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# A BIODEGRADABLE, WIRELESS, IMPLANTABLE MICROPUMP FOR PERIPHERAL NERVE REPAIR

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## ABSTRACT

Peripheral Nerve Injury (PNI) leads to significant motor and sensory impairments, with limited recovery potential in injuries exceeding 3 cm. Conventional treatments often fail to achieve full functional restoration. Suction-based approaches at lesion sites have demonstrated promising outcomes in nerve regeneration. This work presents a novel wireless, magnetically actuated micropump composed of biodegradable materials, such as poly(octamethylene-maleate(anhydride)citrate) (POMaC), for nerve repair applications. The micropump integrates a magnetic ring within its membrane, enabling deflection under alternating magnetic field (4 Hz,  $\pm 150$  mT), generating a net under-pressure of 1.3 kPa within 8 minutes. It provides a potential solution to facilitate nerve healing.

## KEYWORDS

Peripheral Nerve Injury, nerve implants, biodegradable micropump, magnetic actuation.

## INTRODUCTION

Peripheral Nerve Injury (PNI) is a critical condition affecting approximately 300,000 individuals annually in Europe [1]. This condition results in partial or total loss of motor, sensory, and autonomic functions in the lesioned area due to interruption of axon continuity. Healing is often incomplete or non-existent, depending on the severity of the injury [2]. Current treatments, such as micro-suturing, autografting, and nerve entubulation, still do not provide a satisfying nerve recovery [3], as they can cause inflammation or morbidity at the donor site and are not effective for nerve gaps larger than 3 cm. New methods employing mechanical stimuli have been investigated; for example, the application of under-pressure to proximal and distal nerve endings has been shown to accelerate nerve regrowth. These methods have been demonstrated to be capable of providing a substantial increase in gross nerve growth in mice [4]. However, the experimental setup employed for the treatments has been a bulky and transcutaneous vacuum pump, connected to the nerve through a T-shaped conduit. While this setup provided a feasible solution for mice, the transcutaneous feature can be of great risk for patients in terms of infection, discomfort, and lesions.

Biomedical implantable devices have advanced significantly in recent decades; however, there is currently no example of a wireless and biodegradable technology, such as a micropump, capable of fulfilling the role. The first examples of micropumps trace back to the 1980s with systems fully made of silicon and based on piezoelectric/thermopneumatic actuation [5, 6]. Shortly after, other

materials such as plastic have been investigated as alternatives [7-9]. The valve design is crucial in micropumps, ranging from ball valves and check valves to Tesla elements. A key breakthrough in valveless pumping was achieved using nozzle/diffuser elements [7, 10-12], significantly reducing fabrication costs and improving applicability in implantable devices. These advancements continue to drive the evolution of microfluidic technology, making micropumps an essential component in biomedical and analytical applications. Nozzle/diffuser micropumps are of particular interest for implantable devices because of the simple realization of the diffuser element which significantly lowers fabrication costs. This study focuses on a valveless mechanical micropump with a nozzle-diffuser configuration.

Magnetic actuation via alternate magnetic field generation is selected for its potential as a wireless driver as well as its high biocompatibility and low input voltage requirement [9, 13-15]. Material biodegradability is crucial to ensure resorbability within the body without the necessity of extraction surgery [16], therefore biodegradable elastomers [17] and composites derived from them [18] have been selected as potential materials for the membrane, the magnetically actuated component of the micropump. In particular, poly(octamethylene-maleate(anhydride)citrate) (POMaC) elastomer, and a composite derived from it and Carbonyl Iron Particles (CIP) have been considered suitable due to their stretchability and magnetic properties.

The objective of this study is to develop a fully biodegradable device capable of generating suction through magnetic actuation.

## METHODS

### Micropump fabrication

An exploded view of the micropump and its cross-section are shown in Figure 1, together with a picture of the assembled device. The dimensions of the device's parts are listed in Table 1. The base of the micropump was designed in Fusion 360 and 3D-printed through Digital Light Processing (DLP, Asiga Max) with a plant-based biodegradable resin (Sunlu). The critical dimension of the print was the diameter of the microchannels (100  $\mu\text{m}$ ). The design of the nozzle-diffuser configuration was based on literature examples of optimized dimensions to obtain fluid flow in a valveless pump [13]. The membrane (Fig. 2) was fabricated from a biodegradable and biocompatible elastomer, POMaC, and a magnetic biodegradable composite obtained from mixing POMaC and Carbonyl Iron Particles (CIP). Plasma enhanced chemical vapor deposition (PECVD) was used to deposit a 180 nm anti-adhesion layer of Polytetrafluoroethylene (PTFE) on a 4" 500  $\mu\text{m}$ -thick Si wafer. The wafer was saw-diced in 2x2

cm<sup>2</sup> squares and used as a master mold for the elastomer and composite layers; Polydimethylsiloxane (PDMS, Slygard 184) was cast on the diced Si, to obtain a negative mold in a 10:1 ratio (base:curing agent). POMaC and POMaC/CIP were cast in the PDMS molds and crosslinked via UV exposure (365 nm) and oven baking (80 °C; POMaC: 24 hours, POMaC/CIP: 5 hours). The 500 μm-thick layers were laser-cut (Trotec R400) to obtain the membrane and magnetic ring shapes; the layers were aligned and bonded via UV exposure. Surgical glue (Tisseel) was placed in the dedicated reservoir and used to seal membrane and base together, while maintaining the biodegradable feature.

Table 1: Dimensions of micropump base and membrane features.

Micropump Part	Dimension [unit]
Chamber diameter	9.0 [mm]
Chamber depth	0.6 [mm]
Nozzle/diffuser angle (2α)	20 [°]
Nozzle/diffuser inner diameter	0.1 [mm]
Nozzle/diffuser outer diameter	0.5 [mm]
POMaC thickness	0.5 [mm]
POMaC side	13.0 [mm]
POMaC/CIP thickness	0.5 [mm]
POMaC/CIP inner diameter	4.0 [mm]
POMaC/CIP outer diameter	8.0 [mm]

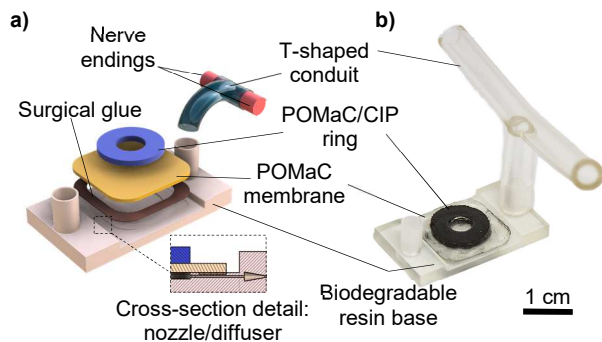


Figure 1: a) Exploded view of the design with the cross-section detail of the nozzle/diffuser, and b) picture of the fabricated micropump, attached to a T-shaped conduit to entubulate nerve endings.

### Under-pressure characterization

Micropump under-pressure was generated and characterized through a custom-made setup: a diametrically magnetized N42 Neodymium magnet was turned at 2 Hz to generate an alternating magnetic field at 4 Hz. The magnet was rotated through a stepper motor (Nema 17) connected to an Arduino Uno (Rev 3) microprocessor powered by a 12 V power supply (Agilent 6613C DC). The alternating magnetic field oscillated between 0 and ±150 mT at a distance of 1 cm from the magnet (measurement performed with WT10A Teslometer, Weite Magnetic Technology CO). The micropump was positioned at 1 cm from the magnet, while an integrated silicon pressure sensor (MPX4115, NXP) recorded pressure variations at its inlet. The micropump was actuated for 10 minutes (magnet rotating), followed by 10 minutes of no actuation to detect possible leakages. Data

were acquired through a LabVIEW interface (National Instruments). A Butterworth filter (cut off: 10 Hz) was used for illustration purposes.

### Biodegradability test

The biodegradability of the micropump was assessed via accelerated degradation testing, by placing the device in a 7.4 pH phosphate-buffered saline (PBS) solution at 80 °C. The PBS solution was refreshed every 48 h, to ensure the same level of acidity throughout the test.

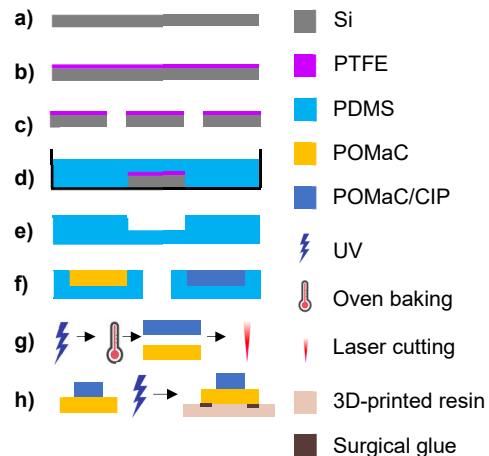


Figure 2: Fabrication process of the membrane: a) a 500 μm thick Si wafer was covered with b) a layer of 180 nm of PTFE deposited via PECVD. The wafer was c) saw-diced in 2x2 cm<sup>2</sup> squares and d) used as master mold to obtain e) a 10:1 (base:curing agent) PDMS negative mold with a 500 μm depth. POMaC and POMaC/CIP were f) cast in the molds, then g) UV crosslinked, oven-baked, released, and laser cut. The obtained shapes were h) UV bonded and assembled with the 3D-printed resin through surgical glue.

## RESULTS

### Micropump fabrication

The fabricated micropump exhibited precise structural integrity, with all components aligning as designed. The 3D-printed base, manufactured using DLP, successfully achieved the critical microchannel dimension of 100 μm, as verified through optical microscopy. The plant-based biodegradable resin provided adequate resolution and surface quality, confirming the suitability of the selected material and printing technique. The biodegradable POMaC and POMaC/CIP membranes were successfully cast and crosslinked, forming uniform layers with thicknesses of 500 μm, as planned. Laser-cutting provided well-defined edges for the membrane and magnetic ring, facilitating proper alignment and bonding. The bonding method, utilizing UV exposure, ensured a secure attachment between the layers without compromising the material properties. The assembly of the micropump components using surgical glue (Tisseel) successfully sealed the membrane and base while maintaining biodegradability. The adhesive demonstrated strong adhesion without observable leakage under initial under-pressure testing. The use of a biodegradable sealing method aligns with the intended applications in transient biomedical devices, ensuring complete degradation over time without leaving harmful residues.

## Under-pressure results

The micropump's under-pressure characteristics were evaluated using a custom experimental setup. The system utilized a diametrically magnetized N42 Neodymium magnet rotating at 2 Hz to generate an alternating magnetic field, oscillating at 4 Hz between 0 and  $\pm 150$  mT at a 1 cm distance. The micropump, positioned at this distance, was monitored using an integrated silicon pressure sensor which recorded pressure variations at the inlet. Actuation for 10 minutes demonstrated a pressure drop, followed by a 10-minute idle period to assess potential leakage (Figure 3). The acquired data indicated a net pressure drop of 1.3 kPa without significant loss, confirming effective magnetic actuation. The micropump was capable of reaching this under-pressure of 1.3 kPa in 8 minutes. The pressure stabilized at 100.0 kPa for 2 minutes, and when the rotation of the magnet was interrupted (actuation OFF), it remained stable at the same pressure for 10 minutes. No pressure leakage was observed during this monitoring period, demonstrating the reliability of the micropump's sealing and operational consistency.

## Biodegradability results

The biodegradability of the micropump was assessed through accelerated degradation in a 7.4 pH PBS solution at 80 °C (Figure 4). The PBS solution was refreshed every 48 hours to maintain consistent acidity levels throughout the test. Over time, visible degradation of the micropump components was observed, particularly in the POMaC-based membrane, which gradually degraded. POMaC and surgical glue were fully dissolved in PBS within 7 days, with no visible residue remaining after this period. The POMaC/CIP composite persisted in fragmentary form up to day 10. The 3D-printed resin exhibited progressive layer-by-layer biodegradation, with fractures observed in the inlet channel by day 7. By day 10, the resin's erosion continued, with cracks appearing in the micropump base, confirming the device's transient nature and alignment with biodegradable system requirements.

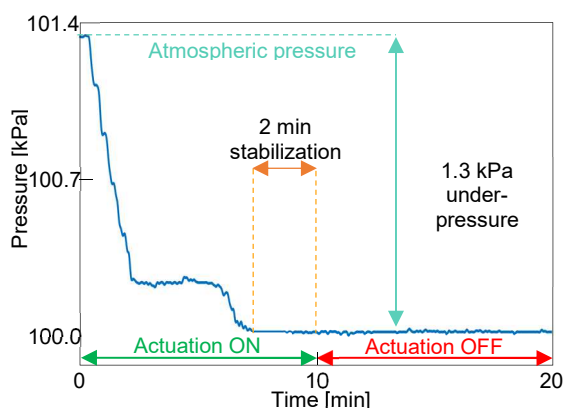


Figure 3: Under-pressure generated by the micropump actuated by alternating magnetic field. The micropump is actuated by a magnet rotating at a frequency of 2 Hz, which generates an alternating magnetic field of 4 Hz at a 1 cm distance. Continuous actuation for 10 minutes results in the generation of an under-pressure of 1.3 kPa after 8 minutes, followed by a stabilization period at 100.0 kPa for 2 minutes. Subsequently, actuation is turned off; no pressure leakage is observed over the following 10-minute monitoring period.

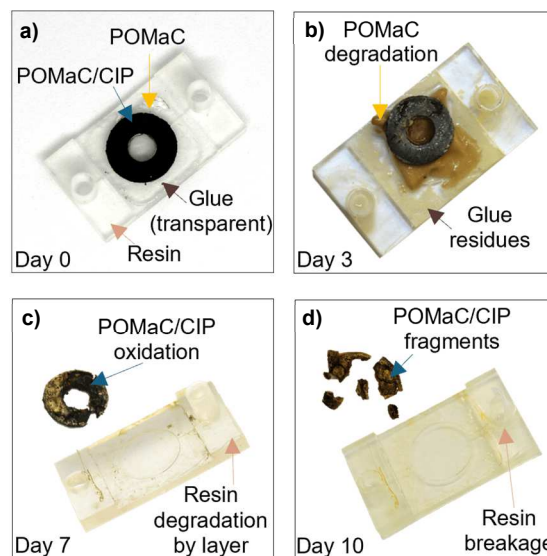


Figure 4: Accelerated degradation test of the micropump in PBS (pH 7.4) at 80 °C. Pictures taken at a) day 0: initial condition; b) day 3: POMaC starts degrading and detaching; c) day 7: POMaC/CIP oxidates, full dissolution of glue and POMaC occurs, the 3D printed resin degrades layer by layer and presents a fracture at the inlet channel; d) day 10: only fragments of POMaC/CIP are left, erosion of the resin continues.

## CONCLUSION

This study demonstrates the successful fabrication and assembly of a biodegradable micropump using DLP printing and elastomeric membrane synthesis. The integration of POMaC/CIP for magnetic actuation and the use of biocompatible adhesives enabled a fully functional device with potential applications in transient biomedical systems. While various polymeric and magnetically actuated micropumps have been reported in the literature [13, 9], a fully biodegradable, wireless, and implantable micropump capable of generating under-pressure without necessitating surgical extraction remains absent. The device presented in this work addresses this gap by achieving an under-pressure of up to 1.3 kPa relative to atmospheric conditions, aligning well with the operational requirements outlined in research studies on PNI in mice utilizing a transcutaneous pumping system [4].

Future work will focus on optimizing the micropump fabrication process, possibly moving to cleanroom-based approaches to enhance the repeatability of the device and miniaturization.

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