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Citation for published version:

Risbridger, DR, Beck, RJ, Mohanan, SPC, McCarthy, A, Shires, M, Jayne, D & Shephard, JD 2019, Novel optical technologies for ultrashort pulsed laser surgery. in A Amelink & SK Nadkarni (eds), *Novel Biophotonics Techniques and Applications V.*, 110751N, Proceedings of SPIE, vol. 11075, SPIE, European Conferences on Biomedical Optics 2019, Munich, Germany, 26/06/19. <https://doi.org/10.1117/12.2527081>

Digital Object Identifier (DOI):

[10.1117/12.2527081](https://doi.org/10.1117/12.2527081)

Link:

[Link to publication record in Heriot-Watt Research Portal](#)

Document Version:

Publisher's PDF, also known as Version of record

Published In:

Novel Biophotonics Techniques and Applications V

Publisher Rights Statement:

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Proceedings Volume 11075, Novel Biophotonics Techniques and Applications V; 110751N (2019)
<https://doi.org/10.1117/12.2527081>

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SPIE.

Event: European Conferences on Biomedical Optics, 2019, Munich, Germany

Novel optical technologies for ultrashort pulsed laser surgery

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ABSTRACT

Colorectal cancer is the fourth-most prominent cause of cancer related fatalities across the globe. Conventional electrocautery techniques used in the resection of colon tissue cause a relatively high degree of collateral damage to the healthy tissues bordering the target sites. Ultrafast infrared lasers offer significantly improved localisation in the ablation of such biological tissues arising from a plasma-mediated ablation mechanism. This improved localisation is two-fold, with lateral confinement and precise depth control being advantageous in minimising thermal necrosis and avoiding bowel perforation respectively.

Various laser scanning strategies and optical elements have been investigated, with the intent to exploit the inherent advantages offered from applying photonics to these procedures. Evaluation of the corresponding ablation characteristics was carried out using three-dimensional optical profilometry and histological analysis. If adopted in operating theatres, surgeons could benefit from more control when carrying out resection of neoplasia in the mucosal or submucosal layers of colon tissue, compared to previous electrocautery methods.

Keywords: Ultrafast, laser surgery, plasma-mediated ablation, tissue, fibre delivery, laser, infrared, cancer.

1. INTRODUCTION

Ultrashort pulsed lasers have been incorporated successfully into various medical procedures, offering precise resection with minimal thermal damage to the adjacent tissue surrounding the surgical zone. Previous methods involved using continuous wave (CW) lasers, long pulsed lasers or electrocautery tools which have all been shown to be prone to higher degrees of thermal damage¹.

Conventional laser based surgical modalities rely on the linear absorption of the laser pulse². As a result the thermal ablation and necrosis observed on the tissue depends on the energy and the wavelength of the incident laser. The laser pulse is absorbed by the tissue chromophore, leading to the significant thermal damage courtesy of the heating and vaporization of the targeted tissue which occurs. This surgical modality is therefore not suitable for bowel resection where higher precision and control is required.

Surgical procedures upon the thin structures within the human body require high precision, minimising necrotic tissue margins to avoid severe complications. For example, precise control of both the lateral extent of necrotic tissue and depth of resection are of paramount importance in bowel surgery, as bowel perforation leads to high rates of morbidity and even potential mortality. To investigate optimal processing parameters and setups, picosecond laser processing strategies with high fluence values (above the plasma formation threshold) are used to resect the tissue of a porcine model^{3,4}.

Hollow-core negative-curvature optical fibres have demonstrated delivery of such appropriately high energy densities at infrared wavelengths⁵. These offer the potential for picosecond pulse delivery while maintaining low bend radii making them ideally suited for minimally invasive applications.

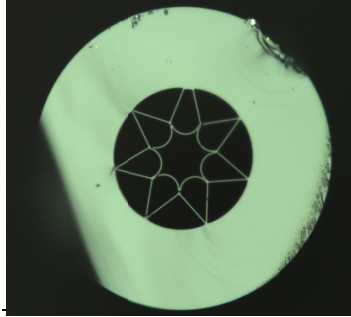


Figure 1: SEM Image of Novel Silica Negative Curvature Fibre.

Another promising, recent development within the field of minimally invasive surgery is the application of Bessel beams towards tissue ablation⁶. It has been well documented that the most efficient technique to generate a Bessel beam involves illuminating an axicon with a Gaussian beam. In reality, this generates a “quasi-Bessel beam”, as the conventional definition of a propagation invariant Bessel beam would require an infinite amount of energy input. Regardless, the improved depth-of-focus offered by a Bessel beam is linked to the non-diffractive nature of the core. This leads to a more consistent intensity profile, which has already shown promise in material processing applications, where the use of a quasi-Bessel beam (opposed to a Gaussian beam) has resulted in improved ablation rates and increased aspect ratios of the resultant ablation craters⁷.

These traits are particularly appealing when applied to biological tissues, as the “self-limiting” propagation of the quasi-Bessel beams means that they have the potential to offer precise depth control. This, paired with the inhomogeneous and highly scattering nature of biological tissues, makes them ideally suited for carrying out photoablation in various surgical procedures.

2. METHODOLOGY & RESULTS

The laser used is commercially available and has a central wavelength of 1028 ± 5 nm, variable repetition rates of 60 kHz to 1 MHz and tunable pulse widths ranging from 232 fs to 10 ps. A maximum average power of 5 W and a base repetition rate of 60 kHz was predominantly used for the ablation trials. Examples of histological images of ablated porcine colon tissue sections are shown in figure 2.

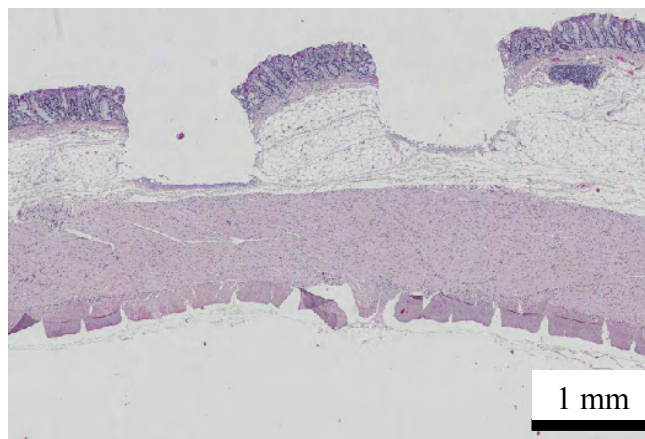


Figure 2: Histology image of laser ablated section of *ex-vivo* porcine colon tissue with 20 kHz pulse repetition rate.

Recent work has involved testing various axicons of differing physical angles. The outputs of these axicons were aligned with a 5x magnification reimaging setup. After carrying out some theoretical modelling of the axial intensity profiles for the axicons some laser resection studies were carried out on *ex-vivo* porcine colon tissue samples. The corresponding ablation characteristics were evaluated using three-dimensional optical profilometry and histopathology.

Comparing the quasi-Bessel beam ablation profiles to the Gaussian ones, higher aspect ratios were achieved using ultrashort pulses with the reimaged axicon setup. The average aspect ratio obtained with these parameters was approximately 3:1. These ultrashort pulse-widths benefitted from a higher degree of lateral confinement. However, for minimally invasive applications efficient fibre delivery is necessary. With this context it becomes clear that longer pulse lengths would be desirable, as nonlinear effects that are encountered in the fibre when delivering high peak power pulses in the femtosecond regime could be avoided.

3. CONCLUSION

The soft-tissue ablation trials using quasi-Bessel beams have shown some initial promise, as these have showcased well-defined crater boundaries and minimal induced thermal damage. They allow the intensity profiles to be tailored to the surgical modality required.

However, longer pulse widths will be required to fully utilise the potential of these surgical modalities, as this will enable efficient fibre delivery. The unmodified output of the axicons will be tested as higher output intensities are necessary for plasma-formation to occur with these longer pulse widths in the picosecond regime.

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ACKNOWLEDGEMENTS

The authors would like to thank Dr. Richard Carter, who provided invaluable guidance and the EPSRC for providing the grant (EP/N02494X/1) that made this research possible.