

Spectral Video in Image-guided Microsurgical Applications: Integrating Imaging Technology into the Clinical Environment and Ergonomic Considerations

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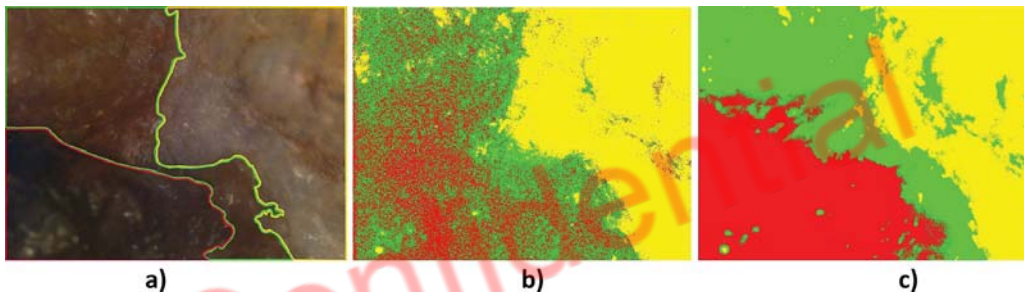


Fig. 1: Real-time spectral video view under the microscope. In this worked-out example of possible applications of spectral technology, the calculated RGB representation of a seven band spectral cube was annotated by an expert neurosurgeon (a). When a bone (yellow), a dura (green), and a muscle tissue (red) was captured in RGB (b) and spectral cube (c), the spectral representation clearly matches better with the expert's annotations. In addition, parts invisible to human eye and RGB sensor are better shown in the spectral image.

Abstract—Numerous visualization tools are involved in surgeon's decision making during a procedure. Image-guided navigations systems such as computed tomography and magnetic resonance have become an integral part of many surgical procedures. In tumor removal microsurgeries, the distinction between a tumor tissue and surrounding normal tissues are often negligible, highly impacted by color contrast and illumination of operative field. To enhance surgical decision making, we investigate the use of real-time spectral imaging in operating room. Coupling a spectral camera with a surgical microscope, however, is challenging due to numerous standards and ergonomic requirements of operating room. In this paper, we fulfill these ergonomic considerations and describe the process of integration of spectral camera in the clinical environment.

Keywords—Intra-operative, spectral video, surgical decision aid, operating room ergonomics, future surgical systems

I. INTRODUCTION

Numerous computational and imaging methods are applied in surgical decision making daily. In microneurosurgery, for example, augmented projection on scalp increases the precision of initial cut [1]. Image fusion obtained from pre-operative systems such as computed tomography (CTI), ultra-

sonography, and magnetic resonance imaging (MRI) is utilized for medical imagery to decrease the invasiveness and improve accuracy and safety of the procedures [2].

Especially in tissue handling and removal, surgeon's precision is critical. To recover properly, tumor mass requires to be removed fully with an optimal safety margin, however, without unnecessary interference to healthy tissues [3]. In these cases, we propose, spectral imaging as a suitable solution to recognize the margin between healthy and affected regions in the tissue. Real-time contrast enhancement, in particular, allows to reveal probable regions and thus, increases the probability of the complete tumor removal [4, 5]. Spectral imaging (SI) and specifically non-ionizing real-time contrast enhancement is promising tool to guide the surgery and increase a likelihood of complete tumor removal [6, 7].

Spectral imaging, although superior in tissue understanding, has been of limited use in operation rooms (OR). Among technological limitations, time consuming image capturing and data processing have traditionally stood out. Moreover, spectral imaging cameras often need additional devices for controlling, data storing, and scene monitoring; together hin-



Fig. 2: Overview of the spectral video camera in the clinical environment. (A) Seven-band spectral video camera, (B) Zeiss OPMI Vario S88 surgical microscope, (C) lifting arm of the suspension system with attached spectral video cabling, (D) main binocular tube for the lead surgeon, (E) the flexible foldable tubular for a surgeon's assistant, (F) screen with the customized software and the real-time preview from spectral video camera, (G) computer with a dedicated frame grabber, (I) multi-Purpose medical cart with electrical transformer, (H) foot control panel allowing to control different surgical microscope functions.

dering to other medical devices in already occupied operation rooms. Indirectly, these limitations have prevented from the use of spectral imaging in OR for their potential risk to patient's safety.

In this work, we overcome all aforementioned obstacles and introduce real-time and mobile spectral imaging device for clinical environments. Figure 2 illustrates the proposed system embedded in the surgical microscope. To fulfill all ergonomic consideration, the proposed solution has been developed in a collaboration between engineers, medical technology researchers and neurosurgeons, and it was installed in situ in a local hospital.

The contribution of this work is following:

- Real-time spectral imaging of human tissues
- Immediate spectral data visualization
- Light-weight mobile solution fitting in OR ergonomics
- Presenting future solutions in tissue contrast enhancement for surgical decision making and limitations of the current system

II. BACKGROUND

A. Spectral imaging techniques

In principle, spectral Imaging (SI) allows to collect and process visual information across the electromagnetic spectrum, creating a unique *spectral signature* for each image pixel. In border enhancement task, light reflected and emitted from a tissue can create a *spectrally-based contrast* at multiple wavelengths. Spatially located spectral signatures have been employed in various tissue identification tasks, such as

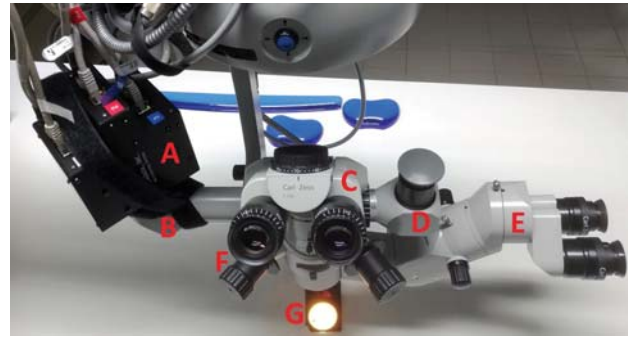


Fig. 3: Attachment of the spectral video camera to the surgical microscope: (A) FluxData video camera body with signal and power supply cabling, (B) SLR camera adapter to the surgical microscope with additional rapid fastening, (C) binocular tube with wide-field eyepieces, (D) second port for external camera, (E) stereo co-observation tube for the assistant, (F) hand-grips for moving the surgical microscope, (G) microscope illumination collimated at the non-fluorescent plate with ex-vivo samples.

lesions in healthy tissues, cancer biomarkers, and fluorescent proteins [8]. When designing a novel medical imaging system, fast spectral characteristics operating on optimized number of spectral components will allow for customizable image acquisition optimized for dedicated application [9].

Various methods allow for acquiring spectral signatures from biological specimens. In *filter-wheel-based imaging*, a set of band-pass filters is used to gather a stack of images which are consequently processed in gray-scale. In this case, spectral resolution highly depends on the number of filters employed. The main challenge in spectral imaging is in capturing moving objects, such as a human retina, since short exposure times are needed [10]. Here, the filter-wheel-based systems come short since they are relatively slow and require additional post-processing phase as spatial image registration.

Variable filters have offered faster approach in spectral imaging. Electro-optical components, such as acousto-optic tunable filter (AOTF) and liquid crystal tunable filter (LCTF) provide wavelength scanned images, however, without any moving parts during image acquisition. Consequently, variable filters allow for fast switching between wavelengths [11, 12, 13]. A drawback of the system is in the low transmission in the blue part of the spectrum, resulting in long exposure times.

Line-scanning spectral imaging (push-broom imaging) is based on acquiring the spectrum from one line of a sample plane at a time by using a PGP (prism-grating-prism). A spectral data cube is obtained from a sequence of line scans by moving either the object or the spectral line camera. The spectral image is obtained in the data processing phase [14].

Finally, the application of *variable light sources* instead of the filters has been promising breakthrough. The spectral cube is captured similarly to the filter-based imaging system, however, multiple narrow-band light sources replace the white light with multiple filters [15]. Available spectrally tunable light sources are straightforward to customize and allow to generate the designed SPD, typically challenging to achieve

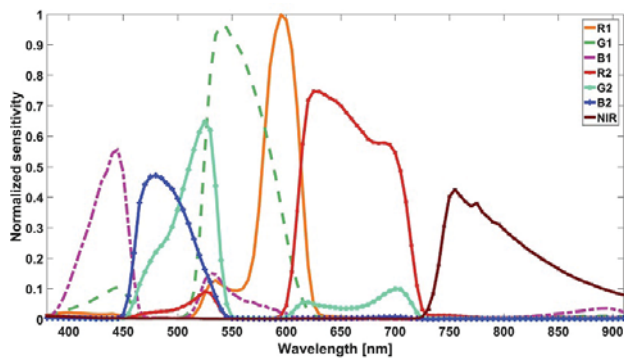


Fig. 4: Spectral sensitivity of the FluxData video camera employed in this study. Images obtained through each characterized band are shown in Figure 6.

when using filters [16, 17]

Working principle of the spectral video camera used in this study is based on a three-CCD (3CCD) camera. 3CCD system solution uses three separate charge-coupled devices (CCDs), where each one receiving filtered red, green, or blue color ranges. In case of used video camera, CCD1 and CCD2 are color sensors having conventional R, G and B filters organized in a Bayer pattern, while CCD3 is a monochromatic sensor (see Fig. 4) [18]. Light coming in from the lens is split by a complex prism into three beams, which are then filtered to produce colored light in different spectral bands. The trichroic prism assembly has high light efficiency and small amount of the incoming light is absorbed. All three CCDs are exposed simultaneously, and therefore the spectral information captured with only a single shot does not require additional post-processing, neither mechanically moving elements.

B. Spectral imaging applications

Spectral imaging has recently received considerable attention in medical and clinical applications due to the efficiency, reliability, and design flexibility [19]. Spectral imaging provides a non-invasive method to analyze spectral absorptions data regarding tissue oxygen saturation [20], to identify abnormalities in dentistry [21], to detect and analyze the intestinal ischemia during surgery [22], for segmentation of abdominal organs [4], and to provide delineation of tumor tissue during neurosurgical operation [7, 23]. Additionally, in this

FluxData 1665MS7	
Resolution	1392 x 1040 pixels
Spectral range/ SI Bands	380-1000nm / 7
Frame rate	30 FPS
Image mode	2xCCD Bayer BG, 1xCCD mono
Digital interface	3 x IEEE-1394b
Dimensions	117.1mm x 111.5mm x 91.9mm
Weight	1.25 kg

TABLE I: Specification of FluxData 1665MS7 used in this study.

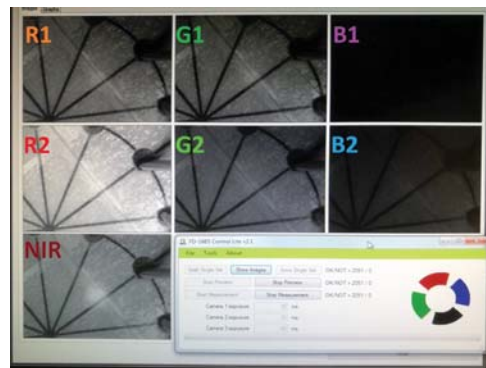


Fig. 5: User interface for spectral video image acquisition during pre-clinical trials.

area the development of LCTF-based SI system allowing for data collection and analysis through a dedicated neurosurgical operation microscope was reported [24]. The acquisition time for a full spectral image (420nm to 720nm with 10nm interval) varied between 2.5 and 3.5 s.

C. Ergonomics in the operating room

In recent years, the ergonomic factors that have been introduced with new technology have not been taken into account [25]. New equipment is often utilized without proper consideration of design issues. Despite of its physical ergonomics related to lifting, moving, positioning, other various factors have to be also well planned. Most of the computer-integrated OR systems comes in separated modules that are kept away from the operating table. Since surgical team typically includes surgeon, surgical assistant, surgical technologist, nurse, and anesthesiologist, free-space space and easy access to non-integrated equipment from the sterile area is required. Also new device or graphical interface should be self-explanatory and all functions should be intuitively controlled. New devices cannot influence operation protocol neither interrupt the surgery. Cabling from equipment should not cause tripping hazards nor hanging on the way between surgeon and patient.

III. METHODS

The integration of spectral video in surgical procedures required steps as device integration, calibration, and testing. In each step, no prior state-of-the-art has been available in clinical settings. Here we report on the chain of actions in successful embedding in the context of OR.

A. Spectral integration: Procedure and Control

The spectral video camera (FluxData 1665MS7) employed in this work has been described and characterized in previous work [18]. The technical description is summarized in Table I and the complete integration is illustrated in Figure 2.

B. Spectral calibration and data acquisition

The real-time spectral imaging system allowed to capture a spectral image with seven spectral bands simultaneously; the preview was available with frame rate 30 fps with the

custom developed software, illustrated in Figure 5. Each CCD was connected to a computer with a separate GigE connection, allowing a time control of sensor-wise exposure and data handling. FluxData video camera was connected to the computer from the upper-back side of the microscope so that the microscope remained mobile and flexible for surgical use. Next, the FluxData video spectral camera was attached to a co-observation tube that enables an assistant surgeon to observe the surgical field at the same magnification as the lead surgeon. The camera was mounted through a lens adapter, available for SRL cameras, and secured with an additional rapid fastenings. Both cabling and camera mount were tested in various maneuvers with microscope to examine the mount stability, wiring flexibility, microscope support, and mobility of the suspension arm.

After the attachment of the video camera, we carefully tested the final balance of the microscope to ensure unrestrictive ergonomics. Accessibility to all microscope functions were examined and approved by the lead neurosurgeon.

The power supply of SI system together with control unit (computer, screen) was completely embedded into a mobile electronics cart (Knurr EliMobile) and supplied from an electrical transformer. Hospital ICT services inspected the system for a potential leakage current and approved the system as of the highest safety. The approval was required for moving the SI system to the operation room and for connecting it to electrical system there. The length of the SI system cabling allowed to keep one meter safety distance between the mobile cart and the microscope, as required by the ICT services. If needed, all wires could be instantly disconnected and the complete embedded SI system removed from the microscope.

The SI system needs to be calibrated against a white reflectance reference every time before the measurements. During the measurement of white reference, the real-time spectral preview allowed us to correct exposure times selection for every CCD sensor. To remove noise from the system, we also measured a black reference with the same exposure times as in the case of white reference. All measured spectral images were normalized with the intensity values of the original spectral images with following equation:

$$I_R = \frac{I_{raw} - I_{dark}}{I_{white} - I_{dark}} \quad (1)$$

where I_R is the corrected relative reflectance image, I_{raw} is the original image without any corrections, I_{white} is the white reference image obtained from the calibration procedure using Spectralon white reflectance standard, and I_{dark} is the dark image.

IV. PRE-CLINICAL TEST AND TISSUE PREPARATION

The SI system functionality was tested using three different ex-vivo tissues: bone, dura mater, and muscle. Trials were conducted in the wet lab at the Microsurgery Centre in Kuopio University Hospital (see Figure 2) with respect to ethical permissions and the institutional approval. In this study, the employed tissues were acquired from freshly frozen temporal

bones. Sample tissues were dissected, prepared, and annotated by ENT (an ear, nose and throat) specialist. Spectral images were captured immediately after defrosting and preparation.

During the clinical test, the tissues were positioned at a dark non-fluorescent specimen tray and brought under the microscope. Each spectral frame capture consisted of seven spectral bands ($\sim 20\text{Mb}$). The test video took one minute of sequential spectral video at 30 fps; the final size of the file was $\sim 11.5\text{GB}$. The captured spectral video of the operative field was displayed on the control unit screen where each spectral band was presented separately, as in Figure 5. The RAW spectral images were immediately available for further evaluation (see Figure 6).

V. RESULTS

The results of our work are two folds. Here were report on spectral video output received during the clinical test. Next, we discuss lessons learned in requirements collected when designing the portable on-site medical spectral imaging system.

A. Real-time enhancement of human tissues

Visualizations of images for each spectral band were available in real-time, therefore, the difference in contrast between recorded tissues were immediately apparent in the graphical user interface, as presented in Figure 6. When the information stored in the spectral cube is used, spectral dimension reduction e.g., color-based segmentation, has to be applied first. For this purposes, we applied unsupervised K-mean clustering. Figure 1 demonstrates results after achieved segmentation where traditional RGB image and seven spectral band cube were used as an input. The presented video camera provided highly detailed information of spectral signatures from studied tissues (see Figure 8) and revealed well separated borders in tissues. The border delineation was similar to borders annotated manually by the ENT specialist.

B. Lessons learned

As a result, we report on the requirements collected when embedding spectral video in the clinical environment. Table II summarizes lessons learned.

The main restrictions for in-vivo measurements was the size and the weight of the spectral camera. If the camera is too heavy, the surgical microscope could not have been stabilized and in the end auto-balancing procedure was unsuccessful. Unbalanced microscope disqualifies any SI system from being used in OR. Similarly, if the camera is too bulky, it would have interfered with the surgical procedure, microscope's maneuverability and accessibility to manually adjustable knobs. Anything listed above could cause obstruction of surgeon's work or even risk the safety of the patient. Understanding human limitations in early stage of medical device development can reduce crucial errors, Therefore, system integrations should be repetitively followed by insights from a large group of end users.

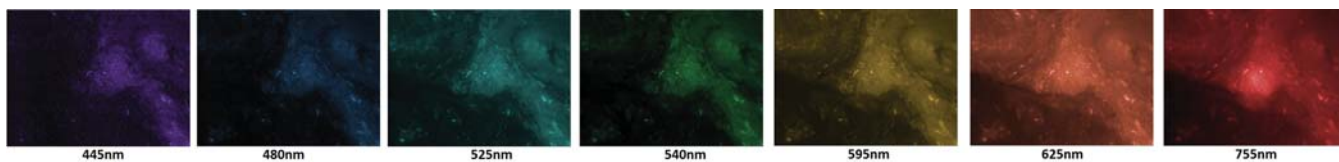


Fig. 6: The RAW output image from spectral video camera (original gray-scale image was colored for spectral band representation). Each presented band contains unique spectral information of the reflectance of every spatial pixel. Different interaction between presented tissues and the incident light can be noticed for each band.

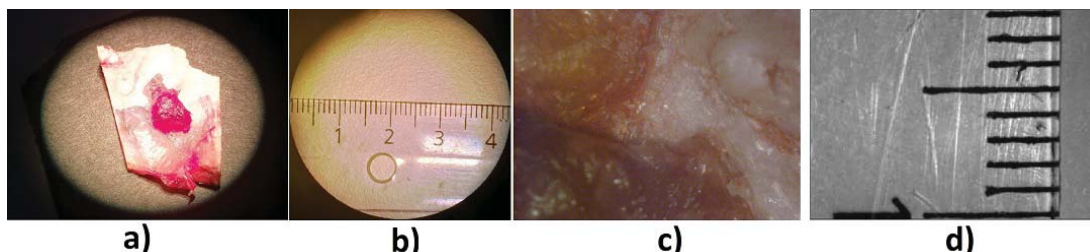


Fig. 7: Field of view comparison between the main binocular tube and the spectral video camera: (A) Studied ex-vivo tissues seen from the side of the microscope, (B) RGB image captured from the eyepiece of the main binocular tube, (C) RGB image calculated from the data obtained by the spectral video camera, (D) Actual physical size of the area captured by spectral video camera. All images were captured while keeping the same adjustments of the microscope.

Requirements	Specification
System installation and imaging time	Complete usability of the system has to be obtained in short time. In any case of interfering with surgeon's work, SI system easy removal/cabling disconnection has to be allowed. Complete imaging is limited to several seconds for in-vivo imaging.
Size, weight, cabling and system portability	The size of the system has to allow deployment in surgical operating rooms. All components have to be stable and supplied from secured power source. Weight of camera and its size is limited by the space around binocular tube and lifting arm capability.
Imaging protocol and operational feasibility	Imaging procedure should not interfere with surgeon's protocol. Calibration should be done beforehand. The design of equipment and imaging procedure have to be easy and intuitive. The systems has to always provide a robust and reliable real-time output.
System Sterility	The SI system has to be free from live microorganisms. Attached camera cannot disturb in using a surgical microscope drape.
Ergonomics	The design of medical equipment has to be focused on the needs of the end users practitioners and specialists. The interaction between human and designed system has to guarantee its usability.

TABLE II: Requirements derived from design and implementation of a portable spectral imaging system.

The imaging device fulfilled all the requirements and was available to be carried into an operating room or an endoscopy suite. The simple mount and preserved microscope mobility was achieved and tested in the clinical environment.

VI. DISCUSSION AND CONCLUSION

Emerging spectral imaging technology offers a novel decision supporting instrument, suitable in situations where pathological targets and vital healthy anatomies are hardly distinguishable by the surgeon's vision. Currently available spectral imaging medical applications have been found out as impractical and infeasible due to their slow processing times and high spatial demands. In this work, we introduced a spectral imaging system with focus on a simple mount, real-time processing, and non-invasive examination and classification of the tissues.

The proposed SI system was tested in the clinical environment with micro(neuro)surgeons. During testing, the spectral signatures of three different ex-vivo tissues were acquired in real-time at 30 FPS. Using a SLR dedicated camera adapter, the current SI system reduced the field of view only by 25% when compared to the original scene. Despite of limited field of view, that could be enlarged by incorporating additional optics, the current attachment allowed to investigate regions

of the interest, while fulfilling all safety and ergonomics requirements.

The spectral signatures were available instantly and their difference in spectral properties in visible range were demon-

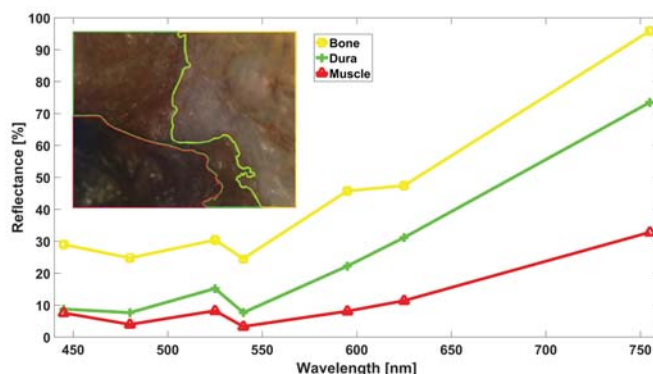


Fig. 8: RGB image used for annotations of measured ex-vivo tissues made by ENT specialist (top left). Spectral reflectance curve of the following tissues: bone, dura, muscle. Reflectance was obtained by spectral video camera from the manually selected area of the image within annotated borders. Color of each curve corresponds to the same color used for area annotation.

strated at side monitors. The final spectral cubes were archived synchronously with the conduct of the surgery for later analysis.

VII. FUTURE RESEARCH

The reported tissue separation was based on visual evaluations of an expert neurosurgeon and presented preliminary tests to demonstrate results delivered by our developed imaging system. In future work, we will extend the systematic evaluation with further studies of pathological reports, including quantitative information and evaluation with respect to tissue classification. Future software development of the described SI system will employ spectral dimension reduction methods like segmentation based on color and texture for better real-time tissue visualization.

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