# Innovating indwelling catheter design to counteract

# urinary tract infection

## Abstract

*Bacteriuria is anticipated in long-term indwelling catheter (IDC) use, and urinary tract infection (UTI) and related issues are common. Defence mechanisms against infection are undermined by presence of a Foley catheter, and adjustments to design could influence UTI risk. We reviewed aspects of IDC and ureteric stent designs to discuss potential impact on UTI risk. Design adaptations have focussed on reducing the sump of undrained urine, potential urinary tract trauma, and bacterial adherence. Experimental and computational studies on ureteral stents found interplay between urine flow, bacterial microcolony formation, and accumulation of encrusting particles. The most critical regions for biofilm and crystal accumulation are associated with low shear stress. The full drainage system is the functioning unit, not just the IDC in isolation. This means reliably keeping the drainage system closed, and considering whether a valve is preferred to a collection bag. Other developments may include one-way valves, obstacles to “bacterial swimming”, and ultrasound techniques. Preventing or clearing IDC blockage can exploit access via the lumen or retaining balloon. Progress in computational fluid dynamics, energy delivery and soft robotics may increase future options. Clinical data on effectiveness of IDC design features is lacking, which is partly due to reliance on proxy measures and the challenges of undertaking trials. Design changes are legitimate lines of development, but are only indirect for UTI prevention. Modifications may be advantageous, but potentially might bring problems in other ways. Education of healthcare professionals can improve UTIs, and should be prioritised.*

***Patient summary****: Catheters to help bladder drainage can cause urinary infections, and improvements in design might reduce the risk. Several approaches are described in this review. However, proving they work is a challenge. Training professionals in key aspects of catheter care is important.*

***Keywords****: Urinary catheter; Foley catheter; Urinary tract infection*

## Introduction

Indwelling urinary catheters (IDCs) are a vital aspect of clinical care, but their use needs to be considered in view of potentially significant problems (1, 2). Short-term use (IDC) is associated with an incidence of urinary tract infection (UTI), which potentially persists even after catheter removal. In long-term use, bacteriuria is anticipated in the substantial majority of users. Hence, symptomatic UTI and / or UTI-related issues, such as recurrent catheter blockages, arise in a high proportion.

The most widespread “Foley” IDC design uses a drainage channel, with eyeholes that allow entry of urine at one end, and a connector to accommodate the drainage bag or a valve at the other. A separate channel allows filling and emptying of a retaining balloon, which aims to keep the drainage holes in the bladder lumen. Variations in the product specifications accommodate differences in urethral length and external diameter (3).

The bladder's defence mechanisms against infection are undermined by the presence of a Foley catheter (4). Conceptually, aspects of this core design may contribute to some of the UTI risk. Hence adjustments to design and manufacturing processes potentially could exacerbate or ameliorate UTI risk. Implicitly, the presence of foreign material, the breach of anatomical defences and the change in urodynamic functions all contribute to the increased UTI risk associated with IDC use. This paper reviews the potential improvements for reducing UTI risk associated with these aspects of IDC design, as summarised in Table 1. Literature search was undertaken in PubMed and PubMed Central using search terms “catheter” and urinary tract infection” with manual search of references cited in key articles. A separate review in covers innovations in the materials and coatings.

***Table 1****. Summary of innovation concepts for reducing catheter-associated UTI.*

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| --- | --- |
| ***Aim of catheter design adaptation*** | ***Examples*** |
| Reducing residual urine in the bladder | Catheter drainage holes close to the bladder base; Flume catheter (5), Optitip catheter |
| Reducing urinary tract trauma | 1. Additional balloon to protect bladder; Duette catheter  2. Low-profile design (6)  3. “Atraumatic” catheter (7) |
| Reducing bacterial adherence/ improving flow | 1. Evaluating shear stresses  2. Intermittent flow (8)  3. Reliable drainage systems (9)  4. Integrated valve; T-control (10)  5. Obstacles against “upstream swimming” (11)  6. Retrograde flushing (12)  7. Acoustic waves to reduce biofilm (13) |
| Preventing blockage | 1. Local anti-bacterial compounds via retaining balloon (14)  2. Catheter lock solutions via lumen (15)  3. Biofilm detachment (substrate strain) (16)  4. Luminal soft robot (magnetic actuation) (17)  5. Activated surface microstructures (18, 19) |

## Microbiological impact in IDC users

To constitute a UTI, there need to be specific systemic and microbiological features, including presence of symptoms, inflammatory response and a single organism cultured in sufficient numbers. Where there is a factor such as presence of an IDC it is referred to as “complicated UTI”. Urine specimens typically find bacteriuria once people have had an IDC in place beyond a few days, but this is usually not considered clinically significant, and guidelines do not support antibiotic treatment to prevent catheter-associated UTI in patients with a long-term indwelling catheter (20). More direct evaluation of the catheter surface reveals extensive bacterial presence, with a range of organisms giving rise to a biofilm. If antibiotics are given, the urine sample may no longer show growth temporarily, but the biofilm will persist. Bacteria in the biofilm can cause problems by their physical extent, and also release enzymes that can alter the nearby environment; in the case of urine, this can lead to precipitation of salts out of solution. The physical and chemical effects in the locality of the catheter lumen or drainage holes can lead to blockage, precipitating a medical emergency. The use of antibiotics could influence the nature of the bacteria present, and provide a selection pressure in favour of more pathogenic organisms.

Against the microbiological pathogenicity, the patient has defences, including immunity, and specific molecules in the urine. For most patients, the relatively low incidence of UTIs probably reflects the ability of the host to kill organisms away from the location of the IDC. However, the IDC itself is a protected environment enabling bacterial persistence. Furthermore, many patient groups have less effective defences, as a result of impaired immunity or immunosenescence.

Thus, UTIs in IDC users are an end point following a complex interplay of factors. Adaptations of IDC design are appropriate measures given the problems patients experience with each UTI. However, such adaptations influence just one step in the chain of factors, so are only indirect when it comes to UTI prevention. In particular, measures to reduce catheter blockage are important because of the seriousness of a blockage event in terms of symptoms, emergency care needs and cost. However, this IDC microenvironment complication is not indicative for systemic UTI risk, so reduced blockage events can only be considered an indirect proxy measure of improvement in UTIs.

## IDC adaptation to reduce residual urine

In the Foley design, the drainage holes are above to the retaining balloon, such that balloon inflation places the holes away from the bladder base. Physical separation of drainage holes from bladder base could allow a persistent reservoir of urine to remain undrained. The stagnation of the urine in this “sump” might be a risk factor for bacterial replication which may predispose to UTI. This concept is hard to test in vivo, but an *in vitro* model, using artificial urine seeded with uropathogenic *Proteus mirabilis* in glass incubation chambers, found reduction of a urine sump volume appeared to influence the time to blockage (5).

Based on the apparent desirability to reduce the sumping risk factor, the Flume catheter has the drainage holes at the same level as the contact point between the bladder base and the retaining balloon [Figure 1], hence should effectively avoid any sump effect. First in human tests of a prototype of this catheter have taken place (5). The catheter is too early in the innovation pathway to report on whether there is an actual reduction of UTI risk in general clinical use. The Optitip catheter (Linc Medical, UK), has two drainage eyes (Figure 2); one below the balloon and one in a reduced profile tip (see Measures to reduce IDC trauma below). As yet, there is no available evidence on the reduction of UTI or other catheter-associated harms.

**Figure 1 *The balloon designs of the standard Foley catheter (left) and the Flume catheter (right).***

**Figure 2 *The Optitip catheter has a hole below the balloon, visible in the photograph, and another hole above the balloon at the end of the tube (not visible)*.**

## Measures to reduce IDC-related trauma of the urinary tract

Several aspects of catheter use place the urinary tract at risk of direct trauma. Given that anatomical integrity is important, damage (where present) is a cause for concern by providing a potential focus for persistence of infecting organisms, and enabling deeper penetration of UTI to increase risk of systemic consequences. However, whether the trauma risks truly predispose to UTIs is hard to confirm. Furthermore, there is little information on the proportion of people genuinely affected by these issues, hence the solutions may not be generalisable.

In the Foley design, the balloon may push the pointed tip into the bladder wall, while suction effects may draw the urothelium into the drainage holes. The first problem can be addressed with a “low-profile” design, which effectively removes the tip, giving direct access to the lumen from the proximal catheter end. Preliminary data in very short-term use has been published (6). The Poiesis Duette Dual-Balloon Foley design aims to reduce both risks through inclusion of an additional balloon, along with the retaining balloon, placed at the tip of the catheter. This shields both the tip (hence reducing trauma to the urothelium) and the drainage holes of the standard Foley design. Likewise, the Flume catheter tip is shielded once the balloon is inflated.

Additional trauma risks with IDCs include;

1. **Avulsion with the balloon inflated**: The FDA regulatory authorisation of urinary catheters stipulates high force resistance to reduce risk of avulsion. However, as a result, if sufficient longitudinal force is applied to avulse the catheter with the balloon inflated (as can happen if a patient stands up when their catheter is tethered), the balloon will transmit a substantial radial force onto the urethra as it comes out (21). This force is lower with the Flume design (21). Another design in very early stage development, an “atraumatic urinary catheter”, showed that injury is less common following forceful extraction when compared with a conventional Foley in a rabbit model (7).
2. **Cuffing**: The retaining balloon may be inflated for up to 3 months for some patients. This prolonged duration means the balloon material may not return fully to its original unstretched state, resulting in a cuff of material protruding around the catheter shaft, which can cause urethral trauma when the catheter is removed (22). This is a well-recognised issue, which should be within the remit of design improvements.
3. **Patulous urethra and traumatic hypospadias**: These indicate tissue breakdown, resulting from chronic physical and inflammatory factors. This is quite an extreme consequence of IDC use, and improvement is highly desirable for many reasons, over and above the risk of UTI.
4. **False passages**: Catheter placement requires the device to follow the course of the urethral lumen as it is advanced. In male patients this relies on the catheter following the natural anatomical curvatures, and any additional distortions resulting from scarring or hyperplasia. Unfortunately, the tip may abut against the urethral wall whilst being introduced, and the longitudinal force may then breach the urethral epithelium. An adaptation introducing slight angulation of the catheter tip can allow an experienced practitioner to reduce the risk of a false passage, since rotation of the tip can facilitate negotiation of these obstacles.

## IDC adaptations to reduce bacterial adherence and improve flow

Adherence of bacteria is a key step in infection; once adherent, the bacteria can proliferate, form biofilm and change the microenvironment, and thereby lead to blockage. Design issues can have implications for adherence. For example, increased surface area in contact with urine may be a risk factor. This extends to the manufacturing process in producing the final product. For example, the process of making the drainage eyeholes needs to result in a smooth surface, since rough surfaces predispose to bacterial adhesion (23). Punching the holes with a metal stamp potentially leads to a rougher surface than a laser-cut hole, with demonstrable implication for bacterial adhesion *in vitro*. This is especially problematic, given that the drainage holes are key for IDC function.

Experimental and computational studies on ureteral stents found interplay between urine flow, bacterial microcolony formation, and the accumulation of encrusting particles, such as urine crystals. Side holes in stents are often the triggering sites for these processes, due to flow stagnation and the formation of laminar vortices. These slow vortices can become entrapment sites for small particles, such as bacteria and crystals, thereby promoting adhesion and growth on the surface (24). The most critical regions, in terms of biofilm and crystal accumulation, are generally associated with low shear stresses (25-27). Using computational fluid dynamics simulations, new stent designs have been proposed to maximize shear stresses (28, 29), which may reduce bacterial attachment and encrustation (29). These findings highlight the key role played by urine flow, which should be considered when designing new IDCs.

At a macroscopic level, a lot of credence is given to a supposed “flushing effect” generated by urine throughput. However, this is probably marginally beneficial, and impractical for many individuals. Alternatively, intermittent flow (using a valve to enable reservoir filling, with sporadic opening for emptying) increases the time for catheters to block with crystalline biofilm *in vitro* (8). Hence, the full drainage system has to be evaluated as a functioning unit, not just the IDC in isolation. Other important considerations include a priority to maintain a closed drainage system. Accordingly, it is important to ensure that any connectors between the IDC and a valve or drainage bag are reliable and minimise risk of disconnection, with associated breach of the closed system. Care of the tubing is needed to reduce chance of it getting kinked or squashed, and hence blocked (3). The drainage bag should not be elevated, in case gravity or siphoning leads to retrograde flow of urine. These apparently simple processes may be important factors for potential individual risks of catheter associated UTI. The Accuryn SmartFoley® and Monitoring System (Potrero Medical, Hayward, CA, USA) aims to reduce standing urine in the drainage system with an Active Drain Line Clearance and three one-way valves to eliminate urinary backflow and airlocks. Introduction of this system was reported to reduce catheter associated UTIs in a burns unit (9). T-Control is a silicone Foley catheter incorporating an integrated valve with three different positions- “open”, “closed” and “insertion”. Trial protocols for this have been proposed (10, 30).

A geometric design using triangular obstacles against bacterial “upstream swimming”, optimized by an artificial intelligence model, has also been proposed to reduce retrograde spread along the catheter lumen (11). However, this needs detailed evaluation to identify whether the approach might be disadvantageous in terms of biofilm adherence.

Retrograde flushing with saline or washouts could in theory displace bacteria, or exert an antibacterial effect. Indeed, a randomized trial of 60 comatose patients found that daily bladder irrigation using saline was associated with reduced risk of UTI (12). However, a Cochrane analysis did not find adequate evidence to support catheter washouts on a wide range of indications (31).

Low-frequency surface acoustic waves have demonstrated the ability to interfere with the early stages of microbial biofilm formation, resulting in a significant reduction of biofilm in catheters (32). Additionally, these waves have been found to enhance the susceptibility of certain bacteria to antibiotic treatments (13). Uroshield (NanoVibronix, USA) is a small device designed to be attached to the tubing of an IDC, transmitting low-frequency acoustic waves along both the inner and outer surfaces of the catheter.

### Preventing or clearing blockages

Catheter designs could incorporate measures to facilitate use of techniques to counteract blockage. The drainage balloon appears to provide a means for introducing anti-bacterial compounds, with the benefit of proximity to the drainage holes in most designs. Triclosan in this location reduces *Proteus mirabilis* biofilm in an *in vitro* setting (14). For individual users this can improve blockages, but an attempt to run a clinical trial, with UTI rates as an outcome measure, did not reach the planned end-point (33). Another approach is to place the anti-bacterial substance into the catheter lumen, described as “catheter lock solution”, and triclosan/ cranberry appear to prevent all tested strains from adhering onto catheter surface *in vitro* (though filled via the eye hole, whereas clinical use would necessitate retrograde filling) (15). However, although certain antimicrobial substances/coatings can decrease bacterial attachment on urinary stents and catheters, their effectiveness may be undermined by the formation of crystal deposits that form soon after placement, providing a surface for bacteria to adhere over the antimicrobial layer (34, 35).

Alternatively, physical methods can be applied. For example, *Proteus mirabilis* crystalline biofilms detach from silicone elastomer substrates upon application of strain to the substrate, and increasing the strain rate increases biofilm detachment (16). Potentially, methods could be developed to achieve surface strain selectively in a catheter lumen (16). Another concept has been proposed to clean biofilm from the lumen of a urethral catheter with a soft robot, actuated by a magnetic field (17). Such a method would need to ensure that displaced biofilm was drained outwards only, and that retrieval of the robot could be ensured (otherwise a retained robot would be the cause of blockage).

Furthermore, dynamic, activatable microstructures on the walls of stents and catheters have been introduced to increase wall shear stresses 'on demand,' effectively cleaning surfaces from biofilm and crystals through two different approaches. The first approach employs magnetically actuated microstructures (i.e. pillar-like structures (18)) that prevent biofilm formation through periodic vibration. This vibration locally increases fluid velocity, thereby increasing wall shear stress. However, the effectiveness of this method is limited by the challenge of inducing high-frequency vibrations magnetically (above 100 Hz), which restricts the range of achievable velocities and wall shear stresses. To overcome these limitations, the second approach uses ultrasound-activated cilia operating at frequencies above 20 kHz (19). When activated by ultrasound, these cilia vibrate, producing acoustic streaming with high fluid velocities, resulting in significant wall shear stress. Initial microfluidic results indicate that these microstructures can effectively clean typical urinary crystals and biofilm off surfaces, suggesting a potential for transcutaneous cleaning using ultrasound.

## Demonstrating reduced UTIs

The lack of clinical data on the effectiveness of these IDC design features is, in part, due to the challenges of undertaking trials. Users of long-term IDCs often have complex needs and many are reliant on carers for the day-to-day management of their device. The provision of associated health services is usually spread over multiple providers (e.g. community nursing for planned IDC changes, general practice for prescription and acute care for unplanned management). Additionally, the length of intervention period needed to support the identification in a meaningful change in incidence of UTIs and other outcomes is likely to be at least six months. These factors mean that trial recruitment and data collection is resource intensive and burdensome, with a risk of high levels of participant withdrawal. Whilst large-scale trials with short-term hospitalised IDC users have provided useful insights into UTI and other outcomes, definitive trials of community-based long-term IDC users are limited.

## Discussion

IDC use is a well-recognised risk factor for the development of UTI. Any measure to reduce infections is a welcome tool, given the nature of the symptoms, and the potential consequences- particularly in patients with extensive comorbidity. However, many factors make it hard and expensive to research and confirm a reduction in infections. Understandably, many researchers focus on proxy measures, such as reduction in blockages. Achieving reduced blockages is highly desirable in itself, but affirming that this truly translates into a reduction in UTIs is likely to be an over-simplification. Proxy measures are simply that; catheter blockage is a local infection, not a systemic one, predisposed by the micro-environment. The presence of bacteriuria is inevitable, and may well not lead to systemic infection, particularly in people whose immune systems are fully functioning. Measures to reduce trauma or the presence of a residual "sump" are indirect factors, which may be applicable to only a subgroup of IDC users. Furthermore, modifications may be advantageous in one way, but potentially might bring problems in other ways. Hence, there is very little convincing evidence to demonstrate these innovations genuinely deliver a reduction in UTI risk.

For these reasons, it is essential to develop reliable in-vitro and computational testing (36) platforms that can compare the performance of various catheter solutions in terms of urine drainage, blockages, and other factors accurately and reproducibly. These platforms should be designed to model precisely the geometrical, tissue and fluid mechanical, biological, and chemical properties of the lower urinary tract. More representative *in vitro* models are needed to back up these findings, ideally aspiring to maintained tissue models (37, 38).

A large focus now needs to prioritise the contribution of best practice in catheter-associated UTI prevention strategies (39). Attention to fundamentals, such as training of healthcare professionals overseeing IDC, is known to improve outcomes (40). Quality improvement interventions can achieve large declines in UTI rates; net costs to hospitals vary, but on average are not significantly different from zero over 3 years (41). Hence, it is clear that education of healthcare professionals can have a significant influence, and this should be prioritised in current practice. That will ensure that the whole drainage system, not only the catheter component of it, is considered.

Ultimately, the potential of microorganisms to adapt and thrive in the urinary tract must not be underestimated, and it appears inevitable that UTIs will continue to be a persisting challenge for the foreseeable future (42).

## Conflicts of interest

MJD was investigator on NIHR RfPB PB-PG-0317-20026, A new urinary catheter to improve bladder drainage: first-in-human testing of the Flume catheter. <https://fundingawards.nihr.ac.uk/award/PB-PG-0317-20026> and NIHR131172, Multicentre trial of the clinical and cost effectiveness of a novel urinary catheter design in preventing catheter-associated urinary tract infection compared with the traditional Foley design for adults requiring long-term catheterisation (CADET). <https://fundingawards.nihr.ac.uk/award/NIHR131172>

FC is co-inventor on patent application Nr CH00336/2024 ‘Medical device for use as ureteral stent, biliary stent or urinary catheter in a human or animal body, medical system comprising such a device and method of ultrasonically activating such a device’

CM is investigator on NIHR131172, Multicentre trial of the clinical and cost effectiveness of a novel urinary catheter design in preventing catheter-associated urinary tract infection compared with the traditional Foley design for adults requiring long-term catheterisation (CADET). <https://fundingawards.nihr.ac.uk/award/NIHR131172>

MJF was investigator on ‘The effect of low frequency ultrasound on urinary catheter biofilms’ on the Nanovibronix Uroshield device; NIHR RfPB PB-PG-0317-20026, A new urinary catheter to improve bladder drainage: first-in-human testing of the Flume catheter. <https://fundingawards.nihr.ac.uk/award/PB-PG-0317-20026>; NIHR131172, Multicentre trial of the clinical and cost effectiveness of a novel urinary catheter design in preventing catheter-associated urinary tract infection compared with the traditional Foley design for adults requiring long-term catheterisation (CADET). <https://fundingawards.nihr.ac.uk/award/NIHR131172>

## References

1. Thuroff JW, Abrams P, Andersson KE, Artibani W, Chapple CR, Drake MJ, et al. [EAU Guidelines on Urinary Incontinence]. Actas Urol Esp. 2011;35(7):373-88.

2. Drake MJ, Apostolidis A, Cocci A, Emmanuel A, Gajewski JB, Harrison SC, et al. Neurogenic lower urinary tract dysfunction: Clinical management recommendations of the Neurologic Incontinence committee of the fifth International Consultation on Incontinence 2013. Neurourol Urodyn. 2016;35(6):657-65.

3. Murphy C. Innovating urinary catheter design: An introduction to the engineering challenge. Proc Inst Mech Eng H. 2019;233(1):48-57.

4. Feneley RC, Kunin CM, Stickler DJ. An indwelling urinary catheter for the 21st century. BJU Int. 2012;109(12):1746-9.

5. Drake MJ, Anderson K, Gammie A, Morris N, Timlin T, Cotterill N, et al. Development and first-in-human testing of FLUME urinary catheter with protected tip and relocated drainage holes. Continence (Amst). 2023;8:None.

6. Ramezani F, Khatiban M, Rahimbashar F, Soltanian AR, Mousavi-Bahar SH, Elyasi E. Evaluating the Potential of a New Low-Profile Urinary Catheter in Preventing Catheter-Associated Urinary Tract Infections: A Prospective Randomized Blinded Clinical Trial. Health Serv Res Manag Epidemiol. 2023;10:23333928231211410.

7. Azar R, Shadpour P. In Vivo Trial of a Novel Atraumatic Urinary Catheter Design for Prevention of Catheter-Induced Trauma. J Endourol. 2016;30(7):822-7.

8. Sabbuba NA, Stickler DJ, Long MJ, Dong Z, Short TD, Feneley RJ. Does the valve regulated release of urine from the bladder decrease encrustation and blockage of indwelling catheters by crystalline proteus mirabilis biofilms? J Urol. 2005;173(1):262-6.

9. Brockway P, Hill DM, Moll V, Stanton K, Malbrain M, Velamuri SR. A Retrospective, Observational Study of Catheter-Associated Urinary Tract Infection Events Post-Implementation of a Novel Urinary Catheter System with Active Drain Line Clearance and Automated Intra-Abdominal Pressure Monitoring. Life (Basel). 2022;12(12).

10. Medina-Polo J, Salamanca-Castro AB, Ramallo-Farina Y, Modol-Vidal M, Valcarcel-Nazco C, Armas-Moreno C, et al. A study protocol of a comparative mixed study of the T-Control catheter. BJUI Compass. 2024;5(3):345-55.

11. Zhou T, Wan X, Huang DZ, Li Z, Peng Z, Anandkumar A, et al. AI-aided geometric design of anti-infection catheters. Sci Adv. 2024;10(1):eadj1741.

12. Ramezani F, Khatiban M, Rahimbashar F, Soltanian AR. Efficacy of bladder irrigation in preventing urinary tract infections associated with short-term catheterization in comatose patients: A randomized controlled clinical trial. Am J Infect Control. 2018;46(10):e45-e50.

13. Kopel M, Degtyar E, Banin E. Surface acoustic waves increase the susceptibility of Pseudomonas aeruginosa biofilms to antibiotic treatment. Biofouling. 2011;27(7):701-10.

14. Jones GL, Russell AD, Caliskan Z, Stickler DJ. A strategy for the control of catheter blockage by crystalline Proteus mirabilis biofilm using the antibacterial agent triclosan. Eur Urol. 2005;48(5):838-45.

15. Ayyash M, Shehabi AA, Mahmoud NN, Al-Bakri AG. Antibiofilm properties of triclosan with EDTA or cranberry as Foley Catheter lock solutions. J Appl Microbiol. 2019;127(6):1876-88.

16. Levering V, Wang Q, Shivapooja P, Zhao X, Lopez GP. Soft robotic concepts in catheter design: an on-demand fouling-release urinary catheter. Adv Healthc Mater. 2014;3(10):1588-96.

17. Baburova PI, Kladko DV, Lokteva A, Pozhitkova A, Rumyantceva V, Rumyantceva V, et al. Magnetic Soft Robot for Minimally Invasive Urethral Catheter Biofilm Eradication. ACS Nano. 2023;17(21):20925-38.

18. Gu H, Lee SW, Carnicelli J, Zhang T, Ren D. Magnetically driven active topography for long-term biofilm control. Nat Commun. 2020;11(1):2211.

19. Dillinger C, Nama N, Ahmed D. Ultrasound-activated ciliary bands for microrobotic systems inspired by starfish. Nat Commun. 2021;12(1):6455.

20. Lachance CC, Grobelna A. Management of Patients with Long-Term Indwelling Urinary Catheters: A Review of Guidelines. CADTH Rapid Response Reports. Ottawa (ON)2019.

21. Gammie A, Holmes R, Chen HY, Conn A, Morris N, Drake MJ. Development of a more clinically relevant bladder and urethral model for catheter testing. J Med Eng Technol. 2021;45(3):237-44.

22. Parkin J, Scanlan J, Woolley M, Grover D, Evans A, Feneley RC. Urinary catheter 'deflation cuff' formation: clinical audit and quantitative in vitro analysis. BJU Int. 2002;90(7):666-71.

23. Stickler DJ, Morris NS, Winters C. Simple physical model to study formation and physiology of biofilms on urethral catheters. Methods Enzymol. 1999;310:494-501.

24. Clavica F, Zhao X, ElMahdy M, Drake MJ, Zhang X, Carugo D. Investigating the flow dynamics in the obstructed and stented ureter by means of a biomimetic artificial model. PLoS One. 2014;9(2):e87433.

25. Zheng S, Amado P, Obrist D, Burkhard F, Clavica F. An in vitro bladder model with physiological dynamics: Vesicoureteral reflux alters stent encrustation pattern. Front Bioeng Biotechnol. 2022;10:1028325.

26. De Grazia A, LuTheryn G, Meghdadi A, Mosayyebi A, Espinosa-Ortiz EJ, Gerlach R, et al. A Microfluidic-Based Investigation of Bacterial Attachment in Ureteral Stents. Micromachines. 2020;11(4):408.

27. Particle Accumulation in Ureteral Stents Is Governed by Fluid Dynamics: In Vitro Study Using a “Stent-on-Chip” Model. Journal of Endourology. 2018;32(7):639-46.

28. Zheng S, Obrist D, Burkhard F, Clavica F. Fluid mechanical performance of ureteral stents: The role of side hole and lumen size. Bioeng Transl Med. 2023;8(2):e10407.

29. Mosayyebi A, Lange D, Yann Yue Q, Somani BK, Zhang X, Manes C, et al. Reducing deposition of encrustation in ureteric stents by changing the stent architecture: A microfluidic-based investigation. Biomicrofluidics. 2019;13(1):014101.

30. Ramallo-Farina Y, Chavarri AT, Robayna AA, Vidal MM, Valcarcel-Nazco C, Armas Moreno C, et al. Effectiveness of the T-Control catheter: A study protocol. BJUI Compass. 2024;5(2):178-88.

31. Shepherd AJ, Mackay WG, Hagen S. Washout policies in long-term indwelling urinary catheterisation in adults. Cochrane Database Syst Rev. 2017;3(3):CD004012.

32. Hazan Z, Zumeris J, Jacob H, Raskin H, Kratysh G, Vishnia M, et al. Effective prevention of microbial biofilm formation on medical devices by low-energy surface acoustic waves. Antimicrob Agents Chemother. 2006;50(12):4144-52.

33. Sperling H, Eisenhardt A, Mumperow E, Gralla O, Lummen G, Seidali K, et al. [Investigation of the use of triclosan in patients with indwelling catheters: a randomized, double blind, multicenter, placebo-controlled clinical study]. Urologe A. 2014;53(10):1512-7.

34. Amado P, Zheng S, Lange D, Carugo D, Waters SL, Obrist D, et al. The interplay between bacterial biofilms, encrustation, and wall shear stress in ureteral stents: a review across scales. Front Urol 2024;3:1335414.

35. Zheng S, Bawazir M, Dhall A, Kim HE, He L, Heo J, et al. Implication of Surface Properties, Bacterial Motility, and Hydrodynamic Conditions on Bacterial Surface Sensing and Their Initial Adhesion. Front Bioeng Biotechnol. 2021;9:643722.

36. Damaser MS, Valentini FA, Clavica F, Giarenis I. Is the time right for a new initiative in mathematical modeling of the lower urinary tract? ICI-RS 2023. Neurourol Urodyn. 2024;43(6):1303-10.

37. Parsons BA, Drake MJ, Gammie A, Fry CH, Vahabi B. The validation of a functional, isolated pig bladder model for physiological experimentation. Front Pharmacol. 2012;3:52.

38. Fry CH, Daneshgari F, Thor K, Drake M, Eccles R, Kanai AJ, et al. Animal models and their use in understanding lower urinary tract dysfunction. Neurourol Urodyn. 2010;29(4):603-8.

39. Patel PK, Advani SD, Kofman AD, Lo E, Maragakis LL, Pegues DA, et al. Strategies to prevent catheter-associated urinary tract infections in acute-care hospitals: 2022 Update. Infect Control Hosp Epidemiol. 2023;44(8):1209-31.

40. Fish L, Heathers R, Litherland M, Jung M, Yu K. Implementation of a multi-modal intervention adopting new technologies, clinical services, and feedback improves catheter-associated urinary tract infections. Hosp Pract (1995). 2024:1-5.

41. McCleskey SG, Shek L, Grein J, Gotanda H, Anderson L, Shekelle PG, et al. Economic evaluation of quality improvement interventions to prevent catheter-associated urinary tract infections in the hospital setting: a systematic review. BMJ Qual Saf. 2022;31(4):308-21.

42. Werneburg GT. Catheter-Associated Urinary Tract Infections: Current Challenges and Future Prospects. Res Rep Urol. 2022;14:109-33.