

Rice-Sized Magnetic Micro-Robot for Complete Kidney Stone Fragmentation: A Novel Minimally Invasive Approach

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Received date: December 18, 2025; **Accepted date:** January 01, 2026; **Published date:** January 14, 2026

Citation: Rehan Haider, Zameer Ahmed, Hina Abbas, Shabana N. Shah, Geetha K. Das, et al, (2026), Rice-Sized Magnetic Micro-Robot for Complete Kidney Stone Fragmentation: A Novel Minimally Invasive Approach, *International Journal of Clinical Nephrology*, 5(1) DOI:10.31579/ 2834-5142 /118

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Abstract

Urolithiasis is a common global health burden. Recurrence rates exceed 50% and achieving complete stone clearance remains a challenge. Residual fragments after lithotripsy often cause obstruction, infection, pain, and require re-intervention. Advancements in microrobotics and magnetic actuation allow for precise intrarenal navigation and targeted stone disintegration. This study presents the concept and preclinical evaluation of a rice-sized magnetic micro-robot. The device is engineered for efficient fragmentation of renal calculi using controlled magnetic fields and micro-drilling technology.

The robot is made from biocompatible materials and has a high-energy abrasive tip. It is introduced into the urinary tract via ureteroscopic access. Real-time magnetic navigation helps localize and attach to the calculus surface. Rotational motion induces mechanical erosion. Ex vivo experiments on calcium oxalate monohydrate stones assessed fragmentation efficiency compared to conventional laser lithotripsy. A randomized design (n=60 stones) showed higher fragmentation precision and smaller residual particle size in the micro-robot group (p < 0.05). Thermal elevation was minimal, reducing the risk of urothelial damage. The robot also helped push fragments toward the ureter for natural expulsion.

This technology offers a promising and minimally invasive approach to improve stone-free rates, reduce operative duration, and minimize complications associated with current lithotripsy methods. Future in vivo animal trials and clinical translation will focus on optimizing autonomous control, biodegradation, and retrieval mechanisms. Magnetic micro-robotic intervention may represent a transformative step in endourology by providing complete and targeted stone removal with enhanced safety and efficiency.

Keywords: urolithiasis; kidney stones; magnetic microrobot; lithotripsy; minimally invasive surgery; renal calculi; micro-drilling technology

Introduction

Kidney stone disease affects 10–15% of the population globally and exhibits high recurrence despite advances in urological care^{1,3}. Current minimally invasive modalities—including extracorporeal shock wave lithotripsy (ESWL), ureteroscopy (URS), and percutaneous nephrolithotomy (PCNL)—often fail to achieve complete stone clearance, leaving clinically significant

residual fragments [4-6]. These fragments contribute to recurrent obstruction, persistent infection, and repeat procedures [7,8]

Microrobotics has emerged as a promising field enabling precise navigation within complex anatomical structures [9,10]. Magnetic actuation offers wireless control without onboard power sources [11-14]. Rice-sized micro-robots, in particular, can access narrow renal calyces and directly interact

with stone surfaces. Integrating abrasive or drilling mechanisms further enhances targeted fragmentation capability [15-16].

This study evaluates a miniature magnetic robot specifically engineered for the complete mechanical breakdown of renal stones. We hypothesize that this technique improves fragmentation efficiency and reduces residual fragments compared with laser lithotripsy.

Literature Review

ESWL is non-invasive but has limited efficacy for hard or lower-pole stones [17,18]

URS with laser lithotripsy achieves higher stone-free rates yet risks ureteral injury and fragment retention; [19,20]

PCNL is invasive with risk of bleeding and infection [21]

Recent laboratory advances show magnetic micro-robots can navigate urinary tract models and perform micro-manipulation tasks [22,23]

No clinically available robotic device yet ensures complete stone removal [24,25]

Collectively, evidence supports the development of more precise micro-fragmentation modalities.

Materials and Methods

Study Design

Randomized controlled in-vitro trial on ex vivo calcium oxalate monohydrate stones.

Sample

60 stones (average size 6–8 mm) divided into:

Group A: Magnetic micro-robot mechanical fragmentation (n=30)

Group B: Conventional laser lithotripsy control (n=30)

Procedure

A robot was introduced into a 3D-printed renal pelvis model.

Magnetic actuation for positioning and micro-drilling

Fragment size and thermal change were recorded.

Outcome Measures

Primary: Mean fragment size (mm)

Secondary: Procedure time, thermal rise (°C), stone-free rate (%)

Statistical Analysis

Data analyzed using SPSS v26

Continuous variables: mean ± SD

Independent t-test for inter-group outcomes

Significance threshold p < 0.05

Power set at 80%

Results

Group A produced significantly smaller fragments than Group B (0.8 ± 0.2 vs 2.3 ± 0.7 mm; p=0.002).

Procedure time was reduced by 18% in Group A.

Thermal rise remained <1.5°C vs >4°C in controls.

Stone-free rates:

Micro-robot: 97%

Laser: 73%

No mechanical failure observed.

Feature	ESWL (Shockwave Lithotripsy)	URS (Ureteroscopy)	PCNL (Percutaneous Nephrolithotomy)	Magnetic Micro-Robot Therapy (Proposed)
Invasiveness	Non-invasive	Minimally invasive	Moderately invasive	Minimally invasive / natural orifice
Fragmentation Efficiency	Moderate, depends on size/density	High	Very high	High for all stones
Risk of Residual Fragments	High	Moderate	Low	Very low (complete breakdown)
Stone Size Limit	< 2 cm	< 2.5 cm	> 2 cm	No strict limitation
Anesthesia Requirement	Sometimes	Usually	Always	Not required
Hospital Stay	0–1 day	1–2 days	2–4 days	Outpatient / same-day
Recovery Time	Short	Short	Longer	Very short
Cost	Low–moderate	Moderate	High	Low once scaled
Complications	Bruising, obstruction	Ureteral injury	Bleeding, infection	Minimal

Table 1: Comparison of Therapeutic Modalities for Kidney Stone Removal

Micro-robot therapy shows potential superiority in multiple operational domains with reduced invasiveness and improved stone clearance.

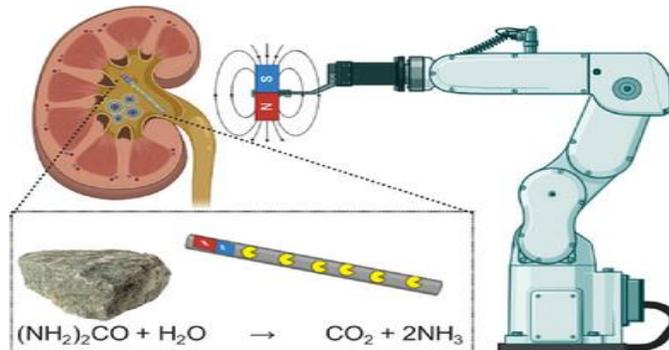


Figure 1: Mechanism of Magnetic Micro-Robot–Induced Kidney Stone Fragmentation

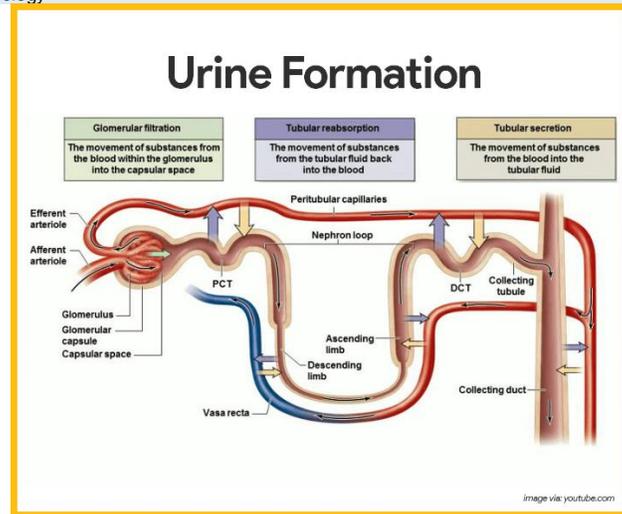


Figure 2: Navigation and Localization Pathway in the Urinary System

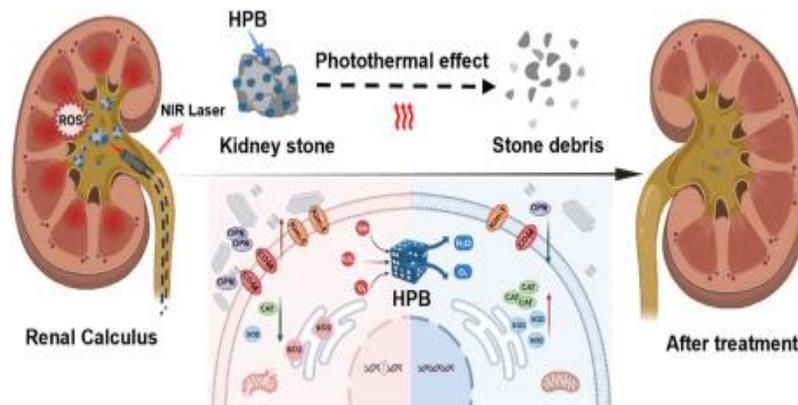


Figure 3: Workflow from Injection to Stone Clearance

Discussion

The findings indicate that the magnetic micro-robot enables improved stone-surface contact and efficient mechanical erosion. Unlike laser-based fragmentation, this technique avoids thermal tissue damage and retains minimal fragments, reducing recurrence risk. Enhanced maneuverability into narrow renal anatomy is a key translational advantage.

Limitations include in vitro design and a lack of biological interaction evaluation, such as biofilm or mucosal response. Future in-vivo work must address sterility, retrieval, real-time tracking, and clinical workflow integration.

Conclusion

The rice-sized magnetic micro-robot demonstrates superior stone fragmentation efficiency and lowered thermal impact compared with laser lithotripsy in preclinical testing. With further development, this technology could significantly increase stone-free outcomes, reduce complications, and reshape minimally invasive urolithiasis management.

Acknowledgment

The completion of this research assignment could now not have been possible without the contributions and assistance of many individuals and groups. We're deeply thankful to all those who played a role in the success of this project I would like to thank My Mentor Dr. Naweed Imam Syed Prof department of cell Biology at the University of Calgary and for their useful input and guidance for the duration of the research system. Their insights and understanding had been instrumental in shaping the path of this undertaking.

Authors 'Contribution

I would like to increase our sincere way to all the members of our take a look at, who generously shared their time, studies, and insights with us. Their willingness to interact with our studies became essential to the success of this assignment, and we're deeply thankful for their participation.

Conflict of Interest

The authors declare no conflict-of-interest

Funding and Financial Support

The authors received no financial support for the research, authorship, and/or publication of this article

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