AI-Enabled Fibre-Based Raman Spectroscopy and Multimodal Nonlinear Imaging for Intraoperative Tumor Margin Assessment and See-and-Treat Workflows

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Abstract

Accurate and fast intraoperative identification of malignant tissue remains a major challenge in oncologic surgery. Conventional strategies such as visual inspection, palpation, and frozen-section histology are limited by subjectivity, invasiveness, and turnaround time, which can lead to uncertainty in tumor margin assessment. Label-free optical technologies offer a promising alternative by providing real-time chemical and structural readouts without staining or exogenous contrast agents. In this contribution, we discuss recent progress toward clinically translatable biophotonic platforms that combine high-resolution morphochemical imaging with AI-based decision support.

A key technology direction is the development of fiber-based spectroscopic and imaging tools for intraoperative tissue assessment. One highlight is the RamanInvaScope fiber probe, which is already being applied in in vivo settings to support intraoperative decision-making. As an MDR-oriented device platform, RamanInvaScope represents a central example of clinical translation and is currently being further developed and evaluated for routine operation in surgical environments. In parallel, we advance multimodal nonlinear imaging approaches that integrate coherent Raman microscopy (CARS/SRS) with complementary contrasts such as two-photon excited fluorescence (TPEF) and second harmonic generation (SHG). By combining biochemical and morphological information, these systems aim to deliver instantaneous intraoperative readouts that support tumor margin delineation and reduce uncertainty during resection. Beyond diagnostics, this multimodal strategy also establishes a pathway toward future “see-and-treat” workflows, where optical information directly guides intervention, potentially including selective laser-based tissue ablation.

To enable robust, operator-independent interpretation of the acquired data, we employ AI-driven spectral classification and image analysis, with a focus on automated tissue discrimination and semantic segmentation in clinically relevant scenarios. In addition to rapid multimodal screening, we highlight hyperspectral coherent Raman imaging (CRI) as a complementary route toward increased chemical specificity. Broadband coherent Raman methods such as BCARS and broadband SRS provide full vibrational fingerprints and therefore support more detailed tissue differentiation and the development of data-driven digital histopathology concepts. Altogether, the convergence of multimodal fibre-based photonics, AI-based analysis, and hyperspectral Raman spectroscopy paves the way toward precision-guided oncologic surgery with improved reliability and clinical impact.

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