Multispectral upconversion luminescence intensity ratios for ascertaining the tissue imaging depth
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1 Introduction

Fluorescence imaging has great potential in early stage cancer diagnosis because of its high sensitivity and resolution.\(^1\)–\(^4\) Especially with the development of near infrared (NIR) light excitable lanthanide ion (Ln\(^3+\)) doped upconversion nanoparticles (UCNPs), more and more attention has been paid on the upconversion scheme.\(^4\)–\(^9\) NIR light excitation has minimal absorption/scattering in animal tissue and will not excite the biological environment, which make UCNPs superior in luminescence imaging over traditional fluorescence compounds like organic dyes and quantum dots (QDs) that need ultraviolet (UV) to visible (Vis) light for excitation. As Chen et al. demonstrated in 2012, the Tm\(^{3+}\) doped UCNPs can image up to 3.2 cm thick in pork tissue, thus UCNPs is an excellent luminescent probe for \textit{in vivo} imaging of deep tissue.\(^13\) Zhang also synthesized several different UCNPs and systematically studied their microscopic luminescence imaging depths by embedding the nanoparticle labeled cells in different animal tissues.\(^18\) Moreover, benefiting from the abundantly discrete energy level structures of the doped Ln\(^{3+}\) ions, UCNPs show a unique optical property of multiband upconversion luminescence (UCL) spanning from ultraviolet to near infrared, and the spectrum can be modulated by simply varying the doping ions, \textit{e.g.} Er, Tm, Ho, etc. and/or relevant concentrations.\(^20\)–\(^24\)

Based on this, multicolor imaging methods can be aptly achieved for simultaneously imaging several different lesions with single 980 nm excitation.\(^25\),\(^26\) We also developed a multifunctional nanoplatform for cancer cell imaging and photodynamic therapy upon the selective energy transfer from multicolored NaYF\(_4\):Yb,Er UCNPs to surface covalently functionalized photosensitizers Rose Bengal (RB).\(^27\) All these efforts indicated the prospect of UCNPs in tissue imaging and/or therapy.

Despite this progress, how to relate these images to the exact position of the lesion, \textit{i.e.} how to accurately locate the tissue depth of luminescence probe labeled cancer, remains a big challenge.\(^28\),\(^29\) In clinical oncology it has been proved that the invasion depth has a close relationship with cancer metastasis,\(^30\)–\(^32\) and thus the determination of cancer depth is of great significance in cancer staging and prognosis. However, because of the intrinsic complex of the interactions between light and animal tissues (absorption, scattering, reflection, \textit{etc.}), it is usually difficult to resolve the lesion from traditional single-color planar imaging (only lateral distribution of the luminescent probes is acquired) in which the detected signal intensity...
2 Experiments and methods

2.1 Synthesis of NaYF₄:Yb,Er UCNPs

Hydrophobic NaYF₄:Yb(20%),Er(2%) UCNPs of hexagonal phase were firstly synthesized by a solvothermal method according to the literature. In a typical synthesis procedure, 236.54 mg YCl₃·6H₂O (0.78 mmol), 77.48 mg YbCl₃·6H₂O (0.2 mmol), and 7.64 mg ErCl₃·6H₂O (0.02 mmol) were dissolved in 3 mL oleic acid (OA) and 7 mL 1-octadecene (ODE), and heated up to 156 °C under an argon atmosphere and maintained at that temperature for 1 h to obtain the OA stable lanthanide precursors. The precursor solution was cooled down to room temperature, then 148.21 mg NH₄F (4 mmol) and 100.02 mg NaOH (2.5 mmol) were added into the solution and heated up to 300 °C and maintained for 90 min. The received nanoparticles were washed with ethanol at least three times and re-dispersed in 10 mL hexane.

In order to make the NaYF₄:Yb,Er water dispersible, the hydrophobic ligands of oleic acid (OA) capping outside UCNPs were removed according to a previously reported ligand-free method. Briefly, 5 mL of OA capped UCNPs was mixed with 10 mL HCl solution (pH ~ 3) and then rigorously stirred for 2 h at room temperature. After that, UCNPs were transferred into the water layer after standing 10 min. The ligand free UCNPs in the water layer were washed with ether 3 times at least and re-dispersed in 5 mL water.

2.2 Liquid phantom experimental stage

To simulate the UCL attenuation in tissue, a special sample chamber equipped with a two-dimensional (2-D) translation stage was setup in our study, as shown in Fig. 1A. The propagation distance of the excitation light and emission light can be separately controlled. UCNPs, encapsulated in a small glass capillary (1 mm outer diameter) at a concentration of 10 mg mL⁻¹, were dipped into the liquid phantom vertically. The tissue-equivalent liquid phantom was used as a simulation model and poured into a 10 mm × 10 mm silica cuvette, which was fixed on the 2-D translation platform. The optical properties were adjusted by the relative concentration of India Ink (absorption component) and Intralipid (scattering component). The spectra at different depths were recorded by PMT in the SPEX system with a 980 nm laser excitation of 700 mW cm⁻². In excitation mode (Ex mode, Fig. 1B), the liquid phantom cuvette moves along the excitation direction, i.e. X-axis, in steps of 1 mm, the UCL spectra were recorded at each step with an SPEX spectrophotometer. In emission mode (Em mode, Fig. 1C), the cuvette moves along the emission direction, i.e. X-axis, in steps of 1 mm. In reflection mode (Ref mode, Fig. 1D), the cuvette moves along the excitation direction and the emission direction simultaneously.

Considering the absorption difference of real animal tissue at the two wavelengths (540 and 650 nm), a second absorption component (Rose Bengal) was also added into the liquid phantoms at different concentrations to simulate further the imaging depth of NaYF₄:Yb,Er nanoparticles in real tissue. The optical properties of liquid phantoms can be well tuned by the relative concentration of the three components India Ink, Rose Bengal and Intralipid. The absorption coefficients and scattering coefficients are given below, sample A: μₐ = 0.872 cm⁻¹, μₐ = 8.2 cm⁻¹ (540 nm), μₐ = 0.306 cm⁻¹, μₐ = 5.2 cm⁻¹ (650 nm); sample B: μₐ = 1.362 cm⁻¹, μₐ = 8.2 cm⁻¹ (540 nm), μₐ = 0.308 cm⁻¹, μₐ = 5.2 cm⁻¹ (650 nm); sample C: μₐ = 1.362 cm⁻¹, μₐ = 16.4 cm⁻¹ (540 nm), μₐ = 0.308 cm⁻¹, μₐ = 10.4 cm⁻¹ (650 nm).
2.3 Characterization
Structural characterization was performed with a Philips Morgagni™ transmission electron microscope (FEI Company, US). UV-Vis absorption spectra of solutions in a quartz cuvette (1 cm) were recorded with a Hewlett-Packard/Agilent 8453 diode-array biochemical analysis UV-Vis spectrophotometer. The steady-state UCL spectra of UCNPs were detected using a SPEX Fluorolog-3 spectrophotometer (HORIBA JobinYvon, France) where a CW semiconductor diode laser of 980 nm was used for excitation.

2.4 Animal tissue depth evaluation using UCNPs
To validate the methodology of using multicolor UCL imaging to determine the tissue depth, layered pork muscle tissue (thickness = 0.65 mm) was utilized as the model. In the experiment, 50 µL of NaYF₄:Yb,Er UCNP solution (10 mg mL⁻¹) were firstly dropped onto a layer of pork muscle, which can seep into the tissue within a few seconds. Then more layers of fresh pork muscle (label-free) were covered layer by layer onto the one labeled with UCNPs, and the corresponding UCL spectra at different tissue depths were recorded using an SPEX Fluorolog-3 system under 980 nm excitation (700 mW cm⁻²). The luminescence intensities at 540 nm and 650 nm were used for quantitative analysis. The real color UCL imaging was recorded using a Canon Power Shot S120 digital camera by putting an 890 nm short-pass filter (Semrock) in front to eliminate the scattered 980 nm laser light.

3 Results and discussion
3.1 Characterization of NaYF₄:Yb,Er nanoparticles
Fig. 2A is the transmission electron microscopy (TEM) image of the ligand free NaYF₄:Yb,Er nanoparticles and the average diameter is 39 nm. Fig. 2B is the corresponding selected area electron diffraction (SAED) pattern, which confirms that the as-synthesized UCNPs are in hexagonal phase which is known to have high upconversion efficiency.35

Fig. 3A is the energy level structures of Yb³⁺ and Er³⁺ co-doped UCNPs and there are two main UPL bands around 540 nm and 650 nm, respectively. Considering that the allowed excitation power density is limited in animal tissues, we began with the excitation power dependence of the UCL spectrum. The upconversion spectra shown in Fig. 3B were taken under relative weak excitation densities from 175 to 700 mW cm⁻², well below the UCL saturation threshold. The UCL in the visible region exhibits the feature of Er³⁺, a green band around 540 nm and a red one around 650 nm, corresponding to transitions of ⁴S₃/₂–⁴I₅/₂ and ⁴F₉/₂–⁴I₅/₂ in the doped Er³⁺ ions, respectively (Fig. 3A). The spectra demonstrate a monotonic increase with the excitation power without saturation. The excitation power density dependence of the two UCL bands is shown in Fig. 3C.

3.2 Depth dependent UCL in liquid phantom
To study the path-length effects on UCL spectra a 2-D translation platform was built up as shown in Fig. 1A, in which the excitation and emission processes could be separately controlled by simply adjusting the liquid phantom cuvette along different directions. Fig. 4 are the extinction spectra of the different components of the liquid phantom used in our study. India Ink and Intralipid were served respectively as the main absorption and scattering components. From the spectra we can see that their extinction coefficients at short wavelength (e.g. 540 nm) are higher than those at longer wavelength (e.g. 650 nm). Both the Intralipid and India Ink have linear response of extinction and emission processes could be separately controlled by simply adjusting the liquid phantom cuvette along different directions. Fig. 4 are the extinction spectra of the different components of the liquid phantom used in our study. India Ink and Intralipid were served respectively as the main absorption and scattering components. From the spectra we can see that their extinction coefficients at short wavelength (e.g. 540 nm) are higher than those at longer wavelength (e.g. 650 nm). Both the Intralipid and India Ink have linear response of extinction and scattering components. From the spectra we can see that their extinction coefficients at short wavelength (e.g. 540 nm) are higher than those at longer wavelength (e.g. 650 nm). Both the Intralipid and India Ink have linear response of extinction and scattering components. From the spectra we can see that their extinction coefficients at short wavelength (e.g. 540 nm) are higher than those at longer wavelength (e.g. 650 nm). Both the Intralipid and India Ink have linear response of extinction

![Fig. 2](image-url) (A) TEM image of the NaYF₄:Yb,Er UCNP. (B) Selected area electron diffraction (SAED) diagram of UCNPs.
coefficients to their concentrations (Fig. S1 and S2 in the ESI†), thus we could control the optical properties by modulating the relative concentrations of the two. Since the hemoglobin in real animal tissue has high absorption around 540 nm, Rose Bengal was also added into the liquid phantom to further enhance the absorption in this spectral region. Fig. 4B shows the extinction spectra of liquid phantoms with and without Rose Bengal. The small peak detected around 540 nm in the red curve can be attributed to the characteristic absorption of Rose Bengal. The absorption in this spectral region. Fig. 4B shows the extinction spectra of liquid phantoms with and without Rose Bengal. The relative concentrations of the two. Since the hemoglobin in real animal tissue has high absorption around 540 nm, Rose Bengal thus we could control the optical properties by modulating the concentration. Exemplary relation is found in Em- and Ref modes, whereas it remains almost constant in Ex mode. This indicates that the propagation path-length of excitation light has a negligible effect on the G/R ratio.

3.3 Theoretical model

In our experiments the 980 nm laser was collimated into a planar beam of 10 mm2 to excite the UCNP capillary tube embedded in the cuvette that is filled with liquid phantoms. The UCL was thus treated as a line light source, and the energy fluence attenuated isotropically in the tissue. Based on the optical diffusion theory,† we assume the distribution of the excitation light and the emission light along their propagation direction (z) inside tissue could be written as:

$$D_x \frac{d^2 \phi_e(z)}{dz^2} - \mu_{a,x} \phi_e(z) = -\mu'_{a,x} P_{980} e^{-\mu'_{a,x} z}$$  \hspace{1cm} (1)

$$\frac{d^2 \phi_m(z)}{dz^2} + \frac{2}{z} \frac{d\phi_m(z)}{dz} - \mu_{eff,m} \phi_m(z) = \frac{P_{980}}{D_m} \delta(z)$$  \hspace{1cm} (2)

Here $\phi_e$ and $\phi_m$ are the incident intensities of excitation light and emission light inside the tissue, $P_{980}$ and $P_{980}$ are the initial intensities of the incident excitation light (e.g. 980 nm) and the emission light (e.g. 540 or 650 nm), $\mu_{a,x}$, $\mu'_a$ and $\mu'_{a,x}$ are the absorption coefficient, reduced scattering coefficient and the total attenuation coefficient for the excitation light, $\mu_{eff,m}$ is the effective attenuation coefficient for the emission light, $D_x$ and $D_m$ are the diffusion coefficients of excitation and emission, respectively. The solution for the emission diffusion equations is:

$$\phi_m(z) = \frac{P_{980(z)} e^{-\mu_{eff,m} z}}{4\pi D_{em} z}$$  \hspace{1cm} (3)

From eqn (3) we can see that the fluorescence energy fluence $\phi_m$ is affected not only by the initial luminescence intensity $P_{980}$ but also by the tissue optical property $\mu_{eff,m}$. Regarding NaYF4:Yb,Er UCL, we can divide the fluorescence energy fluence into two parts $\phi_{540}$ and $\phi_{650}$, corresponding to the two emission bands around 540 and 650 nm, respectively. The intensity ratio $R$ detected is therefore:

$$R = \frac{\phi_{540}(z)}{\phi_{650}(z)} = \frac{P_{540}(z) e^{-\mu_{eff,540} z}}{4\pi D_{540} z} \frac{P_{650}(z) e^{-\mu_{eff,650} z}}{4\pi D_{650} z} = \frac{P_{540}}{P_{650}} \frac{D_{650}}{D_{540}} (\mu_{eff,540} + \mu_{eff,650})$$  \hspace{1cm} (4)

and
The first item on the right side of eqn (4) is constant that is determined by the intrinsic optical properties of UCNPs, as proved in Fig. 5A. And the diffusion coefficients of 3.4 Ascertaining the tissue imaging depth with multispectral upconversion luminescence

In sample A, the attenuation slopes are detected in Ref mode are given in Fig. 6 (the corresponding spectra data are given in Fig. S4–S6 in the ESI†). In sample A, the attenuation slopes are −5.46 and −4.71 for green and red bands, respectively (Fig. 6A). Adding more RB into the phantom, the slope of the green band changes to −5.95 while the red band remains almost constant (−4.74, Fig. 6B). This is because RB has maximal absorption around 540 nm, which makes the green band attenuate faster. In Fig. 6C, more Intralipid is in sample B, the scattering increases while the absorption remains the same around 540 nm and 650 nm. Sharper decreases of the intensities are observed with the slopes of −6.12 and −5.23, which is predictable since scattering is enhanced in both excitation and emission. Fig. 6D shows the G/R ratio of samples A, B and C, where the fitted slopes are −1.72, −2.76 and −2.80, respectively. Deviating from sample A, the slope variations are approximately the same for samples B and C although they have different amounts of Intralipid (the amount of India Ink/Rose Bengal was the same). This result tells us that the G/R intensity ratio is more sensitive to the absorption coefficient than the scattering coefficient. In fact it is in line with eqn (4) and (5), where the effective attenuation coefficient has a linear relationship with μ_s but a quadratic one with μ_a.

So far we have built up the quantitative relationship between the propagation depth of UCNPs in tissue mimic liquid phantoms and the UCL spectra. In the following, we will validate the method employing layered pork muscle tissue. Fig. S7† shows the extinction spectra of pork muscle with different thicknesses (or layers). As pork muscles contain a high concentration of myohemoglobin which has relatively high absorption around 540 nm, the effective attenuation coefficient is thus higher than that of 650 nm. The photographs in Fig. 7A and B are the real color UCL images recorded in Ex- and Em modes, respectively. The incident excitation power density at 980 nm was 700 mW cm⁻² at the surface. In Ex mode, although the emission intensity dropped proportionally with the tissue depth (the actual

\[ \mu_{\text{eff}}^2 = 3\mu_a\mu'_s = 3\mu_a(\mu_a + \mu_s) \]  \hspace{1cm} (5)

3.4 Ascertaining the tissue imaging depth with multispectral upconversion luminescence

‘Real tissue’ contains hemoglobin and other chromophores, which lead to more absorption around 540 nm compared to 650 nm. To mimic this, studies were performed in liquid phantoms with different optical properties by varying the concentration of India Ink, Rose Bengal and Intralipid. The corresponding attenuation slopes detected in Ref mode are given in Fig. 6 (the corresponding spectra data are given in Fig. S4–S6 in the ESI†). In sample A, the attenuation slopes are −5.46 and −4.71 for green and red bands, respectively (Fig. 6A). Adding more RB into the phantom, the slope of the green band changes to −5.95 while the red band remains almost constant (−4.74, Fig. 6B). This is because RB has maximal absorption around 540 nm, which makes the green band attenuate faster. In Fig. 6C, more Intralipid is in sample B, the scattering increases while the absorption remains the same around 540 nm and 650 nm. Sharper decreases of the intensities are observed with the slopes of −6.12 and −5.23, which is predictable since scattering is enhanced in both excitation and emission. Fig. 6D shows the G/R ratio of samples A, B and C, where the fitted slopes are −1.72, −2.76 and −2.80, respectively. Deviating from sample A,
excitation power decreased), the color remained unchanged. In contrast, the color of UCL in Em mode changed from green to red with the tissue depth, reflecting the higher absorption of muscle hemoglobin to 540 nm emission. More quantitative analyses were carried out by recording the UCL spectra at different depths of Em-, Ex- and Ref modes (data are shown in Fig. S8–S10 in the ESI†), and the UCL intensities around 540 nm and 650 nm are given in Fig. 7C and D. Fig. 7C is the depth dependent UCL intensity recorded in Ex mode, where a similar tissue penetration depth dependence is observed for the green and the red emission. Fig. 7D shows the results of Ref mode; the slopes for green and red bands are −7.33 and −5.48, respectively. To determine the reproducibility of the results, all the spectra are recorded at least three times for each tissue depth. The results as shown in Fig. 7D are reproducible with the error bar less than 10%. Compared with the results on liquid phantoms, the G/R attenuation slope in pork muscle is much higher (−4.74), as shown in Fig. 7E. This discrepancy might attribute to the higher effective coefficient difference of the two bands in the pork muscles than that in the liquid phantoms. As the G/R ratio detected is determined by the inherent properties of NaYF₄:Er³⁺:Yb,Er UCNPs, which is independent of the absolute amount of UCNPs and the excitation power density at the low density level. To prove this hypothesis, different amounts of UCNPs were further embedded in the bottom pork layer and the ascertained tissue depth (as shown in Fig. 7F) was calculated from the G/R ratio (data are shown in Fig. S11†). From the linear fitting we see that the calculated depths are in excellent agreement with the actual tissue ones. The standard error is less than 0.15 mm in the range 1–10 mm. In a word, the multispectral UCL imaging can be utilized as an effective method to accurately ascertain the UCNP depth in tissue, i.e. the marked lesion depth position can be accurately determined, which has great potential in tissue engineering and disease diagnosis.

4 Conclusions

In conclusion, a theoretical model has been established to relate the relative intensities of the UCL spectra to the tissue imaging depth of UCNPs. The method was validated in liquid phantoms and pork muscle tissue. Although in this work we have focused on NaYF₄:Er³⁺:Yb,Er UCNPs, other upconversion materials can be similarly employed as well for even better penetration, e.g. introducing Tm³⁺. This new approach shall lift significantly the power of nanotechnology assisted luminescence imaging by providing also accurate information of the depth of UCNP labeled lesion.

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Notes and references

25. Q. Dou, N. M. Idris and Y. Zhang, Biomaterials, 2013, 34, 1722.