ASTRO: A Novel Robotic Tool for Laser Surgery of the Prostate

S. Russo[1], P. Dario[1], A. Menciassi[1]

[1]The BioRobotics Institute, Scuola Superiore Sant'Anna

s.russo@sssup.it

INTRODUCTION

Transurethral laser surgery of the prostate for the treatment of benign prostatic hyperplasia (BPH) is traditionally performed via the resectoscope (Fig. 1), a telescopic straight instrument that allows only translation and rotation along/about its longitudinal axis, thus dramatically limiting dexterity and tactile feedback at the tip. These issues represent a limitation since, in most procedures, the laser tip must be in contact with prostatic tissue [1]. In particular, the closer the contact, the better will be the distribution of laser energy and consequently tissue ablation will be more homogeneous; homogeneous ablation avoids formation of craters that can entrap tissue fragments, debris and perfusion liquid that partially absorb and scatter the incident light thereby hindering laser effect [2]. A number of attempts to achieve force and tactile sensing in minimally invasive surgery (MIS) are reported in literature [3]-[7]. Different actuation strategies for flexible, continuum and snake-like robots for MIS can be found in [8]-[11]. In this paper, we present the design and preliminary evaluation of a novel, miniaturized, flexible robotic tool for laser assisted transurethral surgery of BPH. The aim of the system is to allow a more homogeneous tissue ablation, in order to speed up surgical procedure duration and recovery time. The design includes an optical fiber based tactile sensor system to monitor contact between prostatic tissue and laser, and a cable driven actuation mechanism to steer the tip of the laser. Preliminary study demonstrated the theoretical ability of the system to sense contact forces up to 0.4 mN and to steer the tip in 3D of about ± 10 °.

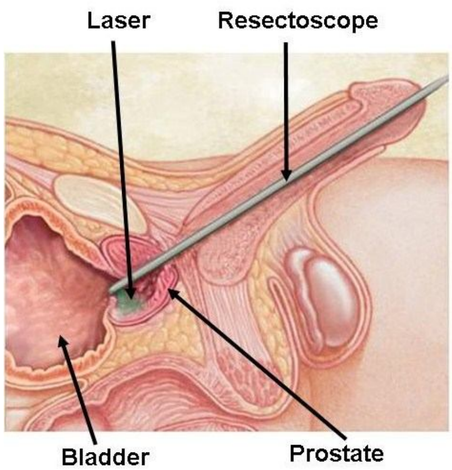

Fig. 1 Overview of prostate laser ablation procedure. The resectoscope is inserted through the urethra to access the prostate.

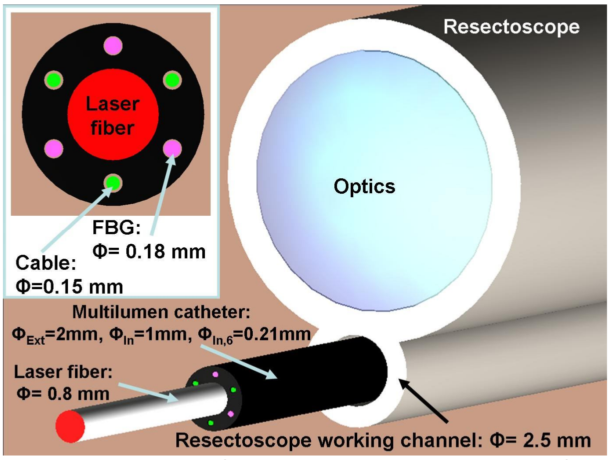

Fig. 2 CAD model of the ASTRO system and detail of the section.

MATERIALS AND METHODS

This paper presents the design of a novel, miniaturized, flexible robotic tool for transurethral laser surgery of BPH: ASTRO (Actuated and Sensorised Tool for laseR assisted surgery of the prOstate), shown in Fig. 2. ASTRO consists of a flexible multilumen catheter with an outer diameter of 2 mm (Φ_{Ext}), in order to be inserted in the working channel of a commercial resectoscope (Karl Storz 27042LV: Φ= 2.5 mm), and a central working channel of 1 mm (Φ_{In}), which will allow the insertion of a commercial laser fiber for the ablation of the prostate. Moreover, ASTRO has six small lumens ($\Phi_{In,6}$= 0.21 mm), around the periphery forming the vertices of a hexagon, to integrate sensors for contact detection between laser and prostatic tissue, and cables for actuation. Three Fiber Bragg Grating (FBG) sensors (SmartFBG, Smart Fibres) are integrated in a way to allow 3 DOF contact force sensing at the tip of the laser. The multilumen is in black opaque polyamide (PA12) in order to ensure optical isolation between the laser and the FBG sensors. Young's modulus of PA12 is 1.1 GPa, thus allowing the multilumen to serve both as a mechanical continuum for strain transmission between laser and sensors (that have a coating of polyimide with a Young's modulus of 2.5 GPa), but also to be flexible enough to be bent by cables. The melting point of PA12 (178 °C) is compatible with the application since temperature of prostatic tissue vaporization is around 100 °C. Moreover, the temperature drops dramatically as soon as we move away from the ablation site, because of saline solution's continuous flow inside the resectoscope sheath. FBG technology has been chosen because of its small dimensions (Φ= 0.18 mm), electromagnetic interference immunity, sterilizability, and biocompatibility. These sensors are affected by cross-sensitivity of temperature and strain, the shift in Bragg wavelength Δλ being expressed as:

$$\Delta\lambda = k_{\varepsilon}\varepsilon + k_T \Delta T \quad (1)$$

where k_{ε} is the strain sensitivity, ε is the strain, k_T is the temperature sensitivity and ΔT is the variation of temperature. Redundant FBG sensors are used to compensate for errors due to temperature effects, such as in [5]. Thanks to the saline solution's continuous flow, we can assume that temperature variations will not be high at the sensor level: three FBG sensors are embedded parallel within ASTRO at 120° from one another, at 2 cm away from the tip of the laser. In this way, sensors experience the same ΔT, but different strain in terms of compression and tension, and therefore the temperature compensation can be performed easily. Three nylon cables (Φ= 0.15 mm), that will be actuated by motors, are fixed at the tip of ASTRO and used for laser steering. FEA simulations were performed in order to assess the adequacy of sensor and actuation strategy choices.

RESULTS AND DISCUSSION

The best positioning of the FBG sensors, along with the minimum detectable ASTRO contact force, were estimated with FEA. Iterations of decreasing contact force, applied at the ASTRO tip, versus computed strain measured at the FBG level were performed: the results of the simulations are reported in Fig. 3 (a). Since the FBG strain resolution is given as 0.4 με, the minimum force that can be measured, positioning the FBG sensors at 2 cm from the laser tip, resulted in 0.4 mN, as shown in Fig. 3 (b). As regards actuation, the necessary pulling force, to be applied on a cable by a motor, for steering the laser to reach a proper contact with prostatic tissue, was estimated with FEA. Since the diameter of the prostatic urethra in a healthy prostate is around 6 mm and the ASTRO tip is 2 cm length (shown respectively as d and l in Fig. 4 (a)), a tip bending of ± 10 ° (θ) was estimated to be sufficient to have a proper contact in all cases. Thus, the required pulling force resulted in 12 N, as shown in Fig. 4 (b). Future works will be the fabrication and testing. In conclusion, the proposed system could allow a homogeneous treatment of BPH, shortening the operative and recovery time. Furthermore, it is compatible with current commercial instrumentations (resectopes and laser fibers).

ACKNOWLEDGEMENTS

This research is supported by MILoRDS Project (Minimally Invasive Laser Robotic assisted Diagnosis and Surgery) funded by Tuscany Region, POR CReO Fesr 2007-2013.

REFERENCES

[1] M. Issa, et al., The Evolution of Laser Therapy in the Treatment of Benign Prostatic Hyperplasia, Reviews in Urology, 7, 9, 2005.

[2] H.Kang, et al., In Vitro Investigation of Wavelength-Dependent Tissue Ablation: Laser Prostatectomy Between 532nm and 2.01 mm, Lasers in Surgery and Medicine, 42, 237–44, 2010.

[3] E. Van Der Putten, et al., Haptics in minimally invasive surgery – a review, Minimally Invasive Therapy, 17:1, 3–16, 2008.

[4] P. Puangmali, et al., State-of-the-Art in Force and Tactile Sensing for Minimally Invasive Surgery, IEEE Sensors Journal, 8, 4, 2008.

[5] I. Iordachita, et al., A sub-millimetric, 0.25 mN resolution fully integrated fiber optic force sensing tool for retinal surgery, Int. J. Comput. Assist. Radiol. Surg., 4(4), 383-90, 2009.

[6] Y. Hu, et al., Bioinspired 3-D Tactile Sensor for Minimally Invasive Surgery, Journal Of Microelectromechanical Systems, 19, 6, 2010.

[7] P. Polygerinos, et al., Measuring Tip and Side Forces of a Novel Catheter Prototype: A Feasibility Study, IEEE/RSJ International Conference on Intelligent Robots and Systems, 11-15, 2009.

[8] Y. Fu, et al., Steerable catheters in minimally invasive vascular surgery, Int J Med Robotics Comput Assist Surg, 5: 381–391, 2009.

[9] K. Harada, et al., Bending laser manilupator for intrauterine surgery, IEEE International Conference on Robotics and Automation, 611-616, 2007.

[10] H. Mingyen, et al., Towards the development of a SMA-actuated MRI-compatible tendon-driven neurosurgical robot, IEEE International Conference on Robotics and Automation, 683-688, 2012.

[11] K. Ikuta, et al., Pressure Pulse Drive: A Control Method for the Precise Bending of Hydraulic Active Catheters, IEEE Transactions on Mechantronics, 17(5), 876-883, 2012.

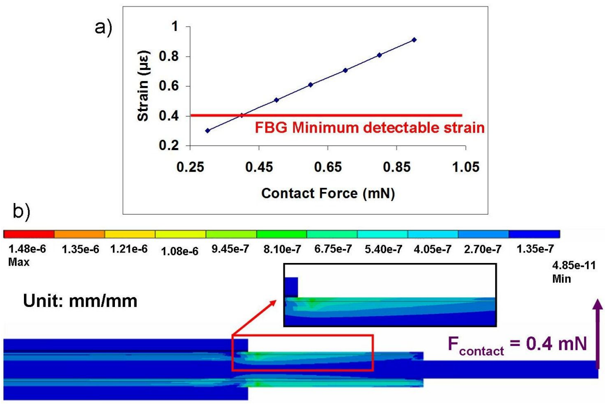

Fig. 3 Evaluation of minimum detectable contact force of ASTRO system: a) contact force applied versus computed strain measured at the FBG level, b) FEA: Von Mises stress in the section of ASTRO system with 0.4 mN contact force applied.

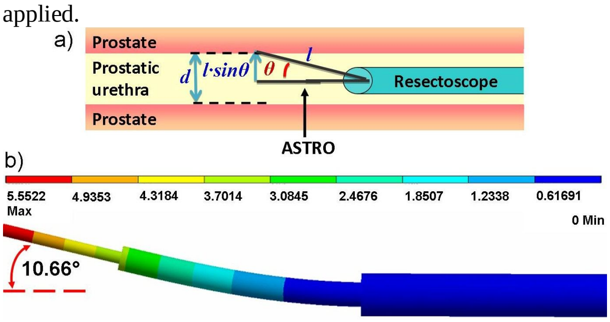

Fig. 4 ASTRO tip steering: a) estimation of necessary tip bending, b) FEA: tip steering with 12 N cable pulling force.