A lysosome-targetable fluorescent probe based on HClO-mediated cyclization reaction for imaging of hypochlorous acid

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Received: 5 September 2021 / Accepted: 27 September 2021
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Abstract
Misplaced or excessive hypochlorous acid in lysosomes has a close association with lots of diseases, so monitoring hypochlorous acid in lysosomes is particularly necessary. In the present work, a novel lysosome-targetable fluorescent probe (Lyso-R-HClO) for hypochlorous acid based on a HClO-mediated cyclization reaction was developed. In the fluorescent probe, the morpholine unit and the site of a HClO-mediated cyclization reaction were, respectively, used as the lysosome-targetable group and the response group. The probe has high selectivity and high sensitivity to hypochlorous acid, with a linear range from $5.0 \times 10^{-8}$ to $3.0 \times 10^{-6}$ M and a detection limit of 15 nM; it was successfully used to image endogenous and exogenous lysosomal HClO. Finally, Lyso-R-HClO was further applied to image lysosomal HClO produced in bacteria-infected macrophage with satisfactory results, which indicate that it is an useful tool for studies of lysosomal HClO and the role of lysosome.

Keywords Fluorescent probe · Hypochlorous acid · Lysosome-targetable · Imaging

Introduction
Hypochloric acid (HClO), which belongs to reactive oxygen species (ROS), plays major roles in the immune system [1, 2]. Acidic lysosomes of phagocytes are the main production sites of hypochlorous acid, where hypochlorous acid is usually produced by the myeloperoxidase (MPO)-catalyzed peroxidation of Cl$^-$ [1, 2]. Misplaced or excessive HClO has a close association with lots of pathological processes, including neurodegeneration diseases [3], arthritis [4], and atherosclerosis [5]. For example, an overdose of hypochloric acid in lysosomes can bring about apoptosis through lysosomal rupture, and further induce chronic disease [3, 6]. However, the functions of HClO in lysosomes are still not completely clear, which makes it difficult to fully understand its functions in the pathways of cell signaling and various diseases. Thus, it is of great significance to real-time monitor HClO in lysosome.

Compared with traditional methods for detection, a fluorescent probe has many advantages, such as high sensitivity and selectivity, real-time imaging, and non-damaging detection, and has also become an important tool for imaging in living systems [7–11]. Moreover, a fluorescent probe has further become a powerful tool for...
subcellular imaging in recent years [12–15]. Up to now, researchers have reported a series of fluorescent probes for HClO based on different mechanisms (Table S1) [16–44], but there are still few probes for the real-time detection of lysosomal hypochlorous acid [32–42], in which there are still some problems. Due to the short-wavelength emission ($\lambda_{em} < 560$ nm, in general), some of them are disturbed by autofluorescence [32–36]. Some of them lack continuous lysosomal anchoring abilities due to the departure of the morpholine group from the probe [37–39]. Some of the above probes belong to “turn off” fluorescent probes [40]. Therefore, developing lysosome-targetable fluorescent probes with excellent performance to further study the biological function of HClO in lysosome is still challenging.

In this paper, a novel lysosome-targetable fluorescent probe (Lyso-R-HClO) for hypochlorous acid based on a HClO-mediated cyclization reaction was developed. In the fluorescent probe, the morpholine unit and the site of a HClO-mediated cyclization reaction were, respectively, employed as a lysosome-targetable group [46], and a response group. The probe has high sensitivity and selectivity to hypochlorous acid (linear range of detection, $5.0 \times 10^{-8}$–$3 \times 10^{-6}$ M; detection limit, 15 nM), and also excellent imaging performances, including low autofluorescence and excellent lysosome-targetable ability, which was successfully used to image endogenous and exogenous lysosomal HClO. Finally, Lyso-R-HClO was further applied to image lysosomal HClO produced in bacteria-infected macrophage with satisfactory results.

**Experimental**

**Chemicals and apparatus**

The chemicals were purchased from Sigma-Aldrich or Energy Chemical. The spectrofluorometer used was an LS55 spectrofluorometer (PerkinElmer). The UV–Vis spectrophotometer used was a TU-1900 UV–Vis spectrophotometer (Beijing Purkinje General Instrument Co., Ltd.). The mass spectrometer used was a Bruker microTOF II mass spectrometer. The instruments used for $^1$H NMR spectra and $^{13}$C NMR spectra were a DRX-400 NMR spectrometer (Bruker) and an Avance III-HD 600 NMR spectrometer (Bruker). Silica gel plates and silica gel for column chromatography were both purchased from Yantai Jiangyou Silica Gel Development Co., Ltd. The pH meter used was a Delta 320 pH meter (Mettler-Toledo). All of the fluorescence images were obtained on an FV1200-MPE confocal microscope (Olympus).

**Synthesis**

Lyso-R-HClO was synthesized following the synthetic route depicted in Scheme 1. For mechanism verification, Compound A was prepared by the reaction of Lyso-R-HClO with NaClO (Scheme 2). Lyso-R-HClO and Compound A were both characterized by MS, $^1$H NMR, and $^{13}$C NMR in the supporting information.

Synthesis of Lyso-R-HClO. A mixed solution of 2.00 mL 3-(4-morpholino) propyl isothiocyanate and 5.00 mL DMF (N,N-dimethylformamide) was added to a solution of rhodamine B hydrazide [24] (456.6 mg, 1.0 mmol) in 10.00 mL DMF, and the reaction mixture was kept stirring

![Scheme 1](image1)

**Scheme 1** Synthesis of Lyso-R-HClO. a N$_2$H$_4$, EtOH, reflux, 4 h. b 3-(4-morpholino) propyl isothiocyanate, DMF, 80 °C, 72 h

![Scheme 2](image2)

**Scheme 2** Mechanism of Lyso-R-HClO response to HClO

[Image of Scheme 2]
continuously for 72 h at 80 °C. Subsequently, we evaporated the reaction solvent under reduced pressure, and purified the residue by column chromatography (CH₂Cl₂:CH₃OH = 15:1) to afford Lyso-R-HClO as a faint yellow solid (255.70 mg, yield: 39.8%). ¹H NMR (400 MHz, CDCl₃) δ 8.00–7.89 (d, J = 8.0 Hz, 1H), 7.65–7.55 (m, 2H), 7.24 (s, 1H), 6.73 (s, 1H), 6.43–6.41 (m, 4H), 6.34–6.26 (m, 3H), 3.60–3.58 (t, J = 4.0 Hz, 4H), 3.37–3.31 (m, 8H), 2.33 (s, 4H), 2.24–2.21 (t, J = 4.0 Hz, 2H), 1.64 (s, 2H), 1.48–1.41 (m, 2H), 1.19–1.15 (t, J = 8.0 Hz, 12H). HRMS (ESI): calcd for [M + H]+ 643.3425, found 643.3431.

Synthesis of Compound A. An original NaClO solution (0.50 mL) was added into a solution of Lyso-R-HClO (64.3 mg, 0.10 mmol) in 20 mL of a DMF/PBS (phosphate buffered saline) solution (V/V = 1:1), and the reaction mixture was stirred continuously for 1 h at room temperature. Subsequently, we evaporated the reaction solvent under reduced pressure, and purified the residue by column chromatography (CH₂Cl₂:CH₃OH = 10: 1) to afford Compound A as an atropurpureus solid (37.5 mg). ¹H NMR (600 MHz, CDCl₃) δ 8.42 (s, 1H), 8.21–8.20 (d, J = 6.0 Hz, 1H), 7.71–7.69 (t, J = 6.0 Hz, 1H), 7.63–7.61 (t, J = 6.0 Hz, 1H), 7.26–7.25 (m, 1H), 7.15–7.13 (d, J = 12.0 Hz, 2H), 6.83–6.81 (m, 2H), 6.75 (m, 2H), 3.81 (s, 4H), 3.62–3.58 (m, 8H), 3.35–3.34 (m, 2H), 2.79 (m, 6H), 2.03 (m, 2H), 1.34–1.31 (m, 12H). ¹³C NMR (150 MHz, CDCl₃) δ 163.75, 158.30, 158.15, 155.98, 155.56, 131.62, 130.55, 129.75, 129.73, 129.60, 128.53, 123.96, 114.11, 96.37, 56.45, 52.81, 46.05, 31.93, 29.70, 22.70, 14.12, 12.65. HRMS (ESI): calcd for [M]⁺ 609.3548, found 609.3527.

Spectra measurements

Spectra measurements were in accordance with procedures described in the supporting information.

Cytotoxicity of Lyso-R-HClO

The cytotoxicities of Lyso-R-HClO were determined by the standard MTT (3-(4,5-dimethylthiazol-2-yl)-2,5-diphenyltetrazolium bromide) assay. Firstly, HeLa cells or Raw 264.7 cells were seeded at 1 × 10⁵ cells per well and grown for 24 h. Subsequently, various concentrations of Lyso-R-HClO (0, 5, 10, 20 and 30 µM) were further added to the wells and incubated for 24 h. Then, we added the MTT solution (20 µL) to each well, and incubated for 4 h at 37 °C. Finally, we removed the medium, and added 100 µL of DMSO (dimethyl sulfoxide) to dissolve the crystals to get a completely dissolved solution; we then recorded the absorbance (570 nm) of the solution.

Cell fluorescence imaging

Imaging of exogenous HClO in cells. HeLa cells were first incubated with Lyso-R-HClO (10.0 µM) for 30 min at 37 °C and washed with Dulbecco’s phosphate buffered saline (DPBS) three times, and then required concentrations of NaClO were added to the cells. After 30 min, the cells were washed with DPBS three times and imaged with excitation at 515 nm and emission between 560 and 630 nm.

Imaging of endogenous HClO in cells. The cell experiment was divided into four groups. The first group was RAW 264.7 macrophage cells being incubated with 10 µM Lyso-R-HClO for 30 min. The cells were then washed by PBS buffer before imaging. In the second group, RAW 264.7 macrophage cells were incubated with 10 µM Lyso-R-HClO for 20 min, washed by PBS buffer and subsequently incubated with lipopolysaccharide (LPS, 1 µg/mL) and phorbol myristate acetate (PMA, 1 µg/mL) for 1 h prior to imaging. In the third and the fourth groups, RAW 264.7 macrophage cells were incubated with 10 µM Lyso-R-HClO for 20 min, washed by PBS buffer and subsequently incubated with LPS (1 µg/mL)/PMA (1 µg/mL) and 4-aminobenzoic acid hydrazide (ABH, 200 µM) or N-acetylcysteine (NAC, 2 mM), respectively, for 1 h prior to imaging.

Lysosomal colocalization imaging. HeLa cells were first incubated with 10.0 µM Lyso-R-HClO and 1.0 µM of LysoSensor™ Green DND-189 (or 1.0 µM of MitoTracker Green FM) for 30 min at 37 °C and washed with Dulbecco’s phosphate buffered saline (DPBS) three times; then, 20 µM of NaClO was added to the cells. After 30 min, the cells were washed with DPBS three times and imaged. For LysoSensor™ Green DND-189, the cells were imaged with excitation at 458 nm and emission between 480 and 525 nm. For MitoTracker Green FM, the cells were imaged with excitation at 488 nm and emission between 510 and 530 nm.

Imaging of HClO in bacteria-infected cells. Escherichia coli (E. coli) were cultured at 37 °C in Luria–Bertani culture media (pH 7.4) and agitated on a shaker water bath at a speed of 150 rpm for 8 h. They were then collected during the middle-exponential phase, washed three times by centrifuging for 10 min at 2000 rpm to separate from the nutrient with PBS and quantified by the absorbance at 600 nm. For bacterial infection of macrophages, RAW 264.7 macrophage cells were first incubated with Lyso-R-HClO (10.0 µM) for 30 min at 37 °C and washed with Dulbecco’s phosphate buffered saline (DPBS) three times; E. coli at a concentration of about 5 × 10⁶ CFU/mL was added to Raw 264.7 cells, followed by culturing for different periods of time. The cells were then imaged with excitation at 515 nm and emission between 560 and 630 nm.
Results and discussion

Analytical performance of Lyso-R-HClO

Firstly, we investigated the analytical performances of Lyso-R-HClO to HClO. With the addition of different concentrations of NaClO, the fluorescence intensity of the probe at 590 nm increased significantly, and reached stability within five minutes (Figs. 1a, 2a). According to the fluorescence spectrum and UV–Vis spectrum (Fig. 1a, b), it can be seen that the fluorescence intensity of the probe (590 nm) and the absorbance intensity of the probe (568 nm) both showed gradual enhancements with the increase of NaClO concentration added. The linear response range of the fluorescence intensity of the probe to NaClO was in the range of $5.0 \times 10^{-8}–3 \times 10^{-6}$ M (Fig. 1c). The detection limit for NaClO was determined to be 15 nM, which was helpful for the probe to detect the low concentrations of hypochlorous acid in cells. By investigating the selectivity of the probe toward NaClO among cations, anions, reactive oxygen species, reactive nitrogen species and other substances (Fig. 1d), Lyso-R-HClO was highly selective for NaClO. Subsequently, we investigated the effect of the pH on the detection performance of the probe. As shown in Fig. 2b, the probes showed a good fluorescence response to NaClO between pH 4 and pH 9, which can meet the detection requirements of hypochlorous acid in a lysosomal acidic environment (pH 4.5–5.5). At the same time, when the pH is greater than 5, the fluorescence response of the probe decreases with the increase of the pH. Since $K_a$ of HClO is 7.46 at 35 °C, when the pH is acidic, NaClO mainly exists in the form of HClO, and when the pH is alkaline, NaClO mainly exists in the...
form of ClO\(^{-}\). The results indicated that the probe senses HClO instead of ClO\(^{-}\).

In addition, the probe was further used to detect HClO in the MPO–H\(_2\)O\(_2\)–Cl\(^{-}\) system (Fig. 3). As shown in the figure, the probe showed an obvious fluorescence enhancement in the system of MPO–H\(_2\)O\(_2\)–Cl\(^{-}\), while there was no obvious fluorescence enhancement in the absence of MPO or H\(_2\)O\(_2\). Also, after adding cysteine (a ROS scavenger) to the system, no significant increase in the fluorescence was observed in the test samples. The above results showed that the probe can be used to detect hypochlorous acid in biological systems.

**The reaction mechanism of Lyso-R-HClO to HClO**

Next, we further investigated the response mechanism of Lyso-R-HClO to HClO (Fig. S1). As shown in Fig. S1b, a new molecular ion peak (m/z = 609.3546) appeared in the mass spectrum of the test sample after adding NaClO, and its value corresponded to Compound A (m/z = 609.3527) (Fig. S1a). Subsequently, we further compared the synthesized Compound A with the test sample solution after adding NaClO by TLC (thin-layer chromatography) (Fig. S1c). The results indicated that the R\(_f\) value of the main compound in the test sample was consistent with that of Compound A.

The above results indicate that Compound A was indeed produced with the addition of NaClO in the probe. Therefore, a response mechanism of HClO-mediated cyclization reaction was proposed in Scheme 2.

**Fluorescence imaging of HClO in lysosome**

Prior to imaging, to assess the biocompatibility of the probe, we firstly investigated the cytotoxicity of Lyso-R-HClO in cells. As shown in Fig. S2, after treatments with different concentrations of Lyso-R-HClO for 24 h, the cell survival rate remained above 87%. Subsequently, Lyso-R-HClO was used for imaging exogenous HClO in lysosome (Fig. S3). As shown in the figure, in the presence of different concentrations of NaClO, the fluorescence of lysosomes in cells increased gradually. Next, Lyso-R-HClO was further used for imaging endogenous HClO in lysosome (Fig. 4). As shown in the figure, the cells incubated with only the probe showed a negligible fluorescence. With the addition of LPS/
PMA, the cells showed a strong fluorescence in lysosome. With the further addition of 4-aminobenzoic acid hydrazide (an inhibitor for MPO) or N-acetylcysteine (a ROS scavenger), the fluorescence intensities in the cells were both obviously suppressed. The above results showed that the probe can image endogenous HClO.

To assess the lysosome-targetable ability of the probe, colocalization experiments were investigated (Fig. 5). As shown in the figure, the red fluorescence from Lyso-NIR-HClO (Fig. 5b) showed a high overlap with the green fluorescence from LysoSensor™ Green DND-189 (Fig. 5a), with a Pearson’s correlation coefficient 0.902 (Fig. 5d). Also, the distribution of the fluorescence intensities in the two channels is highly consistent (Fig. 5e). Moreover, colocalization experiments in mitochondria were also performed with a mitochondrial tracker (Fig. 6f–j). As shown in the figure, the red fluorescence showed a bad overlap with the green fluorescence, with a small Pearson’s correlation coefficient 0.619. These results demonstrated that the probe indeed has an excellent lysosome-targetable ability.

|    | Blank | LPS/PMA | LPS/PMA/ABH | LPS/PMA/NAC |
|----|-------|---------|-------------|-------------|
| a  | ![Blank](image1) | ![LPS/PMA](image2) | ![LPS/PMA/ABH](image3) | ![LPS/PMA/NAC](image4) |
| b  | ![Blank](image1) | ![LPS/PMA](image2) | ![LPS/PMA/ABH](image3) | ![LPS/PMA/NAC](image4) |
| c  | ![Blank](image1) | ![LPS/PMA](image2) | ![LPS/PMA/ABH](image3) | ![LPS/PMA/NAC](image4) |
| d  | ![Blank](image1) | ![LPS/PMA](image2) | ![LPS/PMA/ABH](image3) | ![LPS/PMA/NAC](image4) |

![Relative Intensity](image5)

Fig. 4 Fluorescence images of endogenous HClO in RAW 264.7 cells. a, f Lyso-NIR-HClO (10.0 μM) was incubated with cells for 30 min and washed by a PBS buffer. b, g Cells were preincubated with Lyso-NIR-HClO (10.0 μM), washed by a PBS buffer and stimulated with LPS (1 μg/mL)/PMA (1 μg/mL) and ABH (500 μM) for 1 h. c, h Cells were preincubated with Lyso-NIR-HClO (10.0 μM), washed by PBS buffer and stimulated with LPS (1 μg/mL)/PMA (1 μg/mL) and NAC (3 mM) for 1 h. d, i Cells were preincubated with Lyso-NIR-HClO (10.0 μM), washed by PBS buffer and stimulated with LPS (1 μg/mL)/PMA (1 μg/mL) and NAC (3 mM) for 1 h. e Relative pixel intensities for images (f–i). Scale bar = 20 μM

![Fluorescence Images](image6)

Fig. 5 Lysosome and mitochondria colocalization of Lyso-R-HClO. a–e For lysosome colocalization with LysoSensor™ Green DND-189 (1.0 μM); f–j for mitochondria colocalization with MitoTracker Green FM (1.0 μM). a Fluorescence image of LysoSensor™ Green DND-189; f fluorescence image of MitoTracker Green FM; b, g fluorescence image of Lyso-R-HClO; c, h overlay of a and b and overlay f and g, respectively; d, i intensity correlation plot of region inside the red ellipse; e, j Cross-sectional analysis along the pink line. Scale bar = 10.0 μm
Fluorescence imaging of HClO in bacteria-infected macrophage

To investigate the practical application performance of the probe, Lyso-R-HClO was applied for imaging HClO produced in bacteria-infected macrophage (Fig. 6). As shown in the figure, with the extension of bacterial infection time, the fluorescence intensity of cells incubated with the probe increased gradually (Fig. 6f–h). Also, with the further addition of NAC (a ROS scavenger), the fluorescence intensities in cells were obviously suppressed (Fig. 6i). Moreover, the uninfected cell showed a weak fluorescence intensity at all times (Fig. 6j). The above results indicated that the probe has a certain practical value, and is a powerful tool for monitoring hypochlorous acid in lysosome.

Conclusions

In summary, we developed a novel lysosome-targetable fluorescent probe for lysosomal HClO. The probe has a high sensitivity and selectivity to HClO, and also excellent imaging performances, including low autofluorescence and excellent lysosome-targetable ability, which was successfully applied to image endogenous and exogenous lysosomal HClO. Finally, Lyso-R-HClO was further used to image lysosomal HClO produced in bacteria-infected macrophage with satisfactory results, which indicate that it is a useful tool for studies of lysosomal HClO and the role of lysosome.

Supplementary Information The online version contains supplementary material available at https://doi.org/10.2116/analsci.21P264.

Acknowledgements This work was supported by the key scientific research project of higher education of the Henan province (21A350010, 21A140004), research and practice project of higher education teaching reform in Henan Province (2019SJGLX116), University-Industry Collaborative Education Program from the Ministry of Education of China (202002153003), Natural Science Foundation of Hunan Province (2020J1520), the 2020 International Science and Technology Cooperation Project from Anyang Government/Anyang Key R&D and Promotion Project (No. 2020259), the 2020 Open Foundation of CAS Key Laboratory of Nanodevices and Applications (No: 20YZ08), the 2021 Open Foundation of Key Laboratory of Functional Inorganic Material Chemistry (Heilongjiang University).

References

1. C.C. Winterbourn, M.B. Hampton, J.H. Livesey, A.J. Kettle, J. Biol. Chem. 281, 39860 (2006)
2. J.E. Harrison, J. Schultz, J. Biol. Chem. 251, 1371 (1976)
3. Y.W. Yap, M. Whitman, B.H. Bay, Y. Li, F.S. Sheu, R.Z. Qi, C.H. Tan, N.S. Cheung, J. Neurochem. 98, 1597 (2006)
4. M.J. Steinbeck, L.J. Nesti, P.F. Sharkey, J. Parvizi, J. Orthop. Res. 25, 1128 (2007)
5. D.I. Pattison, M.J. Davies, Biochemistry 45, 8152 (2006)
6. P. Boya, G. Kroemer, Oncogene 27, 6434 (2008)
7. X. Li, X. Gao, W. Shi, H. Ma, Chem. Rev. 114, 590 (2014)
8. W. Sun, S. Guo, C. Hu, J. Fan, X. Peng, Chem. Rev. 116, 7768 (2016)
9. G.-J. Mao, G.-Q. Gao, W.-P. Dong, Q.-Q. Wang, Y.-Y. Wang, Y. Li, L. Su, G. Zhang, Talanta 221, 121607 (2021)
10. X. Yu, L. Xiang, S. Yang, S. Qu, X. Zeng, Y. Zhou, R. Yang, Spectrochim. Acta. Part A 245, 118887 (2021)
11. G.-J. Mao, Z.-Z. Liang, G.-Q. Gao, Y.-Y. Wang, X.-Y. Guo, L. Su, H. Zhang, Q.-J. Ma, G. Zhang, Anal. Chim. Acta 1092, 117 (2019)
12. H. Zhu, J. Fan, D. Du, X. Peng, Acc. Chem. Res. 49, 2115 (2016)
13. H. Zhang, J. Fan, J. Wang, S. Zhang, B. Dou, X. Peng, J. Am. Chem. Soc. 135, 11663 (2013)
14. W. Xu, Z. Zeng, J. Jiang, Y.T. Chang, L. Yuan, Angew. Chem. Int. Ed. 55, 13658 (2016)
15. S. Liu, Y. Zhu, P. Wu, H. Xiong, Anal. Chem. 93, 4975 (2021)
16. Y. Yue, F. Huo, C. Yin, J.O. Escobedo, R.M. Strongin, Analyst 2016, 141 (1859)
17. X. Jiao, Y. Li, J. Niu, X. Xie, X. Wang, B. Tang, Anal. Chem. 90, 533 (2018)
18. X. Chen, F. Wang, J.Y. Hyun, T. Wei, J. Qiang, X. Ren, I. Shin, J. Yoon, Chem. Soc. Rev. 45, 2976 (2016)
19. Y.R. Zhang, Y. Liu, X. Feng, B.X. Zhao, Sens. Actuators B 240, 18 (2017)
20. Z. Zhan, R. Liu, L. Chai, Q. Li, K. Zhang, Y. Lv, Anal. Chem. 89, 9544 (2017)
21. Y. Koide, Y. Urano, K. Hanaoka, T. Terai, T. Nagano, J. Am. Chem. Soc. 133, 5680 (2011)
22. Q. Xu, C.H. Heo, J.A. Kim, H.S. Lee, Y. Hu, D. Kim, K.M.K. Swamy, G. Kim, S.J. Nam, H.M. Kim, J. Yoon, Anal. Chem. 88, 6615 (2016)
23. P. Wei, W. Yuan, F. Xue, W. Zhou, R. Li, D. Zhang, T. Yi, Chem. Sci. 9, 495 (2018)
24. H. Zhu, J. Fan, J. Wang, H. Mu, X. Peng, J. Am. Chem. Soc. 136, 12820 (2014)
25. L. Yuan, W. Lin, Y. Xie, B. Chen, J. Song, Chem. Eur. J. 18, 2700 (2012)
26. J.J. Hu, N.K. Wong, M.Y. Lu, X. Chen, S. Ye, A.Q. Zhao, P. Gao, R.Y.T. Kao, J. Shen, D. Yang, Chem. Sci. 7, 2094 (2016)
27. Y.W. Jun, S. Sarkar, S. Singha, Y.J. Reo, H.R. Kim, J.J. Kim, Y.T. Chang, K.H. Ahn, Chem. Commun. 53, 10800 (2017)
28. L. Yuan, W. Lin, Y. Yang, H. Chen, J. Am. Chem. Soc. 134, 1200 (2012)
29. K. Li, J.T. Hou, J. Yang, X.Q. Yu, Chem. Commun. 53, 5539 (2017)
30. Y. Jiang, G. Zheng, N. Cai, H. Zhang, Y. Tan, M. Huang, Y. He, J. He, H. Sun, Chem. Commun. 53, 12349 (2017)
31. J. Zhou, L. Li, W. Shi, X. Gao, X. Li, H. Ma, Chem. Sci. 6, 4884 (2015)
32. L. Yuan, L. Wang, B.K. Agrawalla, S.J. Park, H. Zhu, B. Sivaraman, J. Peng, Q.H. Xu, Y.T. Chang, J. Am. Chem. Soc. 137, 5930 (2015)
33. B. Zhang, X. Yang, R. Zhang, Y. Liu, X. Ren, M. Xian, Y. Ye, Y. Zhao, Anal. Chem. 89, 10384 (2017)
34. B. Zhu, P. Li, W. Shu, X. Wang, C. Liu, Y. Wang, Z. Wang, Y. Wang, B. Tang, Anal. Chem. 88, 12532 (2016)
35. P. Zhang, H. Wang, D. Zhang, X. Zeng, R. Zeng, L. Xiao, H. Tao, Y. Long, P. Yi, J. Chen, Sens. Actuators B 255, 2223 (2018)
36. C. Liu, X. Jiao, S. He, L. Zhao, X. Zeng, Talanta 174, 234 (2017)
37. M. Ren, B. Deng, K. Zhou, X. Kong, J.Y. Wang, G. Xu, W. Lin, J. Mater. Chem. B 4, 4739 (2016)
38. M. Ren, J. Nie, B. Deng, K. Zhou, J.Y. Wang, W. Lin, New J. Chem. 41, 5259 (2017)
39. X. Jiao, C. Liu, Q. Wang, K. Huang, S. He, L. Zhao, X. Zeng, Anal. Chim. Acta 969, 49 (2017)
40. Y. Wang, L. Wu, C. Liu, B. Guo, B. Zhu, Z. Wang, Q. Duan, Z. Ma, X. Zhang, J. Mater. Chem. B 5, 3377 (2017)
41. G.-J. Mao, Z.-Z. Liang, J. Bi, H. Zhang, H.-M. Meng, L. Su, Y.-J. Gong, S. Feng, G. Zhang, Anal. Chim. Acta 1048, 143 (2019)
42. P. Wu, Y. Zhu, L. Chen, Y. Tian, H. Xiong, Anal. Chem. (2021). https://doi.org/10.1021/acs.analchem.1c02831
43. W.-J. Shi, L.-X. Feng, X. Wang, Y. Huang, Y.-F. Wei, Y.-Y. Huang, H.-J. Ma, W. Wang, M. Xiang, L. Gao, Talanta 233, 122581 (2021)
44. W.-J. Shi, Y. Huang, W. Liu, D. Xu, S.-T. Chen, F. Liu, J. Hu, L. Zheng, K. Chen, Dyes Pigments 170, 107566 (2019)
45. H. Yu, Y. Xiao, L. Jin, J. Am. Chem. Soc. 134, 17486 (2012)
46. L. Wang, Y. Xiao, W. Tian, L. Deng, J. Am. Chem. Soc. 135, 2903 (2013)