ANALYTICAL SCIENCES OCTOBER 2015, VOL. 31



# Label-free Detection of $Zn^{2+}$ Based on G-quadruplex

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Herein, we developed a sensing strategy for the label-free detection of $Zn^{2+}$ based on G-quadruplex. In the absence of $Zn^{2+}$, there was a fluorescence enhancement of thioflavin T by interaction with human telomere sequence. On the addition of $Zn^{2+}$, $Zn^{2+}$ induced a more compact G-quadruplex structure to release thioflavin T, resulting in a fluorescence decrease. This simple "mix-then-detect" method gave the detection limit of 0.91 μM with linear dynamic ranges from 0 to 10 μM. Because it does not require the use of expensive and unstable DNAzyme systems, or need synthesis and modification of nanomaterials, this label-free biosensor is simple, fast, cost-effective and applicable for real samples taken from lake water.

**Keywords** G-quadruplex, thioflavin T, $Zn^{2+}$ detection, label-free

**(Received May 7, 2015; Accepted June 19, 2015; Published October 10, 2015)**

## Introduction

Zinc ion plays a vital role in biological systems,[1] with the multiple $Zn^{2+}$-bound proteins acting as regulators of enzymes and transcription-related factors. Zinc homeostasis is required for normal functioning of the immune system, insulin secretion/action, and anti-oxidant systems.[2] Free $Zn^{2+}$ is also a neurotransmitter and neuromodulator in the central nervous system. Diseases such as Alzheimer's, Parkinson's and stroke are associated with abnormal levels of zinc.[3] At the same time, large amounts of $Zn^{2+}$ in the environment have been found to be a threat to fish, cattle and plant species. Therefore, it is environmentally important to minimize $Zn^{2+}$ contamination arising from its widespread usage in industry.[4,5]

Various efficient and reproducible methods, such as atomic absorption spectrometry,[6,7] inductively coupled plasma mass spectroscopy,[8,9] and inductively coupled plasma-atomic emission spectrometry (ICP-AES),[10,11] have been developed for the detection of $Zn^{2+}$. However, these methods are usually complicated, time-consuming, and costly. In recent decades, $Zn^{2+}$ chemical sensors based on luminescence have been developed and applied to $Zn^{2+}$ monitoring in various biological systems.[12,13] However, they suffer from drawbacks including complicated organic synthesis of the sensing platform on these sensors, harmful systems, insufficient selectivity and short excitation wavelength.[14]

The application of functional nucleic acids has recently facilitated development of detection methods that do not require expensive instruments. Various DNA constructs stimulated by different external signals, G-quadruplex/i-motif formation, binding of aptamer-target or activation of deoxyribozymes, *etc.*, have been used for sensing in analytical chemistry and biomedicine.[15-20]

Guanine-quadruplexes (denoted hereafter as G4s) are unique structures formed by G-rich nucleic acid sequences and based on stacked arrays of G-quartets connected by Hoogsteen-type base pairing.[21-24] G4s not only play vital roles in cancer research, but are also regarded as robust tools in analytical chemistry and biomedicine.[25-28] A number of sensors have been developed based on G4s for the detection of metal ions, such as $K^+$,[29,30] $Pb^{2+}$,[31,32] $Ca^{2+}$,[33] $Cu^{2+}$,[34] $Hg^{2+}$,[35-37] $Ag^+$,[38-41] $Sr^{2+}$.[42] Herein, we first developed a label-free detecting strategy for the assay of $Zn^{2+}$ based on G4s; $Zn^{2+}$ can induce the structural transition of the human telomere sequence $AG_3(T_2AG_3)_3$ (denoted hereafter as H22) from a random coil to an antiparallel G4 structure.[43] It was reported that thioflavin T (denoted hereafter as ThT), a benzothiazole fluorogenic dye, could exhibit striking fluorescence enhancement when binding to the human telomeric G-quadruplex structure.[44] So ThT was employed as the label-free fluorescent indicator in the sensoring system. The presented sensoring system consists of G-rich oligomer H22 and G4-binding dye ThT, which eliminates the need for complex and expensive synthesis procedure and also for nanomaterial fabrication.

## Experimental

*Reagents and chemicals*

Oligonucleotides were obtained from Sangon Biotechnology Co., Ltd. (Shanghai, China). Sequences of the oligonucleotides are listed in Table S1 (Supporting Information). The stock solution of DNA samples was prepared in ultrapure water, and

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the DNA concentration was accurately quantified based on UV absorbance measurement at 260 nm. ThT was purchased from Sigma-Aldrich. All other chemical reagents were purchased from Sinopharm Chemical Reagent Co., Ltd. (China). All solutions were prepared with water purified by a Milli-Q system (Millipore, Bedford, MA) and stored at 4°C. Measurements were performed in 50 mM Tris–HCl buffer (pH 8.0), unless stated otherwise.

*Apparatus*

The absorption of DNA solution at 260 nm was recorded on an Eppendorf biophotometer (Eppendorf AG 22331 Humburg, Germany). A fluorescence spectrometer (F-4600, Hitachi Co., Ltd., Japan) with a Xenon lamp excitation source was employed to record fluorescence spectra. In these experiments, a 10 nm slit width for excitation and a 10 nm slit width for emission were used. The accurate concentrations of $Zn^{2+}$ in real samples were determined by ICP-AES (PerkinElmer, Optima 8000), using the most recommended wavelength (213.856 nm).

*Fluorescence measurements*

In all $Zn^{2+}$ detection experiments, an appropriate aliquot of 0.1 M $Zn(NO_3)_2$ standard solution was added to the reaction solution containing 1 μM H22 before this was incubated for 10 min; 10 μL ThT (25 μM) was added to the reaction solution for a final concentration of 2.5 μM. Fluorescence spectra were recorded after the reaction solution was incubated for another 10 min. By applying an excitation wavelength of 425 nm, the solution fluorescence was monitored from 450 to 560 nm. Inorganic metal salts including $Li_2CO_3$, NaCl, KCl, $Mg(NO_3)_2{\cdot}6H_2O$, $CaCl_2$, $Mn(NO_3)_2{\cdot}4H_2O$, $FeSO_4$, $Co(NO_3)_2{\cdot}6H_2O$, $CuSO_4{\cdot}5H_2O$, $Pb(NO_3)_2$, $AlCl_3$ and $Fe(NO_3)_3{\cdot}9H_2O$ were used for evaluating the selectivity of the sensoring system towards $Zn^{2+}$.

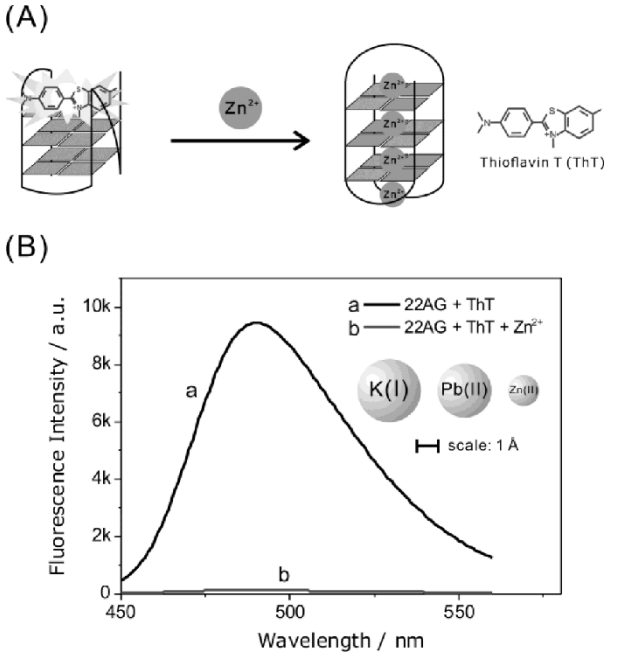
Lake water samples were collected from Dushu Lake in Suzhou, and were filtered by 0.45 μm membrane before assay, then the concentration of $Zn^{2+}$ in the lake water samples was determined by performing a standard addition calibration method. Different concentrations of $Zn^{2+}$ standard solution (0, 1.0, 4.0, 7.0, and 10 μM) were spiked in the filtered samples, then the samples were added to the detecting system respectively and the data were collected according to the same procedure mentioned above.

## Results and Discussion

*Principle of operation*

ThT is a commercially available fluorescent dye and has shown pronounced structural preference to G4s other than single-stranded DNAs, duplexes or triplexes. The binding to most G4s could bring out greatly enhanced emission in the fluorescence intensity of ThT.[45] Recently, by the merit of its excellent property, ThT has been employed as G4s fluorescent indicator for the label-free detection of $Tb^{3+}$,[46] $K^+$,[47] $Hg^{2+}$,[48] biothiols,[49] cancer gene[50] and protein.[51] As shown in Scheme 1a, the biosensor consists of a G-rich DNA H22 and fluorescence dye ThT. The fluorescence spectra were recorded in the absence and presence of $Zn^{2+}$, respectively. As shown in Scheme 1(B), in the absence of $Zn^{2+}$, there was a fluorescent enhancement of ThT owing to binding to the H22 G-quadruplex structure; after adding 50 μM $Zn^{2+}$, a sharp decrease in the fluorescence intensity was observed.

Circular dichroism (denoted hereafter as CD) spectroscopy is widely employed for the study of G4s polymorphism since it is sensitive to the conformational changes of G4s.[52,53] CD measurement was conducted to investigate the principle of the decrease. As shown in Fig. 1, in the 50 mM Tris–HCl buffer without ThT and $Zn^{2+}$, H22 itself folded into a parallel structure having a characteristic CD peak at 260 nm. Upon the addition of ThT, H22 transformed into a mixture of parallel (CD peak at 260 nm) and antiparallel (CD peak at 295 nm) quadruplexes.[54,55] Then a clear structural change was observed after the addition of $Zn^{2+}$, the resulting complex presented a positive peak near 290 nm and negative peak near 265 nm, which declared an antiparallel G4 structure and was accordant to the $Zn^{2+}$-mediated H22 G-quadruplex (dotted line in Fig. 1).[43] The results of CD measurement showed a clear explanation that the fluorescence decrease in Scheme 1(B) was caused by the structural change of




Scheme 1 (A) Depiction of the label-free biosensor for the detection of $Zn^{2+}$ based on G-quadruplex. (B) Fluorescence spectra of ThT with H22 in the absence and presence of $Zn^{2+}$, respectively; ThT: 2.5 μM, H22: 1.0 μM, $Zn^{2+}$: 50 μM. Inset: Relative ionic radius of $K^+$, $Pb^{2+}$ and $Zn^{2+}$ with a 1 Å scale bar.

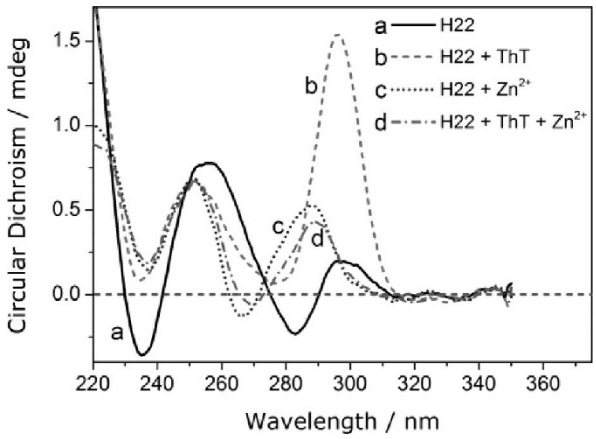



Fig. 1 CD spectra of H22 (3 μM) in the absence and presence of ThT (7.5 μM), $Zn^{2+}$ (90 μM) and ThT/$Zn^{2+}$, respectively.

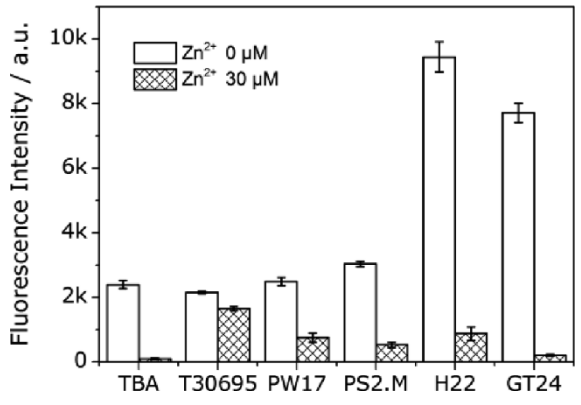



Fig. 2 Fluorescence intensity changes of ThT (2.5 μM) with different G-quadruplex sequences (1.0 μM) after adding 30 μM $Zn^{2+}$.

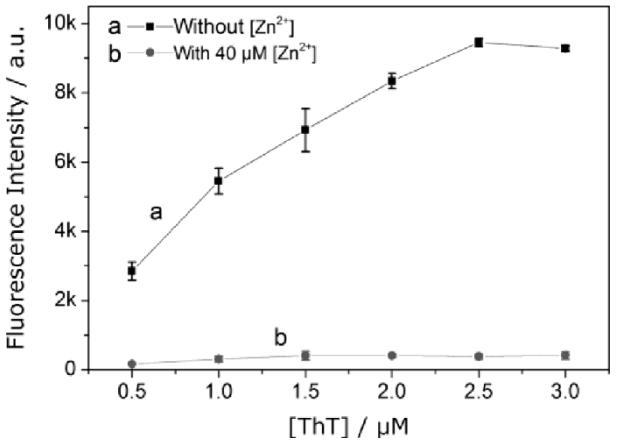



Fig. 3 Effect of ThT concentration on the detection of $Zn^{2+}$ in the presence of 1.0 μM H22.

the G-quadruplex triggered by $Zn^{2+}$. We speculated that the decrease might be the result of ThT released from the $Zn^{2+}$-stabilized G4. Since the ionic radius of $Zn^{2+}$ ($r$ = 0.74 Å) is much smaller than $Pb^{2+}$ ($r$ = 1.29 Å) and $K^+$ ($r$ = 1.51 Å) (inset in Scheme 1(B)),[56] G4s mediated by a smaller ion have been demonstrated to show more compact structures and are unfavorable for the binding to the G4 specific dyes.[57,58]

Besides H22, five most-reported G4 sequences (Table S1, Supporting Information) were also employed to further validate the principle of the $Zn^{2+}$-induced fluorescence decrease. As shown in Fig. 2, the addition of $Zn^{2+}$ into G4-ThT systems all resulted in a fluorescence decrease, providing evidence for our aforementioned speculation. On the other hand, ionic radius is not the definitive element for the binding to dye. The binding also quite depends on the sequences of oligonucleotides, for example, a kind of iridium(III) complex preferentially bound to a G4 (sequence: 5′-G4T4G4-3′) structure mediated by $Ca^{2+}$ rather than $Pb^{2+}$, though $Ca^{2+}$ has a smaller ionic radius than $Pb^{2+}$;[33] and crystal violet preferred a G4 (sequence: T30695) structure mediated by $Pb^{2+}$ rather than $K^+$.[31] The data collected from five other G4 sequences could not provide sufficient evidence for our speculations, but the fastidiousness of the $Zn^{2+}$-mediated compact G4 structure to ThT binding was most likely responsible for the decrease in fluorescence intensity based on the present data.

Another G4s-binding dye berberine (Fig. S1, Supporting Information, denoted hereafter as BBR) was employed to prove our speculation. BBR is known to interact with DNA and to have an effect on telomerase activity,[59,60] and it could cause a fluorescence increase of BBR when binding to G4s.[61,62] Then the fluorescence intensities of the H22-BBR complex were collected in the presence of increasing concentrations of $Zn^{2+}$. As shown in Fig. S2a (Supporting Information), there were corresponding decreases when the H22-BBR complex was challenged with increasing concentrations of $Zn^{2+}$. Besides H22, the other five G-rich sequences were also employed to verify the principle of the turn-off detection for $Zn^{2+}$ based on G4s. As shown in Fig. S2b (Supporting Information), the addition of $Zn^{2+}$ to the G4s-BBR systems all caused decreases of fluorescence intensities. All the collected data seemed directed towards the same explanation, but more investigations are needed since research about the $Zn^{2+}$-G4 structure is rare.

*Selection of optimal ThT concentration*

The fluorescence intensity was first studied as a function of ThT concentration on the assay. Different concentrations of ThT were mixed with H22 in the presence of 40 μM $Zn^{2+}$, then these mixtures were allowed to react for 30 min at room temperature, and finally the fluorescence intensity at 490 nm was measured. The blank sample was treated in the same way without $Zn^{2+}$. As shown in Fig. 3, the changes of ThT fluorescence intensity increased with increasing concentration of ThT in the range from 0.5 to 2.5 μM, and then leveled off from 2.5 to 3.0 μM. Therefore, 2.5 μM of ThT was used in this assay.

*The linear correlation and the detection limit*

As shown in Fig. 4, based on aforementioned results, we developed a label-free biosensor for $Zn^{2+}$ detection by employing a G4 sequence H22 and a G4-binding light-up dye ThT. The binding to H22 initially brought out increased fluorescence of ThT, after introducing $Zn^{2+}$, H22 transformed to a compact G4, which resulted in a fluorescence decrease of ThT. The relationship between fluorescence intensities of ThT and concentrations of $Zn^{2+}$ was firstly studied, a series of spectra of the solutions with increasing concentrations of $Zn^{2+}$ were recorded (Fig. 4(A)). Upon treatment with increasing concentrations of $Zn^{2+}$, the fluorescence intensities of ThT gradually decreased. The fluorescence intensities were dependent linearly on the concentrations of $Zn^{2+}$ over a range of 0 to 10 μM (Fig. 4(B)), and the detection limit for $Zn^{2+}$ was estimated to be 0.91 μM based on the following formula: $C_m = 3*S_b/m$, where $C_m$ is the detection limit, $S_b$ is the standard deviation from the blank samples in the absence of $Zn^{2+}$ and m is the slope of linear relationship ($Zn^{2+}$ concentration *vs.* fluorescence intensity).

*Selectivity*

Figure 5 displays the fluorescence intensities observed upon addition of different metal ions. As shown, compared with other ions a significant fluorescence decrease was observed upon the addition of $Zn^{2+}$. These results indicated that this label-free biosensor could also provide the capability to differentiate $Zn^{2+}$ from many metal ions, demonstrating the good selectivity of this biosensor. This high specificity might be due to the more compact G4 fold mediated by $Zn^{2+}$ and its weak binding with ThT.

*Real sample analysis*

The meaningful determination of $Zn^{2+}$ by the biosensor was

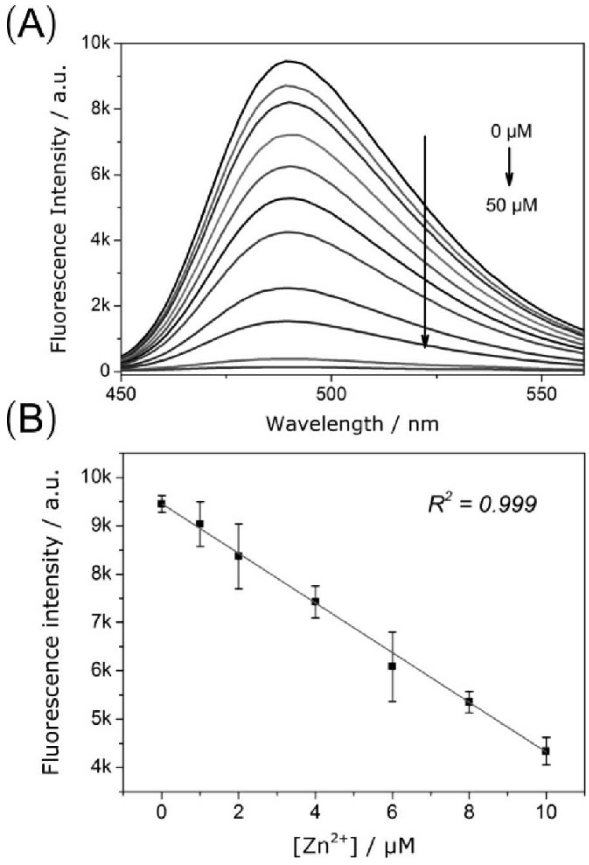



Fig. 4 (A) Fluorescence spectra corresponding to the analysis of increasing concentrations of $Zn^{2+}$ (0, 1.0, 2.0, 4.0, 6.0, 8.0, 10, 20, 30, 40, and 50 μM). (B) Linear relationship in concentration range from 0 to 10 μM (0, 1.0, 2.0, 4.0, 6.0, 8.0, and 10 μM).

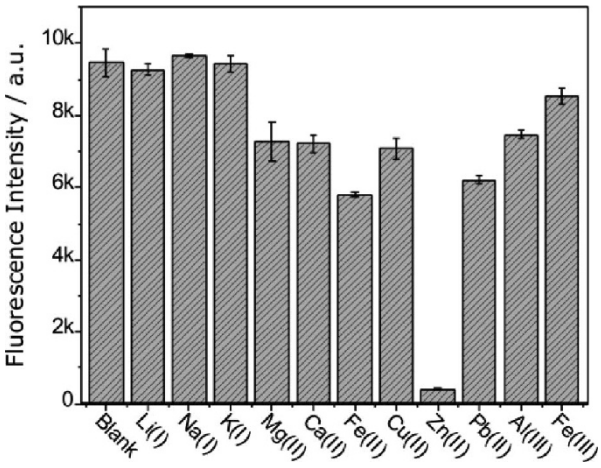



Fig. 5 Selectivity of the biosensor (1.0 μM H22 and 2.5 μM ThT) towards $Zn^{2+}$, metal ions all 40 μM.

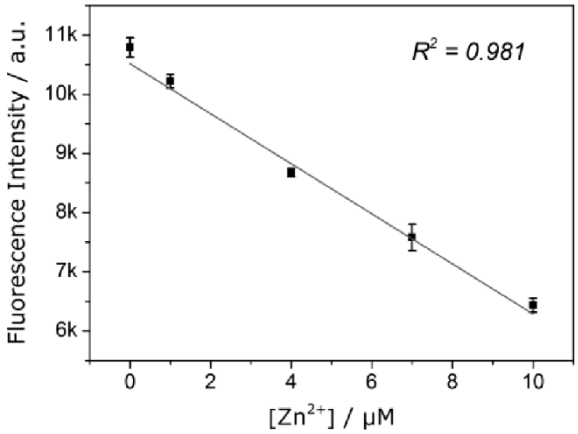



Fig. 6 A linear plot of spiking concentrations of $Zn^{2+}$ (0, 1.0, 4.0, 7.0, and 10 μM) in lake water samples.

conducted with a standard addition method in serum and lake water samples, which aimed at investigating the detecting ability of the biosensor in complex matrixes. The testing results showed that the biosensor was applicable to the analysis of lake water samples, but could not determine the concentration of $Zn^{2+}$ in a serum sample without pre-treatment (data not shown). Serum introduced a complex matrix to our system, which might have prevented the interaction between H22, ThT and $Zn^{2+}$. The results shown in Fig. 6 were obtained by firstly filtering the lake water sample and then diluting by 10-fold. The quantity of $Zn^{2+}$ in the lake water sample was estimated by an external standard method. There was good linear correlation between fluorescence intensities and the spiked $Zn^{2+}$ concentrations. The detection result (2.4 μM) of the lake water sample was in accordance with the data determined by ICP-AES. The result suggested that the proposed method has potential for real sample analysis.

## Conclusions

In this work, we first demonstrated a label-free strategy for the detection of $Zn^{2+}$ based on $Zn^{2+}$-stabilized compact G4s, and developed a fluorescent biosensor by employing a G4s-binding light-up dye ThT. The biosensor had high sensitivity and good linearity for the quantitative analysis of $Zn^{2+}$, and could be applied for real samples from lake water without complicated pre-treatment. Most importantly, no sophisticated experimental techniques or any chemical modification of DNA were required, which offered the advantages of cost efficiency. It was simple in design, fast in operation and possessed high sensitivity and selectivity.

## Acknowledgements

This work was financially supported by the National Natural Science Foundation of China (Nos. 31300096 and 21275156) and Natural Science Foundation of Jiangsu Province (No. BK20130357).

## Supporting Information

Response of the G4s-berberine system towards $Zn^{2+}$. This material is available free of charge on the Web at http://www.jsac.or.jp/analsci/.

## References

1. P. J. Jiang and Z. J. Guo, *Coord. Chem. Rev.*, **2004**, *248*,

205.
2. P. Jothimuthu, R. A. Wilson, J. Herren, X. Pei, W. Kang, R. Daniels, H. Wong, F. Beyette, W. R. Heineman, and I. Papautsky, *Electroanalysis*, **2013**, *25*, 1.
3. E. P. Huang, *Proc. Natl. Acad. Sci. U. S. A.*, **1997**, *94*, 13386.
4. A. Giardina, S. E. Larson, B. Wisner, J. Wheeler, and M. Chao, *Environ. Toxicol. Chem.*, **2009**, *28*, 287.
5. M. S. Rahman, N. Saha, A. H. Molla, and S. M. Al-Reza, *Soil Sediment Contam.*, **2014**, *23*, 353.
6. S. P. Mcgrath and C. H. Cunliffe, *J. Sci. Food Agric.*, **1985**, *36*, 794.
7. T. M. Zhang, B. Yuan, Y. Z. Liang, J. Cao, C. X. Pan, B. Ying, and D. Y. Lu, *Anal. Sci.*, **2007**, *23*, 581.
8. B. Jackson, S. Harper, L. Smith, and J. Flinn, *Anal. Bioanal. Chem.*, **2006**, *384*, 951.
9. L. Dou and W. Xu, *Chin. J. Lung Cancer*, **2010**, *13*, 817.
10. F. Bianchi, M. Maffini, A. Mangia, E. Marengo, and C. Mucchino, *J. Pharm. Biomed. Anal.*, **2007**, *43*, 659.
11. L. Y. Zhou, G. S. Xin, and X. Y. Pu, *Guang pu*, **2012**, *32*, 1103.
12. E. Tamanini, A. Katewa, L. M. Sedger, M. H. Todd, and M. Watkinson, *Inorg. Chem.*, **2009**, *48*, 319.
13. E. M. Nolan and S. J. Lippard, *Acc. Chem. Res.*, **2009**, *42*, 193.
14. Z. C. Xu, J. Yoon, and D. R. Spring, *Chem. Soc. Rev.*, **2010**, *39*, 1996.
15. J. Liu, Z. Cao, and Y. Lu, *Chem. Rev.*, **2009**, *109*, 1948.
16. D. Li, S. Song, and C. Fan, *Acc. Chem. Res.*, **2010**, *43*, 631.
17. J. Zhang, B. Liu, H. Liu, X. Zhang, and W. Tan, *Nanomedicine*, **2013**, *8*, 983.
18. Y. Du, B. Li, and E. Wang, *Acc. Chem. Res.*, **2013**, *46*, 203.
19. J. Liu and Y. Lu, *J. Am. Chem. Soc.*, **2002**, *124*, 15208.
20. Z. Li, M. Liu, L. Fan, H. Ke, C. Luo, and G. Zhao, *Biosens. Bioelectron.*, **2014**, *52*, 293.
21. D. Sen and W. Gilbert, *Nature*, **1988**, *334*, 364.
22. Y. Guo, P. Xu, H. Hu, X. Zhou, and J. Hu, *Talanta*, **2013**, *114*, 138.
23. Y. Guo, J. Cheng, J. Wang, X. Zhou, J. Hu, and R. Pei, *Chem. Asian. J.*, **2014**, *9*, 2397.
24. Y. Guo, L. Zhou, L. Xu, X. Zhou, J. Hu, and R. Pei, *Sci. Rep.*, **2014**, *4*, 7315.
25. H. Z. He, D. S. Chan, C. H. Leung, and D. L. Ma, *Nucleic Acids Res.*, **2013**, *41*, 4345.
26. D. L. Ma, H. Z. He, D. S. H. Chan, and C. H. Leung, *Chem. Sci.*, **2013**, *4*, 3366.
27. B. R. Vummidi, J. Alzeer, and N. W. Luedtke, *ChemBioChem*, **2013**, *14*, 540.
28. E. Largy, A. Granzhan, F. Hamon, D. Verga, and M. P. Teulade-Fichou, *Top. Curr. Chem.*, **2013**, *330*, 111.
29. D. M. Kong, Y. E. Ma, J. H. Guo, W. Yang, and H. X. Shen, *Anal. Chem.*, **2009**, *81*, 2678.
30. H. X. Qin, J. T. Ren, J. H. Wang, N. W. Luedtke, and E. K. Wang, *Anal. Chem.*, **2010**, *82*, 8356.
31. F. Li, Y. Feng, C. Zhao, and B. Tang, *Chem. Commun.*, **2011**, *47*, 11909.
32. S. Liu, W. Na, S. Pang, and X. Su, *Biosens. Bioelectron.*, **2014**, *58*, 17.
33. H. Z. He, M. Wang, D. S. Chan, C. H. Leung, X. Lin, J. M. Lin, and D. L. Ma, *Methods*, **2013**, *64*, 212.
34. L. B. Zhang, J. B. Zhu, J. Ai, Z. X. Zhou, X. F. Jia, and E. K. Wang, *Biosens. Bioelectron.*, **2013**, *39*, 268.
35. T. Li, S. J. Dong, and E. Wang, *Anal. Chem.*, **2009**, *81*, 2144.
36. L. L. Tong, L. Li, Z. Z. Chen, Q. Wang, and B. Tang, *Biosens. Bioelectron.*, **2013**, *49*, 420.
37. S. Lin, B. He, D. S. Chan, P. W. H. Chan, C.-H. Leung, and D.-L. Ma, *RSC Adv.*, **2014**, *4*, 54826.
38. T. Li, L. Shi, E. Wang, and S. Dong, *Chemistry*, **2009**, *15*, 3347.
39. B. Y. Man, D. S. Chan, H. Yang, S. W. Ang, F. Yang, S. C. Yan, C. M. Ho, P. Wu, C. M. Che, C. H. Leung, and D. L. Ma, *Chem. Commun.*, **2010**, *46*, 8534.
40. X. H. Zhou, D. M. Kong, and H. X. Shen, *Anal. Chem.*, **2010**, *82*, 789.
41. M. Wang, K. H. Leung, S. Lin, D. S. H. Chan, C. H. Leung, and D. L. Ma, *J. Mater. Chem. B*, **2014**, *2*, 6467.
42. K. H. Leung, V. P. Y. Ma, H. Z. He, D. S. H. Chan, H. Yang, C. H. Leung, and D. L. Ma, *RSC Adv.*, **2012**, *2*, 8273.
43. C. Wei, Q. Tang, and C. Li, *Biophys. Chem.*, **2008**, *132*, 110.
44. J. Mohanty, N. Barooah, V. Dhamodharan, S. Harikrishna, P. I. Pradeepkumar, and A. C. Bhasikuttan, *J. Am. Chem. Soc.*, **2013**, *135*, 367.
45. A. R. de la Faverie, A. Guedin, A. Bedrat, L. A. Yatsunyk, and J. L. Mergny, *Nucleic Acids Res.*, **2014**, *42*.
46. Q. Chen, J. Zuo, J. Chen, P. Tong, X. Mo, L. Zhang, and J. Li, *Biosens. Bioelectron.*, **2015**, *72*, 326.
47. L. L. Liu, Y. Shao, J. Peng, C. B. Huang, H. Liu, and L. H. Zhang, *Anal. Chem.*, **2014**, *86*, 1622.
48. J. Ge, X. P. Li, J. H. Jiang, and R. Q. Yu, *Talanta*, **2014**, *122*, 85.
49. L. L. Tong, L. Li, Z. Chen, Q. Wang, and B. Tang, *Biosens. Bioelectron.*, **2013**, *49*, 420.
50. X. H. Li, L. J. Gan, Q. S. Ou, X. Zhang, S. X. Cai, D. Z. Wu, M. Chen, Y. K. Xia, J. H. Chen, and B. Yang, *Biosens. Bioelectron.*, **2015**, *66*, 399.
51. X. H. Tan, Y. Wang, B. A. Armitage, and M. P. Bruchez, *Anal. Chem.*, **2014**, *86*, 10864.
52. J. Kypr, I. Kejnovska, D. Renciuk, and M. Vorlickova, *Nucleic Acids Res.*, **2009**, *37*, 1713.
53. D. M. Gray, J. D. Wen, C. W. Gray, R. Repges, C. Repges, G. Raabe, and J. Fleischhauer, *Chirality*, **2008**, *20*, 431.
54. G. Gottarelli, P. Palmieri, and G. P. Spada, *Gazz. Chim. Ital.*, **1990**, *120*, 101.
55. J. D. Wen and D. M. Gray, *Biochemistry*, **2002**, *41*, 11438.
56. R. D. Shannon, *Acta Crystallogr., Sect. A*, **1976**, *32*, 751.
57. F. W. Kotch, J. C. Fettinger, and J. T. Davis, *Org. Lett.*, **2000**, *2*, 3277.
58. X. Y. Wang, Q. Xi, L. Peng, J. Ge, Y. Y. Kan, J. H. Jiang, G. L. Shen, and R. Q. Yu, *Anal. Methods*, **2013**, *5*, 5597.
59. H. L. Wu, C. Y. Hsu, W. H. Liu, and B. Y. Yung, *Int. J. Cancer*, **1999**, *81*, 923.
60. K. C. Gornall, S. Samosorn, B. Tanwirat, A. Suksamrarn, J. B. Bremner, M. J. Kelso, and J. L. Beck, *Chem. Commun.*, **2010**, *46*, 6602.
61. C. Bazzicalupi, M. Ferraroni, A. R. Bilia, F. Scheggi, and P. Gratteri, *Nucleic Acids Res.*, **2013**, *41*, 632.
62. Y. Wei, Y. Chen, H. Li, S. Shuang, C. Dong, and G. Wang, *Biosens. Bioelectron.*, **2015**, *63*, 311.