M. Tian, P. He, X. Yan, A benzothizole-based fluorescent probe for Hg^{2+} recognition utilizing ESIPT coupled AIE characteristics, Tetrahedron Lett. 58 (2017) 3654–3657.
[40] K. Liu, Z. Xu, M. Yin, W. Yang, B. He, W. Wei, J. Shen, A multifunctional perylenediimide derivative (DTPDI) can be used as a recyclable specific Hg^{2+} ion sensor and an efficient DNA delivery carrier, J. Mater. Chem. B 2 (2014) 2093–2096.
[41] D. Zhang, D. Liu, M. Li, Y. Yang, Y. Wang, H. Yin, J. Liu, B. Jia, X. Wu, A simple pyrene-based fluorescent probe for highly selective detection of formaldehyde and its application in live-cell imaging, Anal. Chim. Acta 1033 (2018) 180–184.
[42] M. Hong, Y. Chen, Y. Zhang, D. Xu, A novel rhodamine-based Hg^{2+} sensor with a simple structure and fine performance, Analyst 144 (2019) 7351–7358.
[43] X. Wen, Z. Fan, A novel 'turn-on' fluorescence probe with aggregation-induced emission for the selective detection and bioimaging of Hg^{2+} in live cells, Sens. Actuators, B 247 (2017) 655–663.