Ultrasound in Med. & Biol., Vol. ■■, No. ■■, pp. ■■–■■, ■■

0301-5629/$ - see front matter

https://doi.org/10.1016/j.ultrasmedbio.2018.05.003

● *Clinical Note*

HIGH-FREQUENCY MICRO-ULTRASOUND IMAGING AND OPTICAL TOPOGRAPHIC IMAGING FOR SPINAL SURGERY: INITIAL EXPERIENCES

Raphael Jakubovic,[*,†] Joel Ramjist,[†] Shaurya Gupta,[†] Daipayan Guha,[†,‡] Arjun Sahgal,[§] F. Stuart Foster,[¶] and Victor X.D. Yang[*,†,‡,‖]

[*] Department of Physics, Ryerson University, Toronto, Ontario M5B 2K3, Canada; [†] Biophotonics and Bioengineering Laboratory, Ryerson University/Sunnybrook Health Sciences Centre, Toronto, Ontario M4N 3M5, Canada; [‡] Department of Neurosurgery, Sunnybrook Health Sciences Centre, Toronto, Ontario M4N 3M5, Canada; [§] Department of Radiation Oncology, Sunnybrook Health Sciences Centre, Toronto, Ontario M4N 3M5, Canada; [¶] Department of Physical Sciences, Odette Cancer Research Program, Sunnybrook Research Institute, Toronto, Ontario M4N 3M5, Canada; and [‖] Department of Electrical Engineering, Ryerson University, Toronto, Ontario M5B 2K3, Canada

(*Received* 25 *May* 2017; *revised* 22 *April* 2018; *in final form* 1 *May* 2018)

Abstract—High frequency micro-ultrasound (µUS) transducers with central frequencies up to 50 MHz facilitate dynamic visualization of patient anatomy with minimal disruption of the surgical work flow. Micro-ultrasound improves spatial resolution over conventional ultrasound imaging from millimeter to micrometer, but compromises depth penetration. This trade-off is sufficient during an open surgery in which the bone is removed and the ultrasound probe can be placed into the surgical cavity. By fusing µUS with pre-operative imaging and tracking the ultrasound probe intra-operatively using our optical topographic imaging technology, we can provide dynamic feedback during surgery, thus affecting clinical decision making. We present our initial experience using high-frequency µUS imaging during spinal procedures. Micro-ultrasound images were obtained in five spinal procedures. Medical rationale for use of µUS was provided for each patient. Surgical procedures were performed using the standard clinical practice with bone removal to facilitate real-time ultrasound imaging of the soft tissue. During surgery, the µUS probe was registered to the pre-operative computed tomography and magnetic resonance images. Images obtained comprised five spinal decompression surgeries (four tumor resections, one cystic synovial mass). Micro-ultrasound images obtained during spine surgery delineated exquisite detailing of the spinal anatomy including white matter and gray matter tracts and nerve roots and allowed accurate assessment of the extent of decompression/tumor resection. In conclusion, tracked µUS enables real-time imaging of the surgical cavity, conferring significant qualitative improvement over conventional ultrasound. (E-mail: victor.yang@sunnybrook.ca) © 2018 Published by Elsevier Inc. on behalf of World Federation for Ultrasound in Medicine & Biology.

Key Words: **Micro-ultrasound imaging, High-frequency ultrasound imaging, Spine surgery, Surgical navigation, Optical topographic imaging.**

INTRODUCTION

Intra-operative imaging has gained prominence in the field of image-guided surgery with recent advancement in various regional or whole-body imaging modalities. Intra-operative imaging aides the physician in visualizing patients' anatomy to make real-time decisions about their surgical plan based on the current state of the patient. Adoption of current imaging modalities into a neurosurgical setting, especially in the spine, has been limited by concerns with speed, ease of use, cumbersome size, sterility and/or increased exposure to ionizing radiation. (Hartl et al. 2013; Manbachi et al. 2014; Nelson et al. 2014) In contrast, ultrasound enjoys widespread use within cranial neurosurgery as it provides a fast, non-ionizing method to visualize the patient anatomy without causing major disruption of the surgical work flow (Bucholz et al. 2001). Although its adoptability for spinal surgeries has been limited, ultrasound has proven particularly useful for localization and visualization during tumor resection and spinal decompression (Kolstad et al. 2006; Prada et al. 2014; Zhou et al. 2011).

Address correspondence to: Victor X.D. Yang, Department of Neurosurgery, Sunnybrook Health Sciences Centre, University of Toronto, 2075 Bayview Avenue, Toronto, Ontario M4 N 3 M5, Canada. E-mail: victor.yang@sunnybrook.ca

Conflict of Interest: Dr. Stuart Foster acts as a consultant to FUJIFILM VisualSonics, Inc.

High-frequency micro-ultrasound (µUS) offers a distinct resolution advantage over conventional ultrasound while compromising with reduced penetration depth (Foster et al. 2011). Considering the resolution necessary for neurosurgical applications (within 2 mm of accuracy), a higher resolution system such as that offered by µUS is necessary to track and update tissue boundaries during surgery, potentially improving surgical outcomes. µUS has been used in a variety of applications including the monitoring of arteriovenous fistulas (Jaberi et al. 2011), pediatric vascular development (Latham et al. 2013), hand transplantation (Kaufman et al. 2012) and intima and medial thickening for a variety of indications (Bohman et al. 2010; Eklund et al. 2014; Johansson et al. 2010; Osika et al. 2007; Sarkola et al. 2012). Integration of these probes into the operating room will enable dynamic intra-operative imaging capable of delineating white matter tracts, nerve roots, vascular networks and tumor margins with micrometer resolution. µUS is particularly suited for spinal procedures as the depth requirements are minimal, considering the bone is quite often removed and the ultrasound probe can be advanced directly into the surgical bed.

Fusion of µUS with pre-operative CT or MRI provides real-time anatomic context to the surgeon, bridging the gap from millimeter to micrometer intra-operatively. Although previous works have established the framework for optical tracking of the ultrasound probe, providing inherent ultrasound image registration to pre-acquired computed tomography (CT) or magnetic resonance imaging (MRI), tracked µUS has not been explored (Kolstad et al. 2006; Prada et al. 2014). Integral to this approach and to ensure surgeon adoption is the ability to achieve adequate navigation accuracy without compromising the surgical work flow. As such, we have fused our recently validated optical topographic imaging (OTI) navigation system (submillimeter registration accuracy, 1–2 mm application accuracy (Jakubovic et al. 2017)) with three µUS transducers (central frequencies: 15 MHz, 30 and 50 MHz; axial resolution: 100, 50 and 30 µm).

In this work, we describe the first experiences using intra-operative µUS and our progression toward fusing OTI with µUS. This work establishes navigated high-frequency µUS as capable of providing real-time surgical feedback, which can then be incorporated into the surgical plan, thus informing clinical course.

METHODS

Four patients were recruited into our existing research ethics board-approved spine navigation study (No.004-2015) at Sunnybrook Health Sciences Centre. Micro-ultrasound imaging (VevoMD Imaging Platform, FUJIFILM VisualSonics, Inc., Toronto, ON, Canada) was performed during surgery through the Health Canada Special Access program. A fifth patient was recruited into our research ethics board-approved neurosurgical µUS study (No. 210-2016). Informed consent was obtained from all human patients. Inclusion criteria comprised patients scheduled to undergo spinal decompression with laminectomy and tumor resection. Surgical procedures were not altered in any way and were performed according to the established standard of care.

Briefly, the current standard-practice spinal surgery involves exposure and subsequent removal of the bone with or without X-ray imaging confirmation. This is followed by inspection of the surgical incision site with ultrasound imaging. The surgical cavity was filled with saline and sterile ultrasound probes were inserted into the cavity to image using a sterile sheath and proper re-processing protocol using CIDEX Activated Glutaraldehyde Solution or ethylene oxide (EtO) for pre-sterilization. The surgical target was imaged first by a standard ultrasound imaging platform (Hitachi Aloka Inc., Twinsburg, OH, USA) with central frequency and bandwidth of 10 and 4 MHz, respectively, before being imaged by the µUS probes. Pre-operative MRI was fused to pre-operative CT using a semi-automatic rigid body registration utilizing mutual information before surgery with Analyze 12.0 medical imaging software (AnalyzeDirect Inc., Stilwell, KS, USA).

During surgery, the µUS probe was registered to the pre-operative CT and MR images using our novel OTI system (Fig. 1). Micro-ultrasound probe selection was at the discretion of the surgeon. Three µUS probes with central frequencies of 15, 30 and 50 MHz were available for this study. The OTI system utilizes structured light to obtain a 3-D point cloud of the surface anatomy. The system consists of binocular infrared cameras surrounded by infrared light-emitting diodes for tracking of surgical tools, binocular flash cameras for static imaging and a projector. A pattern of light with known structure is projected onto the surface of the patient and recorded by the binocular cameras. By analysis of the depth distortions of the projected light pattern, a 3-D point cloud is plotted, corresponding to the topographic variations of the surface. The acquired topographic image is registered to pre-operative imaging data utilizing an iterative closest point algorithm. Briefly, the surgeon follows a point-picking protocol to localize the patient anatomy with respect to the pre-acquired CT or MR images and the algorithm evaluates a cost function to minimize disparity between the images. Once the patient anatomy is registered to the pre-acquired CT or MR images, infrared tracking of the µUS probe is made possible by utilizing binocular infrared cameras and our in-house designed µUS probe tracker. By tracking the µUS probe, inherent registration of the µUS image to pre-acquired CT or MRI is achieved, relying on