Personalized Digital Twins for Interventional Healthcare

Laura Marcu, University of California, Davis, CA, USA

Abstract

The emerging paradigm of surgical digital twins seeks to integrate patient-specific data, computational modeling, and intraoperative sensing to enable adaptive, data-driven surgical decision-making. Within this framework, photonic technologies represent a uniquely enabling measurement substrate, providing quantitative, label-free, and physically grounded assessments of tissue pathophysiology and function directly at the point of care. Optical imaging and sensing modalities—including fluorescence-guided and lifetime imaging, Raman spectroscopy, optical coherence tomography, and diffuse optical spectroscopy—extend image-guided surgery beyond anatomical navigation toward real-time molecular and metabolic characterization of tissue. These techniques can enable intraoperative virtual histology–like representations, functional evaluation of perfusion and metabolism, and sensitive detection of residual disease and biochemical heterogeneity at surgical margins, all of which directly inform resection strategies. In this context, optical guidance functions not merely as an adjunct visualization tool but as a verification and feedback layer that continuously updates and constrains predictive models during surgical intervention, effectively closing the loop between model prediction and surgical execution. Continued development and clinical translation of these approaches, including efforts supported by the NIH–NIBIB National Center for Interventional Biophotonics Technologies (NCIBT) at UC Davis, will be essential for enabling adaptive, data-driven surgical workflows and improving precision in cancer and complex disease interventions.