Published in final edited form as:

Opt Lett. 2014 July 1; 39(13): 3830–3832.

Dual-mode optical imaging system for fluorescence image-guided surgery

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Abstract

In this Letter, we present a novel imaging concept that a single imaging system can image different spectral bands with different aperture sizes. It is achieved by using a filter with different transmitted spectral bands in different annular rings as the aperture stop. This concept will enable more efficient system configurations and practical clinical applications. We have demonstrated this concept with a dual-mode near-infrared fluorescence image guided surgical system.

A multimodal optical imaging concept is commonly used in biomedical imaging systems to improve system performance, such as sensitivity and specificity in cancer detection [1–3]. One challenge is that each imaging modality has specific requirements that may be in conflict with the requirements of other modalities. Fluorescence imaging is one of the most commonly used imaging modalities and it typically requires a large aperture for high fluorescence collection because the fluorescence signal is usually very weak [4]. In thick tissue fluorescence imaging, such as image guided surgery, fluorescence imaging systems typically have low resolution because intratissue fluorescence excitation causes strong scattering, decreasing resolution. In addition, fluorescence imaging does not provide detailed information on the tissue surface, such as color information. Therefore, fluorescence imaging is often combined with other imaging modalities to achieve a more comprehensive tissue diagnosis [1–7]. White light reflectance imaging is usually added to the system to obtain detailed information on the tissue surface, and the aperture is relatively small in order to obtain clear image over a large depth of field. When combining fluorescence imaging and white light reflectance imaging modalities either two separate imaging systems are needed to capture fluorescence and white light reflectance images separately or one system with trade-off on aperture size is used to capture two images sequentially [3]. The configuration

with two imaging systems is often large and not suitable for hand-held applications. The current configuration with a single system cannot achieve the optimal performance for each imaging modality.

In this Letter, we present a novel solution for dual-mode near-infrared (NIR) fluorescence image-guided surgical system with a single imaging system. To maximize the performance of each image modality within the same imaging system, we have developed a unique imaging lens that has different aperture sizes for two imaging modalities. This is achieved by developing a filter with different transmission spectral bands in annular rings and placing it at the aperture stop. The concept of this aperture filter is shown in Fig. 1. The central small region A is coated to pass visible light and NIR light and the outer ring B is coated to pass NIR only. This aperture maximizes the fluorescence light collection and ensures sufficient depth of field for white light imaging.

To demonstrate the concept, we have developed an objective for a dual-mode fluorescence imaging system, as shown in Fig. 2. The focal length is 20 mm and the working distance is 750 mm. The aperture filter is placed at the aperture stop. It is designed to capture visible reflectance image (450–650 nm) and NIR indocyanine green (ICG) fluorescence images with a wavelength longer than 810 nm. To simplify the system configuration, we develop a custom dichroic beam splitter to separate the visible light (450–700 nm) and NIR fluorescence light (700–900 nm) to two cameras to capture visible images and fluorescence images simultaneously.

The design modulation transfer functions (MTFs) of the visible channel and NIR channel of the lens with an aperture filter are shown in Figs. 3(a) and 3(b), respectively. The F-number of the visible channel is 4, with a trade-off between the resolution and depth of field. Its MTF in Fig. 3(a) shows that the performance of the objective lens is diffraction limited in the visible. The F-number of the NIR channel with central wavelength 830 nm is 1.75 for high fluorescence light collection; its MTF shown in Fig. 3(b) is lower than the visible channel due to the larger aperture, and the MTF at the Nyquist frequency for a sensor with a 6.0 μm pixel is higher than 0.5.

We fabricated the aperture filter with a traditional coating method and tested it with white light and NIR illumination. Figure 4(a) is the image with NIR transillumination with an 850 nm light emitting diode (LED), and the transmission around the boundary between two regions is low. It is due to the manufacturing defects and can be minimized. Figure 4(b) is the visible transmission image of the aperture filter; only the central region of the aperture filter transmits visible light, and the annular ring can only transmit NIR light.

The transmission spectrum of the aperture filter is also measured via a HR2000+ spectrophotometer. A broadband lamp is used as the light source. The results are plotted in Fig. 5. The blue solid curve represents the transmission in the center of the aperture filter which is transparent to visible and NIR spectrum. The red dotted curve represents the transmission spectrum in the middle of annular ring; it is transparent to NIR spectrum only.

Three objectives with the same lens elements are used to compare the depth of field: F/1.75 objective, F/4 objective, and objective with aperture filter. The F-numbers of the objectives

with aperture filters are 1.75 and 4 in the NIR and visible spectrums, respectively. A custom dual-mode camera with two sensors is used to in this test to obtain visible and NIR images simultaneously. Three 43×56 mm printed USAF resolution targets are placed 915, 762, and 610 mm away from the camera. The camera is focused at the middle target, which is 30 in. from the camera. Figures 6(a)–6(c) are the visible images for the objective with F/1.75, F/4, and aperture-filter objectives, respectively. Figure 6(d) is the NIR image of using the aperture-filter objective. It can be seen that the aperture-filter lens has quite a similar depth of field to the traditional F/4 lens in the visible channel. While in the NIR channel, the aperture filter lens has a shallower depth of field, due to its larger aperture.

The feasibility of this concept in NIR fluorescence imaging is validated via ICG fluorescence imaging. ICG solution samples (Sigma-Aldrich, St. Louis, Missouri) of different concentrations ranging from 130 nm to 5.2 μ m in dimethyl sulfoxide (DMSO) (Sigma-Aldrich) are used to test the NIR detection sensitivities of the system. The ICG samples are illuminated by a high power NIR LED with optical output power of 1 W at peak wavelength of 780 nm.

The NIR fluorescence images of ICG samples with different concentrations are shown in Fig. 7. The concentration of ICG samples is labeled on the left in the figure. The exposure time is 16 ms. Under the same excitation illumination the lens with the aperture filter can detect more ICG fluorescence signal than the F/4 lens, close to that of the F/1.7 objective.

In summary, a new concept of optical system for multimodal optical imaging systems has been developed. It potentially maximizes the performance of each imaging modality. This is achieved by placing a novel aperture filter at the aperture stop of the imaging system. This filter has different transmission spectral bands in annual rings so the effective aperture is different for each spectral band. With this novel concept, the imaging system can be significantly simplified without sacrificing system performance.

Acknowledgments

Research reported in this publication was supported by the National Cancer Institute of the National Institutes of Health under award number R01CA171651.

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Fig. 1.
Aperture filter with different transmission bands in the annual rings.

Fig. 2.

(a) Optical and mechanical structure of the customized lens with aperture filter (the outer diameter is 25 mm) and (b) the photograph of the assembled lens.

Fig. 3. MTFs of lens with aperture filter in (a) F/4 visible channel (450–650 nm) and (b) F/1.75 NIR channel (810–890 nm).

Fig. 4.
(a) NIR and (b) visible images of aperture filter.

Fig. 5.
Transmission spectrum of the aperture filter.

Fig. 6.

Depth of field test of the aperture-filter lens on the visible channel with (a) F/1.75 traditional lens, (b) F/4 traditional lens, (c) aperture filter lens, and (d) NIR image with aperture-filter lens.

Fig. 7. ICG solution test. (a) F/1.75 traditional lens, (b) F/4 traditional lens, and (c) aperture-filter lens.