Lysosomal tracking with a cationic naphthalimide using multiphoton fluorescence lifetime imaging microscopy†

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A naphthalimide-based chemosensing motif turns ON the fluorescence emission in solution in the presence of aqueous iron(III) chloride, and maintains this property in living cancer cells. The emission response to Fe(III) ions occurs simultaneously with a change in pH. The protonation of methyl piperazine-conjugated naphthalimide promotes its lysosomal localisation as assessed by co-localisation tests and fluorescence lifetime imaging microscopy (FLIM) in vitro.

The development of highly sensitive and selective probes for the recognition and measurement of transition metal ions in vitro are necessary tools in biological,1,2 chemical3–5 and environmental science.6–9 Iron is one of the essential metal ions in biological systems since it plays a fundamental role in many biochemical processes;7,10–15 Both its deficiency and overload may lead to biological disorders in vivo, such as anaemia, liver and kidney damage, heart failure and diabetes onset.16–18 Due to its biological significance, fluorescence probes for the precise detection of iron(III) are sought after.19–23 Since in aqueous conditions at neutral pH, Fe(III) halides form insoluble Fe(OH)3 and, in the lysosomes (pH 4.5), species such as [Fe(OH)2]+ and [Fe(OH)]2+ with release of protons,24 there are only a few Fe3+ fluorescent sensors that can directly detect this ion, especially with turn-on fluorescence response.25–27 It is generally accepted that simple and effective chemosensors that involve fluorescence turn-on are advantageous.28,29 By using a “turn on” probe, it is possible to measure low-concentrations because measuring a small increase relative to a dark background, reduces the likelihood of false positive signals and increases sensitivity.30,31 Therefore, we aimed to design and deliver to cells a biocompatible fluorescent probe that turns into a highly fluorescent, protonated species, only in the presence of trivalent cations such as Fe(III) in vitro. We also investigated the effect of an excess of aqueous tricationic chlorides resembling the Fe(III) charge and size ratios and the coupled pH variation caused on a simple naphthalimide-based fluorescent probe tagged with a Lewis base methyl piperazine as the receptor of choice. Photo-induced electron transfer (PET) chemosensors with the ‘fluorophore-spacer-receptor’ format, are one of the most important classes for the design of fluorescent sensors.32 Naphthalimide was the fluorophore tag of choice due to its excellent photophysical properties, including high extinction coefficient, photo-stability and relatively long emission wavelength (500–600 nm).33,34 The intermediate TN was first synthesised from 4-bromo-1,8-naphthalic anhydride and 5-methylthiazol-2-amine by refluxing in absolute acetic acid (60% yield, ESI† Scheme S1). The bromine atom of TN was then substituted by methyl-piperazine in 2-methoxyethanol.

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Scheme 1 Proposed pathway for the TNP protonation leading to the fluorescent [TNPH]Cl. in situ in aqueous FeCl3 media.
yielding TNP, which was treated with either an excess of aqueous FeCl₃ or HCl to give [TNP]H⁺ species (Scheme 1). The coordination chemistry of FeCl₃ with various modifications of N-aryl or N-alkyl-piperazine ligands has been reported.° When coordinated to the Fe³⁺ metal centre, the ligand likely adopts a boat configuration acting as a bidentate chelator, however the [TNP]₃FeCl₄⁻ intermediate proposed in Scheme 1 (on the basis of mass spectrometry) could not be isolated on a laboratory scale from wet solvents used for the sensing and imaging experiments as it rapidly decomposed to form [TNP]Cl⁻ (vide infra). This new compound was fully characterized by ¹H and ¹³C NMR spectroscopies, HRMS, and single crystal X-ray diffraction (Fig. 1 and ESI†). The photo-physical properties of the free TNP were investigated using UV-vis absorption and fluorescence spectroscopies including titration studies with aqueous FeCl₃ under an aqueous environment (Fig. S1 and S6, ESI†). In HEPES buffer, free TNP showed one main absorption band centred at 410 nm (ε = 1.3 × 10⁴ M⁻¹ cm⁻¹) assigned as a π–π* transition (10 mM HEPES; ethanol/H₂O = 80 : 20, v/v; pH 7.4, Fig. S1, ESI†).

Upon the addition of Fe³⁺ (0–10 eq. FeCl₃), the maximum absorption peak exhibits a distinct shift from 410 to 381 nm. When excited in the proximity of its isosbestic point (403 nm in single-photon, or 810 nm in two-photon mode), TNP shows only weak fluorescence emission due to PET. In the presence of FeCl₃, in a variety of (wet) organic solvents, a strong fluorescence emission with a maximum at 515 nm was observed, as shown in Fig. 2. Furthermore, the fluorescence intensities at 515 nm display a nonlinear relationship towards Fe³⁺ concentrations from 0.2 to 10 μM, and the binding constant is (3.75 ± 0.31) × 10⁷ M⁻¹, indicating that TNP is particularly sensitive to the detection of Fe³⁺ (ESI† Fig. S6). An intense peak at m/z 910.1347 in the electron-spray MS ionization (ESI) exhibited the correct isotopic pattern corresponding to the species [TNPFeCl₃]⁻ and also several related fragments indicative of the formation of an [TNP]⁻-[iron] complex with a 2:1 stoichiometry (Scheme 1 and ESI† Fig. S4). The selectivity of TNP toward Lewis acids such as Fe³⁺, Cr³⁺, Al³⁺ was evaluated by adding 10 eq. of various metal ions, including those essential ions of relevance to biological processes in vivo (Cu²⁺, Co²⁺, Ni²⁺, Fe²⁺, Na⁺, K⁺, Ca²⁺ and Mg²⁺) and toxic metals such as Hg²⁺, Cd²⁺, Pb²⁺, Ag⁺. Under the same conditions, no obvious fluorescence changes were observed for the M²⁺ ions tested (Fig. 2b). A Job’s plot analysis indicated that the binding mode of TNP donors to Fe³⁺ was 2:1 (ESI† Fig. S3). TNP is therefore very selective and sensitive for aqueous Fe³⁺ which is essential to life as well as being earth abundant, and we hypothesised that this is due to the initial formation of the corresponding metal complex. In the case of aqueous FeCl₃ (Scheme 1) this was followed by its decomposition to [TNP]Cl⁻ in the wet solvents used (ESI†). [TNP]Cl⁻ was also isolated by reacting TNP with 1.1 eq. of concentrated HCl (Scheme 1). The quantum yield of [TNP]Cl⁻ in DMSO was measured to be 0.017, comparable with other naphthyl-based chromophores (ESI†). Taken together, data suggests that the initial capture of Fe³⁺ by the receptor results in a decrease of the electron-donating ability of the methyl-nitrogen, thus resulting in a reduction of the PET effect, and with time, (in the presence of H₂O) in the formation of the protonated species [TNP]HCl⁻ (as well as presumably [Fe(H₂O)₆(OH)]²⁻ and Fe(OH)₃ and aqueous HCl). The protonated species could well form under differing conditions: specimens with the same unit cell parameters were isolated and characterised by X-ray diffraction from several different aqueous solvent mixtures (EtOH/H₂O, DMSO, wet CHCl₃) (Fig. 1 and ESI†). The onset of enhanced fluorescence upon treatment with an excess of aqueous FeCl₃ was also observed in experiments carried out using 2-photon excitation in wet DMSO for steady-state emission spectra and excited state lifetime measurements. While the fluorescence emissions were remarkably different (ESI†), lifetime measurement via time correlated single photon counting (TCSPC) indicated that the lifetime point decays recorded in solutions (giving rise to data which was modelled to 1 component multi-exponential fitting) are in the region of ca. 5 ns for both TNP and [TNP]Cl⁻ (the latter being generated in situ, from the TNP in the presence of excess FeCl₃ in wet DMSO). Specifically, free [TNP] in solution showed a 4.92 ns ($\chi^2 = 1.28$) and, in the presence of aqueous FeCl₃ (in situ protonation) giving rise to the protonated species [TNP]Cl⁻ increased to 5.56 ns ($\chi^2 = 1.19$).
(ESI† Fig. S24–S26). These results confirmed the iron-mediated protonation of methyl piperazine unit disrupts the PET turning on the fluorescence of the probe. Studies of the pH-dependent response of TNP were also carried out over a pH range of 3.0–9.0 (ESI† Fig. S7). We explored the ability of TNP towards in vitro conversion to [TNPH]⁺ in the acidic environment of lysosomes. The cellular environment of the new probe was determined in HeLa and PC-3 cancer cells using confocal fluorescence spectroscopy and fluorescence lifetime imaging microscopy (FLIM) (Fig. S27 and S28, ESI†), which is used as a sensitive analytical tool for the probes’ environment with advantages when using multiphoton imaging techniques, i.e. the use of tissue-friendly low energy near infra-red photon rather than UV excitation for live cells. The pH evaluation showed that between pH 7.4–9.0 (well within the biologically relevant pH range 6.5–8.5) the emission of free TNP is turned off in aqueous solutions. On the contrary, at lower pH, [TNPH]Cl, a highly fluorescent and kinetically stable organic molecule, was formed. This new lipophilic cation may be employed further to measure pH changes. However, such sensing experiments are beyond the scope of this study. Cells were incubated at 37 °C with TNP and visualised using single photon, epi- and confocal-fluorescence microscopies (Fig. 3 and ESI†) and two-photon confocal fluorescence microscopy coupled with fluorescence lifetime imaging microscopy (FLIM) Fig. 4 and ESI†). Cellular assays were prepared according to standard methods [9,34,37–41]. Generally, cells were incubated with TNP in the presence or absence of FeCl₃ as well as with [TNPH]Cl solutions for 15 minutes in serum free medium (SFM). After washing with PBS, the cells were imaged using laser scanning confocal fluorescence microscopy (in single- or two-photon excitation modes). Control experiments (Fig. S15 and S16, ESI†) were carried out in cells incubated with serum free medium alone, or with 1 to 2% DMSO in SFM. The confocal imaging results suggested that the iron-mediated fluorescence enhancement in cells was most promising using an excitation wavelength of 405 nm (single-photon excitation) or 810 nm (under two-photon excitation). The imaging studies also indicated that TNP alone passes through cell membranes but its fluorescence is extremely weak. Single-photon, as well as two-photon microscopy experiments, were repeated in a PC-3 (a prostate cancer cell line), also incubated at 37 °C (ESI†). In both HeLa and PC-3, in the presence of an excess of aqueous FeCl₃ (minimum 1 mM concentration), the characteristic and intense fluorescence emission and the corresponding lifetime of [TNPH]⁺ can be reliably observed away from that of cellular auto fluorescence. The experiments carried out at 4 °C did not show reliable uptake of TNP, either alone or in the presence of FeCl₃. Imaging experiments of TNP alone with incubation times longer than 1 h or at concentrations higher than 100 μM (with 1–2% DMSO) did not show reliable results due to the lack of fluorescence emission and were not pursued. The ability of [TNPH]⁺ to localise in the acidic intracellular organelles in vitro was investigated in both HeLa and PC-3 cells using 1P- and 2P-confocal fluorescence microscopies and FLIM. Co-localisation studies were carried out using LysoTracker Red CMXRos, and confirm the ability of [TNPH]⁺ to target the acidic organelles and be co-localised in the lysosomes (Fig. 5 and ESI†). Control experiments were carried out on cells incubated with DMSO and TNP alone (10 μM) at various temperatures and compared with probe-free control experiments in cells (incubated with SFM, or with 1 to 2% DMSO in SFM). In conclusion, imaging experiments in cancer cells reliably showed that a strong fluorescence emission is detectable for TNP only when this is converted to [TNPH]⁺: we call this acido-modulation of the fluorescence response of a Lewis base in cells. Imaging experiments in cancer cells suggested that a strong fluorescence emission is detectable for the protonated species [TNPH]⁺ in the presence of iron(III) at moderate concentrations (50 μM), within a comparable order of magnitude with that of commercial chemosensors based on chelators, and of relevance to the detection of free iron on concentration scales, of ca. 18 μM in plasma iron concentrations.

In conclusion, we showed the dual capability of the naphthalimide-based probe in the sensitive detection Fe(III) in vitro, and its application in the selective visualization of the acidic lysosomes using FLIM. This highlights the potential of TNP as a chemosensor for lysosomal tracking, confirmed by co-localisation tests. Further studies are in progress to identify the likely cytotoxicity: ESI† gives initial MTT tests in a range of cells and conditions. Our ongoing interest is to establish a...
The trend for TNP behaviour in the presence of other trivalent ions e.g. of relevance to molecular imaging in vivo such as $^{67}$Ga or $^{68}$Ga species for nuclear medicine as diagnostics, as these would likely mimic the behaviour of trivalent ion. The responsiveness of TNP upon protonation within intracellular compartments as well as in tumour micro-environments are our ongoing investigations.

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Conflicts of interest

There are no conflicts to declare.

Notes and references