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Near-UV to Near-IR Multispectral Illumination in a Digital Surgical Microscope

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Abstract: We present a stereo-multispectral microscope equipped with an additional illumination unit allowing further narrow-band illumination in the spectral range of 400nm up to 800nm. The combination of the normal microscope illumination with the multispectral light unit allows different illumination modalities to be realized, which enables intraoperative spectral tissue analysis with direct visualization. Two illumination methods were tested in two cholesteatoma surgeries. In addition, two cholesteatom samples were illuminated and analyzed *ex vivo*. Cholesteatoma showed fluorescent characteristics in our *ex vivo* analysis. This behavior could be used intraoperatively using a combination of white light and strong near-UV to blue illumination to highlight cholesteatoma tissue in the microscopic image. Thus, the visual differentiability of different tissue types can be improved and the clinical decision-making process can be accelerated.

Keywords: stereoscopic imaging, multispectral imaging, image-guided surgery, surgical guidance, computer assisted intervention (CAI).

1 Introduction

Digitization creates new possibilities to support the surgeon in complex surgical processes. On one hand, digital surgical microscopy makes a three-dimensional (3D) reconstruction of the situs possible. However, such a reconstruction does not help to identify different tissue structures. Normally, different tissues appear similar under white light illumination and it has been shown that multispectral imaging is a promising method to identify optical tissue properties that are normally invisible for the human eye [6]. Tissue structures similar in shape, structure and color appearance reveal different spectral behavior [3]. Such information gain can support the surgical decision-making process and facilitate the intervention when using appropriate intraoperative real-time visualization methods.

This work describes a surgical microscope extended by an additional multispectral illumination source. We show that this system can be used to highlight specific spectral tissue differences intraoperatively for real-time image-guidance [11]. In this study, cholesteatoma samples were illuminated *ex vivo* to show it fluorescent characteristics in the near-UV as well as two patients showing cholesteatoma were analyzed using the multispectral unit of the surgical microscope. Overall, we sought to demonstrate the usability of multispectral imaging to directly differentiate specific tissue types intraoperatively, with the goal of establishing this technology to support intraoperative surgical decision-making.

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2 Materials and Methods

2.1 Imaging Setup

This work is based on a full digital surgical microscope (Munich Surgical Imaging, Germany) having a broad white light mixed of four different LEDs (Fig. 1). In addition, this system is equipped with a multispectral laser illumination unit (Sony Corporation, Japan) allowing additional narrow-band lightning in the range of near-UV ($\lambda = 405$ nm) to near-IR ($\lambda = 808$ nm).

This additional light source is attached to one of the two light sources of the microscope head. This allows two different illumination modes: 1. one of the two different light sources, the standard broad white light of the microscope or a narrow-band light, can illuminate the scene or 2. the standard white light of the microscope can be combined with one additional narrow-band light peaking the illumination spectrum at this specific wavelength.

The camera output images are for each illumination mode a 3-channel (red, green, blue) image with sensor sensitivity beginning at $\lambda = 430$ nm up to $\lambda = 800$ nm [1, 5].

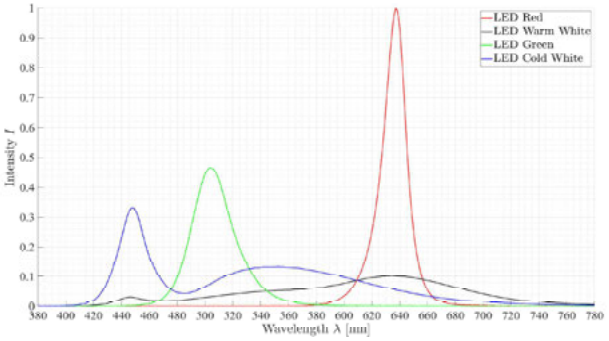


Fig. 1: The multispectral 3D-endoscopic setup with (A) capture unit, (B) filter wheel and (C) display showing live stereo-image.

2.2 Surgical Case

The multispectral setup ability of tissue differentiation was tested with cholesteatoma patients. Cholesteatoma consists of sprawling squamous epithelium and is located in the middle ear. Due to the proliferation of cholesteatoma in the middle ear cavity with further growth into the mastoid and lateral skull base can lead to life-threatening complications. The only possible treatment is surgery and to avoid recurrence, it requires a complete resection, which is a very challenging task as cholesteatoma and bone appear white under normal illumination conditions. [2, 8]

The two patients analyzed in this study were 12 and 15 years old with a long history of recurrent cholesteatoma and consecutive surgical interventions. Both recurrent cholesteatoma had a very extensive size, which allowed extracting samples for *ex vivo* investigation. Intraoperatively, the cholesteatoma has been confirmed microscopically with an expansion in the attic.

2.3 Cholesteatoma Sample Illumination

In a previous study, cholesteatoma and bone samples were analyzed with a spectrometer in the spectral region of $\lambda = 250$ nm to $\lambda = 800$ nm [10]. It had been presented that cholesteatoma tissue shows higher reflectance in the blue and near-UV region compared to bone. However, this behavior is dependent on the blood content of the samples. The more blood adheres to the sample, the more the spectral response depends on the blood spectrum, which then covers the relevant tissue differences.

Further, it was reported by different authors in [4, 7, 9] that cholesteatoma shows autofluorescence when it is excited by radiation in the blue spectrum. This behavior was investigated using cholesteatoma samples and the near-UV ($\lambda = 405$ nm) illumination of the laser light source. As only near-UV illumination is not capable for performing surgeries, it was combined with diffuse ambient white light of low intensity. If the fluorescent behavior of cholesteatoma can be reproduced using such a combined illumination setup, it can potentially be used for intraoperative cholesteatoma visualization.

2.4 Cholesteatoma Visualization

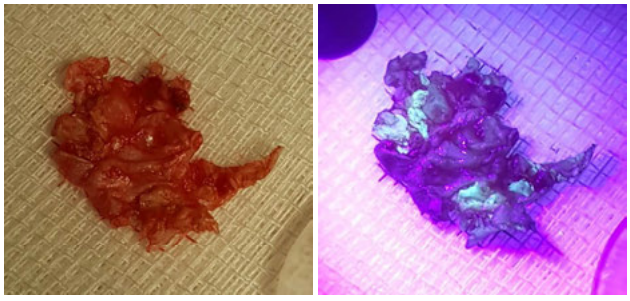
Using white light illumination, ‘clean’ cholesteatoma (i.e. blood-free cholesteatoma) and bone appear white. Due to the one maxim of surgery to keep the situs as blood-free as possible, the expected fluorescent behavior was investigated on ‘clean’ cholesteatoma. For this reason, we tested two intraoperative illumination modes: (1) Near-UV to blue illumination of the extended laser light source as exclusive illumination and (2) near-UV of the laser light source in combination with low intensity microscopic white light.

Due to the low intensity response below $\lambda = 430$ nm of the microscopic sensor, the near-UV illumination is not visible in captured images. Therefore, the near-UV spectrum was extended by the blue spectrum to increase reflectance responses of the entire scene while capturing fluorescent targeted cholesteatoma structures. Using only near-UV illumination in mode (1) would ease and improve cholesteatoma visualization, however, the navigation in the situs will be lost. Blue illumination will allow orientation on a basic level. Mode (2) mixes near-UV light of one illumination channel with low level white light illumination of the other channel to enhance normal surgical visibility with intended cholesteatoma differentiation.

3 Results

3.1 Sample Analysis

The cholesteatoma samples were taken from the first patient and directly analyzed after removal from the patient. The samples were not capsuled and showed ‘clean’ parts and areas soaked with blood. Using a surgical white light, all parts of the samples appeared white and reddish to red, see Fig. 2(a). Illuminating with near-UV ($\lambda = 405$ nm) light, the ‘clean’ parts of the sample showed bright reflectance. At the areas where blood was covering cholesteatoma, the fluorescent behavior was covered and the sample appeared pink, see Fig. 2(b).



(a) (b)

Fig. 2: (a) Cholesteatoma sample under white light illumination. (b) The same sample under near-UV ($\lambda = 405$ nm) illumination.

3.2 Intraoperative Cholesteatoma Visualization

Both introduced intraoperative illumination modes were able to highlight cholesteatoma. Near-UV to blue illumination (Mode 1) resulted in higher reflectance of cholesteatoma compared to surrounding tissue, see Fig. 3. Cholesteatoma showed strong fluorescent behavior with a captured response of white to reddish reflectance. However, depending on the intensity of the illumination, surrounding scattered light and blood content in the scene, the increased reflectance and fluorescent behavior of cholesteatoma is not always precisely distinguishable by the human eye due to its weaker blue sensitivity. To allow robust differentiation additional postprocessing is needed. Further, due to the monochrome illumination of the situs, an clear orientation in the situs is much more difficult, which could be error-prone and lead to a surgical time delay.

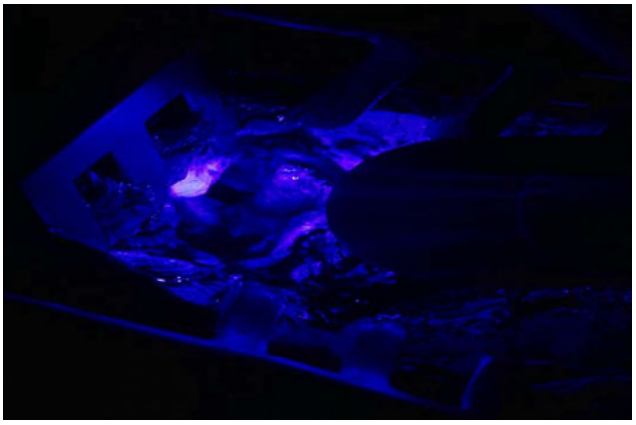


Fig. 3: The left image of the stereo-microscopic view illuminating the situs with mode (1) illumination. Blank cholesteatoma parts show strong fluorescent behavior, white to reddish tissue parts compared to a dark blue scene.

If the situs is illuminated with the near-UV in combination with low intensity white light (Mode 2), cholesteatoma glowed bluish while bone remains white, which allows a direct tissue differentiation between cholesteatoma and bone, see Fig. 4. The visible fluorescent effect of cholesteatoma is depended on the intensity of the microscopic white light illumination. The lower the microscopic white light illumination the better is the visual perception of the fluorescent effect, cf. Fig. 4. In this figure, large parts of cholesteatoma are visible on the top left of the situs. As the microscopic white light is located on the top of the sensor and the near-UV laser illumination on the bottom, the fluorescent effect is increasing on the top of the scene in Fig. 4.

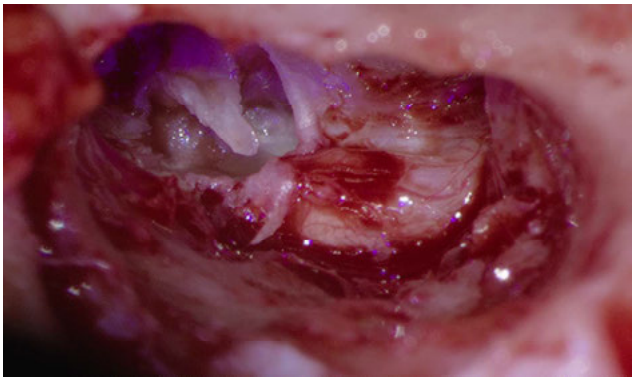


Fig. 4: The left image of the stereo-microscopic view illuminating the situs with mode (2) illumination. The cholesteatoma on the top of the situs show increasing fluorescent behavior with decreasing white light illumination (from middle to top).

4 Conclusion

In this work, we presented a new intraoperative visualization method combining a surgical microscope with an additional multispectral (near-UV to near-IR) laser illumination source. This extended setup allows to determine different tissue types with a more visually distinguishable interpretation through an illumination aligned to the different optical tissue properties. In particular, this multispectral illumination source was used to highlight cholesteatoma tissue in the situs by utilize its fluorescent behavior. For cholesteatoma structures free of blood this was feasible without limitations. If bleeding is present, postprocessing of the captured information seems unavoidable, as it has been done in [12, 13]. However, surgical processes could be accelerated and revision procedures could be reduced for an improved patient outcome, which shows the high clinical potential of the presented concept.

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