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Novel fluorescent probe bearing triarylimidazole and pyridine moieties for the rapid and naked-eye recognition of Cu^{2+}

Shuzhi Liu, Yijiang Liu *, Hua Pan, Hongbiao Chen, Huaming Li *

College of Chemistry, Xiangtan University, Xiangtan 411105, Hunan Province, China

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ABSTRACT

A new fluorescent probe (TPIP) bearing triarylimidazole and pyridine moieties was synthesized and applied to the detection of Cu^{2+} with high sensitivity and selectivity. Upon the addition of Cu^{2+}, the probe displayed an apparent dual-channel signal change of the UV–Vis absorption and fluorescence spectra, and the obvious color change from bright blue to colorless under a UV lamp was discernable to the naked eye. The sensing mechanism of the probe towards Cu^{2+} was verified to be *via* complexation, and the binding reaction was rapidly complete within 30 s. Good linearity was observed between the probe and Cu^{2+}, and the detection limit was calculated to be 1.96×10^{-8} M. The reversibility of the probe was easily achieved by adding EDTA, which released the free probe with over 95% fluorescence recovery. Furthermore, the recognition of Cu^{2+} on TLC plates was realized, indicating the potential utility of the probe.

Introduction

The design and synthesis of small molecule fluorescent probes for the detection of various metal ions has attracted considerable attention in the fields of chemical, biological and environmental analysis.[1–3] Among metal ions, the recognition of Cu^{2+} has received considerable interest in the past decades due to its crucial psychological function in the human body.[4–6] As the third most important trace element (besides Fe^{2+} and Zn^{2+}), Cu^{2+} participates in the catalytic reactions of a variety of metalloenzymes, which are involved in the processes of cell respiration, electron transfer and oxidation, neurotransmitter biosynthesis and degradation, and signal transduction.[7,8] Consequently, the disturbance of cellular homeostasis of Cu^{2+} may result in serious diseases. For example, deficient Cu^{2+} intake increases the risk of leucoderma, arthritis and anemia, while excessive Cu^{2+} levels can cause neurodegenerative diseases such as Alzheimer's and Parkinson's, genetic disorders including Menkes and Wilson's diseases, and even influence tumour growth.[9–12] The extensive use and the easy diffusion of Cu^{2+} increase the likelihood of Cu^{2+}-related contamination. Therefore, the recognition of trace amounts of Cu^{2+} has attracted tremendous attention in recent years.

The use of fluorescent probes has stood out from the traditional methods of atomic absorption spectrometry (AAS), inductively coupled plasma-atomic emission spectroscopy (ICP-AES) and electrochemical methods due to the merits of simple operation, low cost, high sensitivity and real-time analysis.[13–16] The two main strategies for fluorescent Cu^{2+} probes are Cu^{2+}-promoted "reactive" probes and "complexation" probes. The "reactive" probes are noted for their high selectivity, but the reaction processes are time-consuming and usually suffer from strict reaction conditions.[17–20] The "complexation" probes containing N, O, and S atoms in their molecular structures usually display fluorescent quenching behavior, and are reversible with the addition of Cu^{2+} complexing ligands, such as EDTA and S^{2-}.[21,22] For example, Gupta and co-workers reported an imidazoazine-based fluorescent probe, which could be regenerated with 90% fluorescence recovery upon the addition of EDTA, and retaining the same level of efficiency in the reused probe.[23] Additionally, Meng and co-workers developed an "off-on" fluorescent probe based on a rhodamine B derivative, where the addition of EDTA could interact with Cu^{2+} thus releasing the probe with an obvious color change in sunlight.[24] Furthermore, fluorescein-, benzoyl hydrazone-, and benzimidazole-based fluorescent probes have also been applied for the reversible detection of Cu^{2+}.[25–27] Therefore, the development of novel fluorescent Cu^{2+} probes with high sensitivity and reversibility is still highly desirable.

Triarylimidazole derivatives are well-known fluorophores owing to their extended conjugated-system structure, high molar absorption coefficient and good photochemical properties, and have been applied as fluorescent probes.[28,29] Recently, we reported a novel compound containing the triarylimidazole chromophore (TPI-H) to sequentially detect Cu^{2+} and S^{2-} with a detection limit

* Corresponding authors.
E-mail addresses: liuyijiang84@163.com (Y. Liu), lihuaming@xtu.edu.cn (H. Li).

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at the nanomole level.[30] Meanwhile, an azoaniline-arylimidazole dyad was synthesized to detect Cu^{2+} with high sensitivity based on the Cu^{2+}-catalyzed oxidative cyclization.[31] Given the good performance of triarylimidazole-based fluorescent probes, herein, we report the synthesis of a new triarylimidazole-pyridine based fluorescent probe (TPIP), which can be applied to detect Cu^{2+} with high sensitivity and selectivity, rapid response and a visible color change based on the complexation mechanism. The probe could also be easily regenerated by adding EDTA with excellent fluorescence recovery.

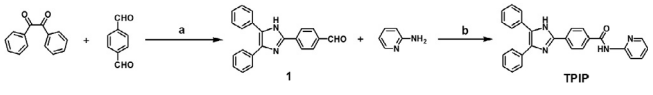
Results and discussion

Synthesis and characterization of TPIP

The probe (TPIP) was synthesized *via* a two-step route as shown in Scheme 1. First, 4-(4,5-diphenyl-1*H*-imidazole-2-yl)benzaldehyde (**1**) was synthesized according to a reported literature procedure.[32] Next, an efficient one-pot dehydrogenative cross-coupling between compound **1** and 2-aminopyridine proceeded under CuI catalysis in DMF, affording the target molecule TPIP in 70% yield as a pale-yellow solid. The molecular structure of TPIP was characterized by ^{1}H NMR (ESI, Fig. S1), ^{13}C NMR (ESI, Fig. S2) and MALDI-TOF mass spectrum (ESI, Fig. S3). The probe was soluble in common organic solvents, and the solvent mixture $CHCl_3/CH_3OH$ (8/2, v/v) was selected for further experiments.

Absorption and fluorescence response of TPIP towards Cu^{2+}

The UV–Vis absorption titration of the probe with various amounts of Cu^{2+} was initially investigated. As shown in Fig. 1a, the probe in $CHCl_3/CH_3OH$ (20 μM, 8/2, v/v) showed two absorption bands centered at 290 nm and 345 nm, which might be attributed to the corresponding pyridine moiety and triarylimidazole moiety. The absorbance of both peaks gradually decreased upon the addition of Cu^{2+}, indicating that the energy levels of the molecule were changed due to coordination between TPIP and Cu^{2+}. The absorption profile remained unchanged when 0.5 equivalents of Cu^{2+} was introduced, suggesting a 2:1 complex between TPIP and Cu^{2+} was achieved. The linear response of TPIP as a function of Cu^{2+} concentration was observed in the range of 0–10 μM (inset Fig. 1a). The association constant (K_a) determined from the UV–Vis titration was calculated to be 8.5×10^{-4}. Upon excitation at 280 nm, the free TPIP displayed a distinct emission peak centered at 436 nm. The fluorescent intensity at 436 nm gradually decreased with increasing amounts of Cu^{2+}, which quenched 98.2% of the fluorescence and stabilized upon the addition of 0.5 equivalents of Cu^{2+} (Fig. 1b). The continuous color change of the TPIP solution from bright blue to colorless under a UV lamp was observable to the naked eye (inset Fig. 1c). It is clearly indicated that the fluorescent intensity is linear to the Cu^{2+} amount in the range of 0–10 μM with a correlated coefficient of 0.995, which facilitated the quantitative detection of Cu^{2+} (Fig. 1c). The detection limit was calculated to be 1.96×10^{-8} M based on the equation DL = 3σ/S, which was far lower than the permissive level of Cu^{2+} (20 μM) assigned by the U.S. Environmental Protection Agency (EPA).



Scheme 1. Synthetic route towards TPIP: (a) CH_3COONH_4, CH_3COOH, reflux, 4 h, 81%; (b) CuI (10 mol%), DMF, 80 °C, 24 h, 70%.

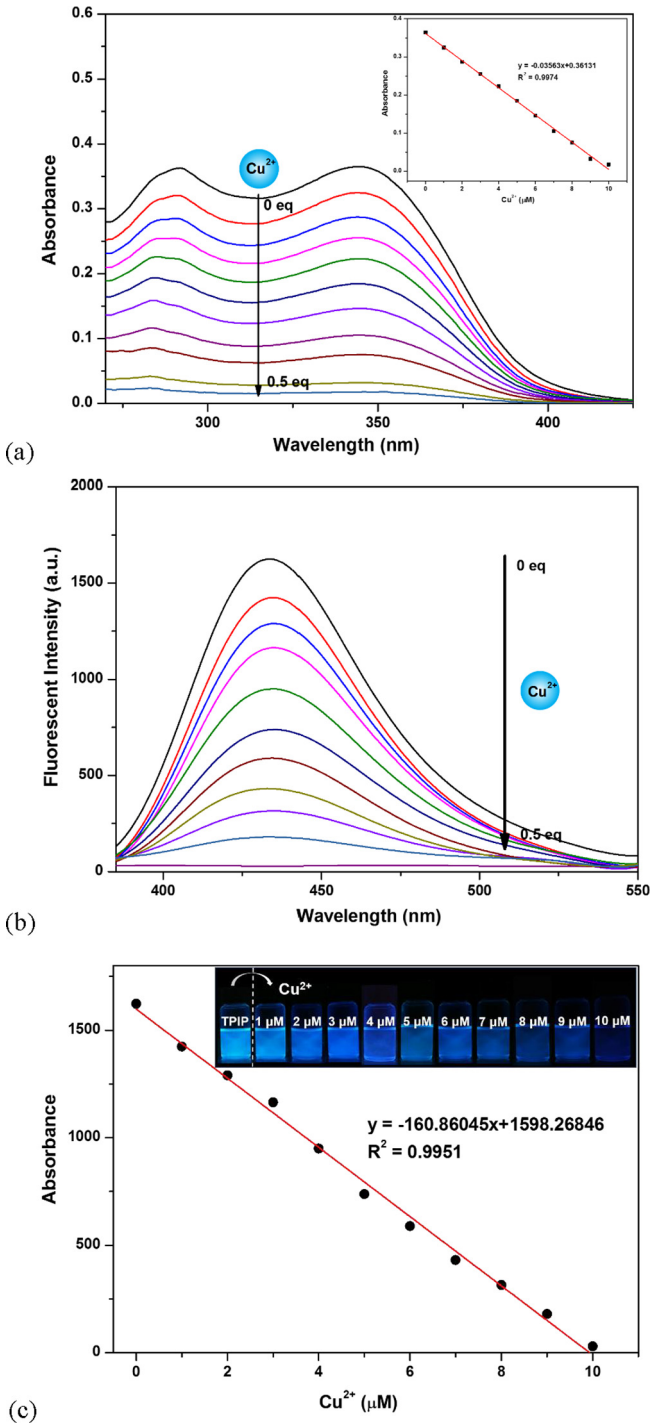


Fig. 1. (a) Absorption spectra and (b) fluorescence spectra (λ_{ex}, 280 nm) of a TPIP solution (20 μM, $CHCl_3$/MeOH, 8/2, v/v) responding to various concentrations of Cu^{2+} (0, 0.05, 0.10, 0.15, 0.20, 0. 25, 0.30, 0.35, 0.40, 0.45 and 0.50 eq.), inset (a) Plot of TPIP absorbance at A_{345} as a function of Cu^{2+} concentration; (c) Plot of TPIP fluorescent intensity at F_{436} as a function of Cu^{2+} concentration, inset photographs of the TPIP solutions with various amount of Cu^{2+} under a UV lamp.

Selectivity and competitiveness of TPIP towards Cu^{2+}

The selectivity of a fluorescent probe is an important property. Thus, the selective coordination between TPIP and Cu^{2+} was studied by fluorescence spectroscopy with various metal ions, including Zn^{2+}, Na^{+}, K^{+}, Ni^{2+}, Mn^{2+}, Ca^{2+}, Co^{2+}, Pb^{2+}, Ba^{2+}, Hg^{2+}, Mg^{2+}, Fe^{3+}, Fe^{2+} and Cu^{2+}. As shown in Fig. 2a, no obvious fluorescence quenching effect was observed when 50 μM of Zn^{2+}, Na^{+}, K^{+}, Ni^{2+}, Mn^{2+}, Ca^{2+},