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A multispectral 3D-Endoscope for Cholesteatoma Removal

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Abstract: We present a stereo-multispectral endoscopic prototype using a filter-wheel to guide the removal of cholesteatoma tissue in the middle ear. An image-based method is used that combines multispectral tissue classification for the detection of tissue to be removed and 3D-reconstruction to determine its metric dimensions. The multispectral illumination used for tissue classification ranges from $\lambda = 400$ nm to $\lambda = 500$ nm with step-size of 20 nm, which results in six different narrow-band illumination modes. For classical RGB imaging and metric calculations, a broadband illumination mode is applied before and after the narrow-band illumination. The spectral information is augmented into the broadband mode using an overlay technique. The combination of multispectral imaging with stereoscopic 3D-reconstruction results in new valuable visualization of intraoperative data. This allows to generate a 3D-model of the patients anatomy highlighting the identified malicious tissue and compare the anatomical dimensions with pre-operative CT data.

Keywords: stereoscopic imaging, multispectral imaging, image-guided surgery, surgical guidance.

1 Introduction

Cholesteatoma is a disease in the middle ear and consists of sprawling squamous epithelium. It can lead to life-threatening complications due to its destructive growth and needs to be treated by surgery as only possible treatment. Cholesteatoma requires a complete resection to avoid recurrence. Especially, the proliferation of this epithelium in the middle ear cavity and further growth into the mastoid and lateral skull base can lead to life-threatening complications [7]. Thus, the goal during surgery is a complete removal while recovering or preserving the hearing ability. Achieving these two objectives at the same time requires a high level of surgical expertise [2].

Digitization creates new possibilities to support the surgeon in complex surgical processes. On one hand, digital stereoscopic image acquisition makes a three-dimensional (3D) reconstruction of the situs possible. This allows contactless metric measurements of anatomical structures [1]. In addition, spectral imaging can be used to detect optical tissue properties that are normally invisible to the human eye [4]. The additional information can support the surgeon during decision making and facilitate the surgical procedure when using appropriate intraoperative real-time visualizations. Thus, such surgical processes could be accelerated and revision procedures reduced for an improved patient outcome [10].

This work describes the setup and the usage of a multispectral 3D-Endoscope prototype for intraoperative cholesteatoma analysis. The analysis allows enriching RGB color images with tissue specific spectral information by sequentially switching between broadband and narrow-band illumination. This opens new opportunities in terms of intraoperative visualization.

2 Materials and Methods

2.1 Imaging Setup

The endoscopic imaging system we use in our setup is a 3D laparoscope, Schölly Fiberoptics GmbH, Denzlingen, Germany, featuring a chip-in-scope bayer pattern RGB CMOS sensor.The sensor and cameras specifications are listed in Table 1. The used CMOS sensor has a sensitivity range going from 380 to 1100 nm and the calibrated lens has an estimated focal length of 4.63 mm. The focus point is at 48 mm which defines the optimal working distance to the surgical area. For illumination, the system contains a Xenon (Xe) lamp. To ensure patient safety, the Xe source holds an UV-filter and an IR-filter to cut-off radiation at $\lambda = 350$ nm and at $\lambda = 700$ nm, respectively.

A filter-wheel is placed between the surgical scene and the Xe light source. The filter-wheel setup and its calibration are described in [9, 11]. In this study, the filter-wheel comprised

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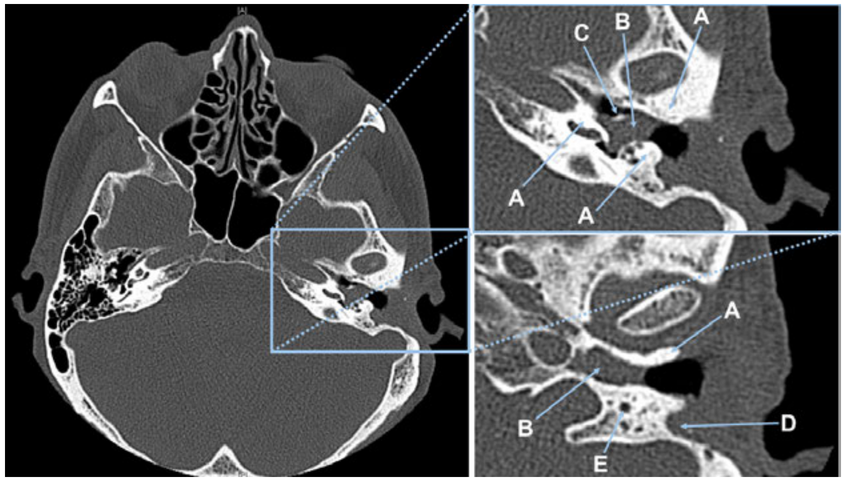


Fig. 1: View left: A complete CT slice of the patient. View top right: Zoom to region-of-interest depicting (A) bone, (B) cholesteatoma and (C) the handle of malleus covered with cholesteatoma. View bottom right: Zoom of a second CT slice depicting (A) bone, (B) cholesteatoma, (D) connective tissue in the pre-surgical removed canal wall and (E) the nervus facialis embedded in bone.

six bandpass filters with wavelengths ranging from $\lambda = 400$ nm to $\lambda = 500$ nm in steps of 20 nm.

The situs is illuminated alternately using the filter-wheel with the broadband mode (full light spectrum of the Xe source) and narrow-band mode (light spectra of the six filters). The scene is captured using the stereoscopic RGB-sensor. This results in an image sequence of seven images, one normal endoscopic RGB image and six images holding reflectance of specific spectral illuminations.

2.2 Cholesteatoma Visualization

Based on a-priori spectrophometer analysis of fresh tissue samples of the major present tissues (cholesteatoma and bone) [8], we identified the best wavelength bands for enhancement of cholesteatoma during the surgical treatment. The main difference between the optical properties of these tissues lies within lies within the spectral range of $\lambda = 400$ nm to $\lambda = 575$ nm, where cholesteatoma shows a much higher reflectance rate than bone. We additionally avoided spectral influences of blood, with its peaks in the range of $\lambda = 555$ nm [3], by selecting six appropriate bands between $\lambda = 400$ nm to $\lambda = 500$ nm.

Tab. 1: Specifications of 3D endoscope camera: sensor and calibrated lens values.

Output resolution	interlaced	1920×1080 px
Frame rate		25 fps
Endoscope diameter		9.2 mm
Light source	Xenon (Xe)	300 W
Focal length		4.63 mm
Interaxial distance		4.16 mm

We propose a basic augmentation concept for spatial color enhancement to highlight the identified cholesteatoma regions while maintaining the original color balance. After calibration, the augmentation is achieved using

$$\begin{pmatrix} R^{bb} \\ G^{bb} \\ B^{bb} \end{pmatrix} = \begin{pmatrix} R^{bb}/\max(R^{bb}) \\ G^{bb}/\max(G^{bb}) \\ (B^{bb}/\max(B^{bb})) + B^{nb}_{cal} \end{pmatrix}, \qquad (1)$$

where R^{bb}, G^{bb}, B^{bb} are the RGB-sensor responses using broadband (bb) illumination and B^{nb}_{cal} represents the calibrated and modified B-channel holding the relevant tissue information using narrow-band (nb) illumination. Areas with specular reflections are neglected during the visualization step.

2.3 Surgical Case

The patient analyzed in this study is a 58 year old male with a long history of recurrent cholesteatoma and consecutive surgical interventions (among others canal wall down technique) beginning in the early 1990s. Intraoperatively, the cholesteatoma has been confirmed microscopically with an expansion in the attic. Due to the history of multiple ear surgeries, the anatomy showed a broad osseus destruction with a missing ossicular chain and a partially removed ear canal wall including an infected mastoid cavity, see Figure 1. The recurrent cholesteatoma expanded widely from a residuum of the reconstructed tympanic membrane in a broad fashion over the round window niche, the intact stapes footplate in the attic and lateral to the facial nerve into the mastoid cavity, see Figure 2.

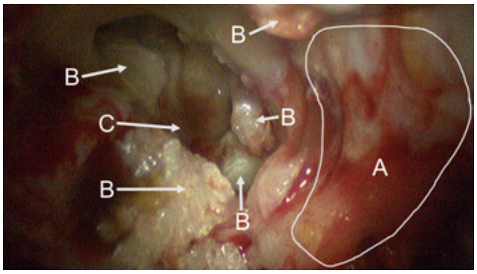


Fig. 2: Endoscopic image showing the situs captured at the beginning of the stereo-spectral image acquisition. In front, a large area of bone structure (A) is visible. Fragments of Cholosteatoma (B) are present at different parts of the image. The round window niche (C) is visible in the background.

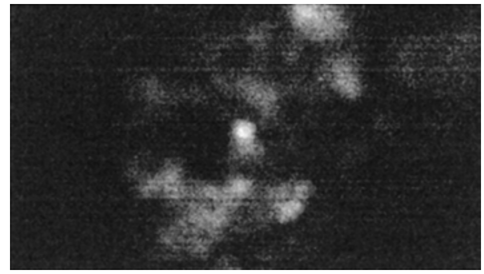
3 Results

Two stereo-multispectral endoscopic videos of the mastoid cavity have been recorded during the cholesteatoma removal procedure. The scanned situs is shown in Figure 2. Both videos contain several filter-wheel sequences which result in a set of twelve sequences in total, eight during the first acquisition and another four sets obtained during the second acquisition.

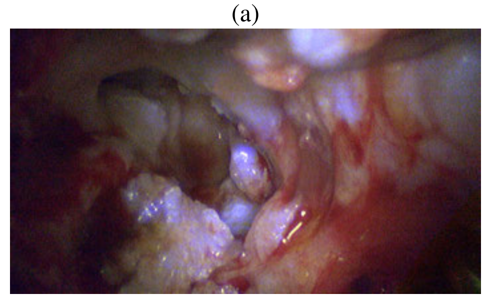
3.1 Spectral Visualization Analysis

All six narrow-band modes show similar behaviors between cholesteatoma and bone. However, the sensor sensitivity is relatively small in the range of $\lambda = 380$ nm to $\lambda \approx 420$ nm and illuminated images with $\lambda = 400$ nm and $\lambda = 420$ nm holds much less intensity than the other four wavelengths resulting in fairly dark images. Especially the image of $\lambda = 400$ nm shows a very small signal-to-noise ratio (SNR). Thus, we select $\lambda = 420$ nm for further augmented visualization.

The blue channel of the captured endoscopic RGB-image with $\lambda = 420$ nm illumination is corrected using Fourier transformation for black balance [5] and then normalized. A resulting monochromatic image is shown in Figure 3a. This image holds only information corresponding to cholesteatoma. This information is added to the B-channel of the next recorded broadband RGB-image (Figure 2) using Equation 1. The resulting image is shown in Figure 3b. This enhanced view facilitates the differentiation between relevant structures that show similar colors under white light illumination. The structures appearing blue in the enhanced view correspond to cholesteatoma, while the white structures are indicating bone. Thus, this enhanced view can guide the surgeon to differentiate between these two tissue types while maintaining the decision process to the surgeon.



(a)



(b)

Fig. 3: (a) Information with $\lambda = 400$ nm illumination. (b) Enhanced spectral RGB view including the information of (a).

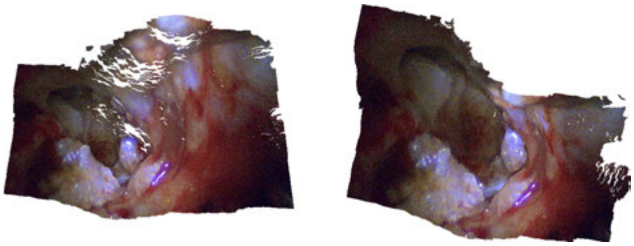
3.2 Multispectral Stereo Acquisition

Besides the single advantages and benefits of stereoscopic and multispectral imaging, the combination of both results in a new valuable visualization of intraoperative data. It allows the generation of spectral 3D model showing the patient's anatomy and highlighting identified malicious tissue. Using the two stereoscopic views, we obtain a very dense spectral point cloud as shown in Figure 4a by applying a robust 3D reconstruction pipeline [6].

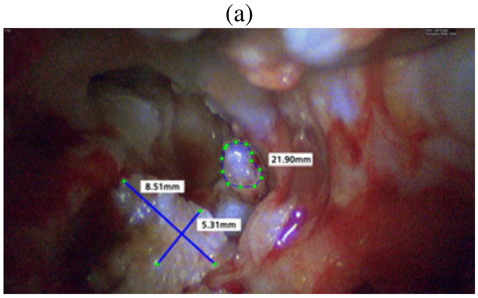
The comparison of the two point clouds, reconstructed with and without cholesteatoma enhancement, allows to observe spatial and depth-related cholesteatoma distribution. Moreover, the sizes of all removed tissue volumes can be estimated using axis or circumference measurements as shown in Figure 4b for two fragments of cholesteatoma. Then, these estimated volumes can be compared intraoperatively to the calculated tissue volume of related pre-operative CT segmentations as shown in Figure 5.

4 Discussion and Conclusion

In this work, we present a new visualization method using multispectral image information to highlight identified cholesteatoma tissue. The overall endoscopic image color impression is preserved and specular reflectances are corrected for the left and right view, respectively. This allows the surgeon to intuitively understand the visually annotated surgical



(a)



(b)

Fig. 4: (a) 3D reconstructed spectral point cloud indicating spatial and depth related spread of cholesteatoma tissue. The point cloud consist of approx. 1.9 million vertices. (b) Enhanced spectral view depicting two different cholesteatoma measurements: cholesteatoma minor/major axis of $8.51/5.31$ mm and cholesteatoma circumference of 21.90 mm.

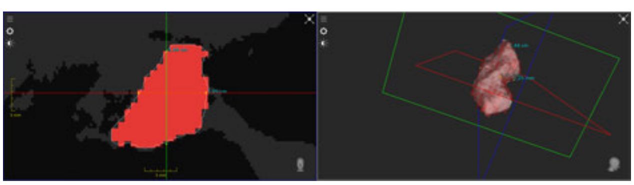


Fig. 5: The segmented cholesteatoma volume of the pre-operative CT (cf. Figure 1). The calculated volume has a size of approximately 2.59 cm^3.

image showing the multispectral added information related to cholesteatoma.

Combining multispectral visualization results and 3D reconstruction opens up new opportunities for intraoperative assistance and image-guided interventions. Especially, the availability of endoscopic spectral 3D data for comparison between intraoperative and pre-operative data. In conclusion, we achieve very promising results with a prototypical stereo-multispectral tissue analysis systems using a sophisticated filter-wheel and 3D endoscope in the operation room.

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Author Statement

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