TESTING THE POTENTIAL OF COMMERCIAL GRADE LASER CUTTERS TO OPEN APERTURES IN POLYTETRAFLUOROETHYLENE ("TEFLON") FILMS

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Abstract: *Commercial CO_2 laser cutters are ubiquitous in industrial fabrication, yet their capacity for precision micro-machining of polymer membranes for biomedical and microfluidic applications remains largely unexplored. We show that an off-the-shelf desktop laser cutter can reproducibly ablate micron-scale apertures in 25 µm Teflon (PTFE) films. Using a 50 mm focal-length lens, apertures were produced while the head translation speed was systematically varied; ImageJ analysis of thresholded micrographs yielded the effective radius and circularity of each aperture. A ten-fold increase in scan speed produced a predictable 50 % decrease in aperture radius, demonstrating fine control of feature size through dwell time. The principal limitation of the current protocol is the moderate circularity (≈ 0.5). Numerical analysis indicates that replacing the 50 mm lens with a 25 mm lens—thereby doubling the numerical aperture—should reduce the lateral spot size, increase energy density and enhance edge regularity. These findings highlight the promise of low-cost laser cutters for rapid aperture fabrication in thin films and outline straightforward optical modifications to approach true micro-machining performance for emerging bioanalytical applications.*

Key words: Teflon, aperture, laser, polytetrafluoroethylene, lipid

1. INTRODUCTION

Thin polytetrafluoroethylene (PTFE, "Teflon") films are widely used in research due to their chemical inertness, hydrophobicity, electrical insulation, and mechanical stability. They are essential in forming artificial lipid bilayers, particularly in the Montal–Mueller method (1), enabling the study of membrane proteins in controlled environments. Their ability to form clean, stable apertures makes them ideal for studying single-molecule transport, biosensing, and drug screening platforms. These unique properties make thin PTFE films a critical material across biology, chemistry, and biomedical engineering. Thin polytetrafluoroethylene films are essential for artificial-membrane work because they are (i) chemically inert, (ii) mechanically robust even at thicknesses below 50 µm, (iii) intrinsically hydrophobic. A 25 µm PTFE sheet, for example, is thin enough that a lipid bilayer spanning a micrometre-scale aperture experiences minimal "wall" effects – the membrane is effectively freestanding – yet thick enough to handle without tearing or stretching as the film is clamped into the two-chamber cell of a Montal – Mueller rig. The electrical insulation of the Teflon film is guaranteed by the PTFE's dielectric strength which keeps the two electrolyte compartments isolated except through the lipid membrane, allowing high-resolution capacitance and conductance measurements. Relevant for the Montal – Mueller method is also the chemical passivity of the Teflon. It resists acids, bases, and most solvents used to dissolve lipids when washing the two – chamber cell for further reusal (2,3); rinsing with ethanol or acetone removes organics without etching the surface.

The aperture formation is one major step needed for the formation of the artificial lipid membrane. Several methods were previously developed for making a circular aperture in the

Teflon film. These include a Hot Tip Perforation (1) which uses a heated metal wire or needle which is pressed through the PTFE film to create a small circular hole. This method is inexpensive and due to its simplicity and reasonably good reproducibility was originally used in the Montal – Mueller study. A follow up of this method was implemented with a mechanical puncher. This used a hollow, sharp edge metal tube or a hollow sharp edge capillary to punch a hole in the Teflon film (1,4). These methods lead to apertures ranging from 80 µm to 500 µm. Complementary to this method electric high voltage, high frequency generators (low currents) are used to generate an electric arc which opens an aperture in the Teflon film placed between the generating electrodes (2, 3). Varying the strength and duration of the electric field, apertures ranging from 10 to 500 µm can be generated. Nevertheless, the positioning of the hole in the plane of the Teflon film can not be determined as the electric arc does not open the aperture on the shortest path between the electrodes but rather on the path of smallest electrical resistance.

On the other hand, focused laser systems can ablate very small, precise holes in thin films with minimal mechanical stress. Lasers offers excellent reproducibility, computer-controlled hole placement and sizing but require access to very expensive laser micromachining equipment. Due to the laser costs this method has not been generally applied to PTFE films employed in the Montal – Mueller method. With the increasing availability of cost-effective CO_2 laser systems integrated into CNC laser cutting platforms, this study aims to evaluate the performance of a commercially available CO_2 laser cutter in fabricating microscale apertures in thin PTFE films.

2. RESULTS

A 25 µm-thick polytetrafluoroethylene film (Sigma-Aldrich, GF57708838) is routinely utilized in our laboratory for black lipid membrane (BLM) experiments based on the Montal–Mueller technique. Apertures in the PTFE film are generated using a high-voltage, high-frequency arc generator (Electro-Technic Products, Model BD10-AV), a device typically employed for the detection of pinholes and vacuum leaks. In this context, the localized high-temperature electric arc is used to thermally ablate and perforate the PTFE film, producing a microscale aperture (Figure 1A). For this purpose, the film is placed on a custom-fabricated support between two electrodes. Due to its insulating properties, the PTFE initially prevents current flow; upon arc discharge, the film is locally melted, allowing the formation of a conductive path between the electrodes via the created aperture (Figure 1B).

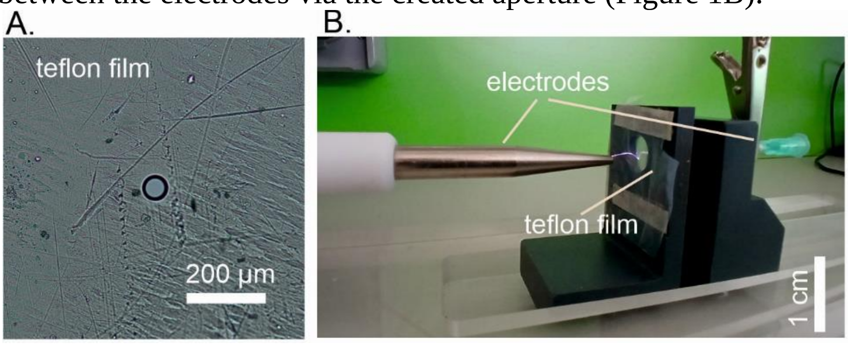

Figure 1. A. Representative optical image of a circular aperture produced in a 25 µm-thick PTFE film using a localized electric arc discharge. The aperture exhibits smooth, well-defined edges suitable for lipid bilayer formation. B. Photograph of the high-frequency generator setup utilized to create the aperture. The system consists of a two conductive needle electrode connected to a high-frequency source, positioned above and below the PTFE film. The electric arc discharge - visible as a brief luminous event during operation - locally heats and melts the polymer, resulting in a clean perforation.

The electric arc takes the path of the least resistance and this randomizes the position of the aperture and also gives variations in the aperture diameter. To circumvent these obstacles here we would like to employ a CO_2 laser cutter (GCC LaserPro, X380). The laser cutter can be precisely positioned onto the target material through a system of mobile mirrors and lenses (Figure 1A, B). The mirror assembly enables dynamic steering of the beam to precise coordinates within the X–Y cutting plane, allowing for high-resolution patterning of the film. When using the CO_2 laser cutter for aperture fabrication, two primary parameters govern the outcome: laser power and scanning speed. The laser power is controlled by modulating the electrical current supplied from the laser power supply unit to the CO_2 laser tube. This current directly influences the intensity of the laser beam generated, thereby affecting the energy delivered to the material and the extent of thermal ablation. This current controls how strongly the plasma inside the tube is excited - and thus, how much laser power (in watts - W) is emitted (up to the nominal power of the laser tube – 100 W). Furthermore, the amount of energy delivered to the material per unit length is inversely proportional to the speed at which the laser head moves. This means that increasing the cutting speed reduces the time the laser spends at each point, thereby decreasing the energy deposited in that area. As a result, faster speeds produce shallower cuts, while slower speeds concentrate more energy on a given spot, leading to deeper cuts or stronger material modifications. For optimal results, both power and speed must be carefully balanced based on the material and application. For the aperture generated here we used a power setting of 10% (approx. 10 W) and we traced a line of 0.2 mm in length. This line was traced at different speeds and obtained apertures similar to the one shown in Figure 1C.

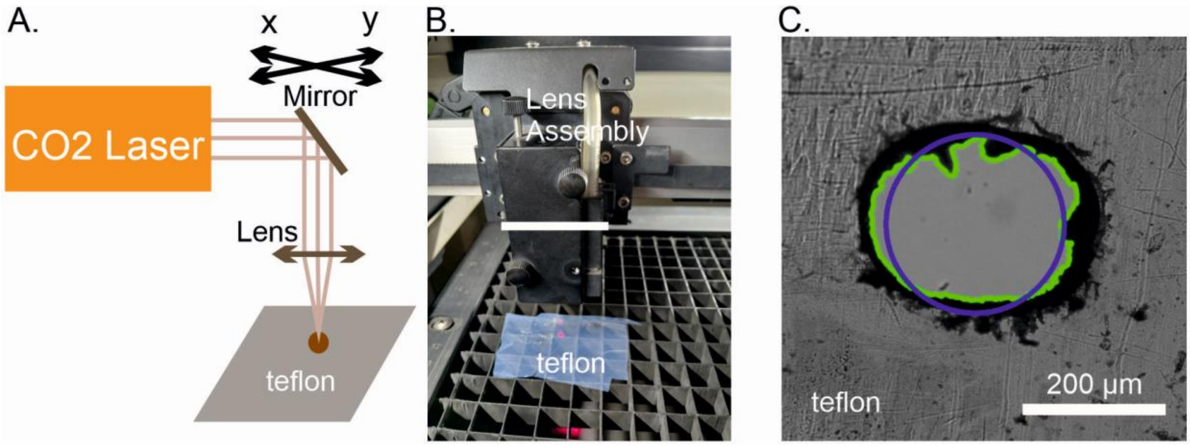

Figure 2. A. Simplified schematic illustrating the working principle of a CO_2 laser cutter. The laser beam is directed and focused onto the target material through a system of mobile mirrors and lenses. The mirror assembly enables dynamic steering of the beam to precise coordinates within the X–Y cutting plane, allowing for high-resolution patterning of thin films. B. Photograph of the cutting head of the GCC LaserPro X380 CO_2 laser cutter with a 25 µm-thick PTFE film positioned for aperture fabrication. The setup enables contactless thermal ablation of the material via a focused infrared laser beam. C. Representative image of an aperture formed in the PTFE film using the CO_2 laser. The green contour delineates the actual perimeter of the aperture as determined by image analysis, while the blue circle indicates the equivalent circular area calculated to match the total open surface.

To analyze the influence of laser power on the aperture opening here we started to analyze the dependence of aperture diameter and circularity on the laser speed (Figure 1). To do so we used ImageJ software (NIH). Each image was first converted to 8-bit grayscale (Image → Type → 8-bit). Thresholding was then applied to isolate regions of interest by setting a lower intensity threshold (values ranging from 100 to 135, depending on image characteristics) and an upper threshold at 255 (Image → Adjust → Threshold). The thresholded image was analyzed to extract shape parameters. Using the Wand (tracing) tool, the largest white patch (region of interest) was manually selected (green line, Figure 2C). Shape descriptors including area, perimeter, and circularity were quantified through the measurement function (Analyze → Measure). Circularity was calculated automatically by ImageJ, using the equation: Circularity = $(4\pi \times \text{Area}) / \text{Perimeter}^2$, where a value close to 1 indicates a perfect circle, and values approaching 0 indicate elongated or irregular shapes. The effective radius of the aperture was determined by calculating the radius of a circle (blue line, Figure 2C) with an equivalent area to the measured region (are encircled by the green line Figure 2C).

In Figure 3A, we present the effective radius of the aperture as a function of laser speed. Our data suggests that the aperture radius scales inversely proportional to the laser speed within the examined range, showing approximately a 50% decrease in the aperture radius with a 10-fold increase in laser speed. Conversely, circularity remained consistent (Figure 3B) within experimental error across varying speeds, and most apertures exhibited the characteristic edge fragmentation illustrated in Figure 2C.

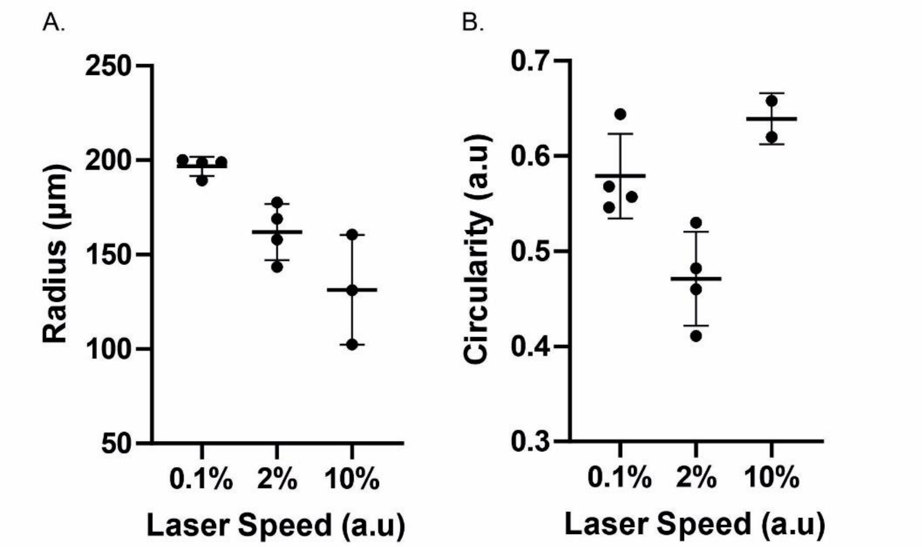

Figure 3. A. Plot of the resulting aperture radius as a function of the CO_2 laser head speed during fabrication. The laser was programmed to traverse a fixed linear path of 0.2 mm, and the speed is expressed as a percentage of the maximum translation speed of the system (approximately 1 m/s). Slower laser head velocities result in increased energy deposition and thus larger aperture diameters due to extended exposure time and greater thermal ablation of the PTFE film. B. Quantitative assessment of aperture circularity based on contour geometry extracted from optical images

3. CONCLUSIONS

Preliminary experiments indicate that a commercial-grade CO_2 laser cutter can be repurposed to mill micron-scale apertures in PTFE films. Using a 50 mm focal-length plano-convex lens, we systematically varied the translation speed of the laser head and quantified the resulting aperture geometry. The effective radius decreased by ~50 % as scan speed increased by an order of magnitude, confirming an inverse dependence of feature size on dwell time at the focal spot. Over the same speed range, the circularity remained statistically constant, indicating that, within the range of our measurements, faster passes shrink the aperture without measurable improvements of edge regularity.

Further optimisation is likely to be achieved by increasing the numerical aperture (NA) of the focusing optics. The lateral focus area (x–y), of the focus volume, scales inversely with NA ($\approx 0.61\ \lambda / NA$), while the axial depth of focus scales as $1 / NA^2$. Replacing the current 50 mm lens with a shorter-focal-length element (e.g. 25 mm) would approximately double the NA for the same beam diameter, thereby raising the peak irradiance (energy per unit area) at the work surface, reducing the lateral spot size, and shortening the interaction length along z, which together should enable smaller, more circular apertures and minimise peripheral thermal damage.

Future work will therefore employ high-NA, short-focal-length optics and explore additional parameters - pulse energy, narrowed laser beam - to refine aperture morphology and reproducibility.

4. REFERENCES

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