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Direct Detection of Nitroxyl in Aqueous Solution using a Tripodal Copper(II) BODIPY Complex

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Nitric oxide (NO) mediates both physiological and pathological processes. In addition to cardiovascular signaling, NO has been invoked to play a neurochemical role in learning and memory, and it is a powerful necrotic agent wielded by macrophages of the immune system. Whereas considerable effort has been invested to develop metal-based probes for detecting nitric oxide, there has been significantly less progress in the synthesis of platforms capable of detecting other reactive nitrogen species (RNS). Of the nitrogen oxides relevant to biology, nitroxyl (HNO), the one electron reduced, protonated analog of nitric oxide, is among the least thoroughly investigated. Interest in nitroxyl has grown with the accumulation of evidence that HNO, which has a $pK_a$ of 11.4 and exists primarily in the protonated form under physiological conditions, displays important biological roles with potential pharmacological applications distinct from those of nitric oxide. For example, HNO reacts directly with thiols, is resistant to scavenging by superoxide, and can activate voltage-dependent $K^+$ channels in mammalian vascular systems. Moreover, biochemical studies suggest that HNO can be formed directly from nitric oxide synthase under appropriate conditions and that NO and HNO may be able to interconvert in the presence of superoxide dismutase (SOD). Despite accumulating evidence of the biological importance of HNO, studies have been hampered by the lack of a biologically compatible probe for the molecule. Only recently have chemical studies on the cons of nitroxyl detection using fluorescence methods under physiologically relevant conditions (50 mM PIPES, 100 mM KCl, pH = 7.0). The probe displays optical properties typical of a BODIPY chromophore, with an absorption band in the visible region centered at 518 nm ($\epsilon = 30,900 \pm 960$ M$^{-1}$cm$^{-1}$). Excitation into these bands produces an emission profile with a maximum at 526 nm, and $\Phi_E = 0.12$ (Fig. 1). Upon addition of one equiv of CuCl$_2$ to a solution of BOT1, the fluorescence intensity decreased by $12\times$-fold ($\Phi_E = 0.01$), which we attribute to photoinduced electron transfer (PET) from the BODIPY singlet excited state to the bound Cu$^{2+}$ ion (Fig. S1, Supporting Information). The positive ion electrospray mass spectrum of this species displayed a peak with m/z = 638.3, which corresponds to that of [Cu$^{4+}$(BOT1)]$^{+}$ (calcd. m/z = 638.2) (Fig. S2). Titration of BOT1 with CuCl$_2$, produced the series of emission changes displayed in Fig. S3, with an apparent dissociation constant of $K_d = 3.0 \pm 0.1$ $\mu$M (Fig. S3), as calculated by a Benesi-Hildebrand analysis. Photophysical data recorded for BOT1 and Cu$^{2+}$(BOT1$^-$) are available (Table S1). Analytically pure [Cu(BOT1)]Cl$-$acetone has been obtained.

Treatment of a 1 $\mu$M solution of Cu$^{2+}$(BOT1$^-$) with 1000 equivalents of cysteine restored the emission to that of uncomplexed BOT1, owing to reduction of the paramagnetic Cu$^{2+}$ ion. The positive ion electrospray mass spectrum of this reduced species showed a peak with m/z = 604.3, which corresponds to the cationic [Cu$^{4+}$(BOT1)]$^{2+}$ complex (calcd m/z = 604.0) (Fig S4). A solution of Cu$^{2+}$(BOT1$^-$) in buffered aqueous solution was treated with excess Angeli's Salt, which generates an equimolar ratio of nitroxyl (HNO) and nitrite under physiological conditions. A $4.3 \pm 0.6$ fold increase in emission was observed, demonstrating fast HNO detection with significant turn-on under physiologically relevant conditions (Fig. 1). Emission turn-on was visualized...
using as little as 50 μM Angeli’s salt. Cu$^{II}$[BOT1] displayed a negligible change in emission when treated with a 1000-fold excess of NaNO$_2$, indicating that the turn-on response induced by Angeli’s Salt is due to HNO production and not the NO$_2^-$ side product. HNO reacts with SODCu$^2+$ to generate NO and reduced SODCu$^{+}$.\(^\text{(19)}\) A similar reaction appears to occur with Cu$^{II}$[BOT1], because treatment of the complex with Angeli’s salt results in production of NO (g), as observed by EI-MS (Fig S5), concomitant with reduction of the paramagnetic Cu$^{2+}$ complex to give the same [Cu$^{II}$[BOT1]]$^+$ species observed by ESI-MS that is obtained upon reduction with cysteine (Fig S4). EPR spectroscopy provides further evidence for reduction of the paramagnetic Cu$^{II}$[BOT1] complex by HNO (Fig S6). The emission response for Cu$^{II}$[BOT1] is highly specific for HNO over other reactive species present in the biological milieu. Apart from NO$_2^-$, other RNS and ROS including NO, NO$_3^-$, ONOO$,^-$, H$_2$O$_2$, OCl$^-$ failed to induce significant emission enhancement of the Cu$^{II}$[BOT1] complex (Fig 1b). The negligible emission enhancement observed upon treatment of Cu$^{II}$[BOT1] with saturated solutions of buffered NO is especially noteworthy and makes this system potentially valuable for studying the proposed disparate roles of NO and HNO in biology.

We next assessed the ability of Cu$^{II}$[BOT1] to operate in live cells. HeLa cells were incubated with 1 μM Cu$^{II}$[BOT1] (1 h, 37 °C). Under these conditions, cells show only faint intracellular fluorescence (Fig 2a). Addition of 200 μM Angeli’s salt increased the observed intracellular red fluorescence over the course of 10 min, consistent with an HNO-induced emission response. No change in emission intensity was observed for the same time period for cultures to which Angeli’s salt was not added (Fig S7). Moreover, treatment of HeLa cells incubated with the Cu$^{II}$[BOT1] probe with the NO donor diethylamine NONOate (200 μM) did not enhance the observed fluorescence (Figure S8). Addition of exogenous cysteine to cells preincubated with Cu$^{II}$[BOT1] induced a rapid increase in observed emission (Fig S9), indicating that exogenous cysteine can reduce Cu$^{2+}$ (vide supra) from some intracellular store and liberate labile Cu$^{2+}$. A related approach to image pools of labile Cu$^{2+}$ using ascorbate as an external reductant has been described.\(^\text{(22)}\) The lack of a substantial fluorescent signal following addition of Cu$^{II}$[BOT1] to cells assures that normal levels of intracellular cysteine and other thiols are insufficient to produce the fluorescent response that we observe for HNO.

Cul$^{II}$[BOT1] is the first fluorescent molecular probe with visible excitation and emission profiles for detecting HNO in living biological samples. It features excellent selectivity for HNO over other biologically relevant RNS, including NO. The development

of cell-trappable, longer-wavelength emission Cu$^{II}$[BOT1] homologues aimed at unraveling the biology of HNO in living systems is in progress.

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Supporting Information Available: Experimental procedures, characterization data, Table S1, and Figs. S1-S9. This material is available free of charge via the Internet at http://pubs.acs.org.

References:
The synthesis, photophysical properties, and a biological application of BODIPY-triazole 1 (BOT1) are described. BOT1 juxtaposes a BODIPY fluorophore with a tripodal ligand platform via a triazole bridge. The triazole linker is afforded by azide-alkyne "click" chemistry and comprises the third arm of the tripodal architecture. BOT1 binds Cu$^{2+}$ in aqueous solution to form a Cu$^{II}$[BOT1] complex in which emission from the BODIPY moiety is efficiently quenched. This complex exhibits a prompt turn-on response when exposed to nitroxyl, and this emission response is specific to HNO over other RNS and ROS. Notably, Cu$^{II}$[BOT1] does not fluoresce in the presence of nitric oxide, making this system the first discrete molecular probe capable of detecting HNO over NO under physiologically relevant conditions. Fluorescence microscopy experiments establish that Cu$^{II}$[BOT1] is membrane-permeable and can successfully signal the presence of HNO in live cells.