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Spectrally resolved confocal microscopy using lanthanide centred near-IR emission†

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The narrow, near infrared (NIR) emission from lanthanide ions has attracted great interest, particularly with regard to developing tools for bioimaging, where the long lifetimes of lanthanide excited states can be exploited to address problems arising from autofluorescence and sample transparency. Despite the promise of lanthanide-based probes for near-IR imaging, few reports on their use are present in the literature. Here, we demonstrate that images can be recorded by monitoring NIR emission from lanthanide complexes using detectors, optical elements and a microscope that were primarily designed for the visible part of the spectrum.

In bioimaging, the unique properties of the lanthanide ions have been hailed for decades.1–4 The narrow emission bands allow for multiplexing, essentially generating a barcode using either nanocomposites or molecular complexes.5–11 Additionally, the long decay time—of the millisecond order for europium and terbium, and microseconds for samarium, holmium, neodymium, erbium and ytterbium, etc—of the lanthanide centred emission allow for time-gated microscopy.12–16 The essential interchangeability of the lanthanide ions allows for the synthesis of bimodal probes; for instance using europium for optical imaging and gadolinium for magnetic resonance imaging.17–19

A key feature of the lanthanide ions is the presence of emission bands of erbium, neodymium, holmium and ytterbium in the NIR region of the spectrum. Application of these emission bands in imaging has yet to see widespread use. The barrier has so far been that the microscopy systems available with most research groups are geared towards the UV/visible range and are not frequently fitted with NIR specific detector systems. Intensity-based NIR imaging performed by following lanthanide centred emission using dedicated home-built set-ups has been realised.20–23 Here, we show NIR spectral-based imaging which provides direct spectroscopic evidence that the specified lanthanide emission is detected. Furthermore, we show spectrally resolved images obtained by observing the luminescence from europium (at 820 nm) and neodymium centred emissions (at 880 nm), and demonstrate detection of ytterbium centred emission (at 1000 nm). The spectra obtained clearly demonstrate that the observed signals arise from lanthanide centered emission.

The set-up used (Fig. 1) exploits a piezo scanning confocal fluorescence microscope that is capable of detecting the fluorescence of single molecules.24 However, none of the elements are specifically designed for NIR imaging or spectroscopy. The coating on the optical elements, transmission through the side port window of Olympus IX71, the grating in the spectrometer and the CCD chip in the camera all have poorer performance in the NIR compared to the visible range (see the ESI† for details). The demonstration given here, using a silicon-based CCD detector, will increase the general applicability of (bio)imaging of lanthanide centred NIR emission.

![Fig. 1 Microscope configuration. Abbreviations: DC, dichroic mirror; P1, pinhole; L1 and L2, lenses; LP, long-pass filter; M1, mirror; CCD charge coupled device.](image-url)
The dyes used in this study (Ln-1 and Ln-2) are shown in Chart 1. The synthesis and characterisation of Ln-1 have been reported elsewhere, where its capacity to sense hydrogen sulfide has also been reported. The reactive azide group was a cause for concern; consequently, we designed and synthesized Ln-2 (see ESI†) that has photophysical properties closely aligned with those of Ln-1, but adds better chemical stability than the hydrogen sulfide-responsive system Ln-1. Both compounds are kinetically stable lanthanide complexes of phenacyl-DO3A-derived ligands, in which the ligand acts as an octadentate N₅O₄ donor to the lanthanide, while the sensitising phenacyl chromophore is in direct contact with the metal centre.

In lanthanide complexes, direct excitation does not provide an effective pathway to the excited state due to the low molar absorptivity of f–f transitions ($\varepsilon \sim 1\ \text{M}^{-1}\ \text{cm}^{-1}$). Instead formation of the lanthanide excited state is commonly mediated through a sensitising chromophore, in a process commonly referred to as the antenna effect, where light is absorbed by the organic ligand and energy transfer occurs to the lanthanide centre (Chart 1), allowing efficient excitation of lanthanide excited states. In this case, the direct contact between the phenacyl-derived chromophore and the lanthanide was considered optimal for the formation of the excited state, allowing effective Dexter-type exchange mediated energy transfer. Furthermore, complexes were selected that could be addressed using a conventional microscopy set-up (405 nm excitation), while the lanthanide ions were selected to be emissive in the ‘biologically transparent window’, between 700 and 900 nm.

To achieve this end, the phenacyl chromophores are ideal, in the ‘biologically transparent window’, between 700 and 900 nm. To achieve this end, the phenacyl chromophores are ideal, in the ‘biologically transparent window’, between 700 and 900 nm. To achieve this end, the phenacyl chromophores are ideal, in the ‘biologically transparent window’, between 700 and 900 nm.
Fig. 3 50 × 50 μm (25 × 25 pixels, 5 s integration time per pixel) confocal fluorescence images of silica beads dyed with Eu²⁺ and Nd¹⁺, recorded following 375 nm excitation using a CCD-based spectrometer system with the beads in a N₂-atmosphere; total imaging time 52 minutes. (A): Images were constructed by integrating the intensity in the spectral range 800–890 nm (background subtracted, see ESI†); (B): the image constructed by integrating the intensity in the spectral range 800–830 nm. (background subtracted, see ESI†); (C): the image constructed by integrating the intensity in the spectral range 860–890 nm. (background subtracted, see ESI†); (D): the optical transmission image showing the scan area (white square).

subtracted emission from europium (800–830 nm, Fig. 3B) and background subtracted neodymium centred emission (860–890 nm, Fig. 3C), thus demonstrating that the spectral signatures of the lanthanides can be used to resolve the nature of the particle labels.

Fig. 4 shows some examples of spectra recorded during the imaging. For presentation purposes, the spectra presented are the sum of the signals from 6 pixels. However, the emission spectra recorded from each pixel are of a high enough quality to produce images with a good signal, where the emission from the two different lanthanide centres are readily distinguished (see Fig. 3). The continuous decreasing slope in the spectrum is due to background emission from the dye and the silica particles (see ESI†). The spectral regions used for creating the images in Fig. 3 are indicated in green for the europium complex Eu²⁺ and in red for the neodymium complex Nd¹⁺. The spectrally resolved images can also be background subtracted, where the narrow lanthanide-centred emission bands allow for a clear distinction between signals and background. By only counting photons in the appropriate region (Fig. 4) above a given background threshold, an improved contrast can be obtained. It should be noted that an intensity-based imaging method (a narrow bandpass filter before a point detector, e.g. PMT) cannot be used to conclude whether lanthanide centred emission or background emission gives rise to the observed signal (though these could obviously be separated using time-gated methods). To remove the background signal originating from chromophore fluorescence, we are working to optimise the energy transfer from the chromophores to minimise fluorescence and maximise the quantum yield for the formation of the triplet state (and hence minimise emission from the singlet state). Rapid energy transfer from the chromophore to the lanthanide centre will also help reduce chromophore bleaching; the probes used in this study undergo rapid photobleaching in the setup used for imaging. The bleaching occurs at a similar rate disregarding the nature of the chromophore and the lanthanide centre. We assign this to the effect of the tightly focused UV light used. While the photostability of Ln¹⁺ and Ln²⁺ is similar, the chemical stability of Ln²⁺ is much greater and this compound can be stored under ambient conditions, whereas rapid degradation of Ln¹⁺ is seen if it is not kept cold and in the dark.

In summary, we have demonstrated spectral imaging of lanthanide emission bands in the NIR region of the spectrum, by using a sensitive confocal scanning microscope designed for use in the visible region of the spectrum. The spectral imaging technique can unambiguously detect the narrow lanthanide centred emission bands and we are currently working towards implementing a time-resolved version that will take advantage of the long lifetime of lanthanide centred emission in combination with NIR spectral imaging.

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Notes and references