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Tailored Solutions in Ureteral Stenting: From Classic Designs to Smart Technologies

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Abstract This review explores recent advancements in ureteral stent design, aiming to improve patient comfort and reduce complications such as pain, infection, and vesicoureteral reflux. Traditional double-J stents, while effective for drainage, are often poorly tolerated. New-generation models include single- and multi-loop designs, short and intraluminal stents, anti-reflux valves, biodegradable materials, and smart features such as pressure monitoring. Innovations like 3D printing allow for individualized stent customization. Although no single design is ideal for all cases, these developments offer promising alternatives tailored to specific clinical scenarios. Continued research, clinical validation, and standardization are essential to optimize outcomes and advance the future of stent technology.

Keywords Ureteral stents, Stent design, Anti-reflux stents, Biodegradable stents, Intraluminal stents, Urinary drainage

1. Background

The concept of the stent originates from the 19th century, when British dentist Charles Stent developed a compound to stabilize dental molds, a name that eventually became synonymous with a broad class of implantable medical supports [1]. In the field of urology, a major advancement occurred in 1967 when Zimskind and colleagues introduced the first internal silicone ureteral stent designed to manage ureteral obstruction [2]. Another pivotal moment in stent innovation came in 1978, when Finney proposed a design featuring double J-shaped coils at each end to secure the stent within the renal pelvis and bladder, effectively reducing dislodgement [3]. Since then, continuous advancements have been made in both the geometry and composition of stents — evolving from basic silicone and polyurethane to more sophisticated polymeric blends and metal-integrated coatings. Despite these innovations, the double-J (DJ) stent remains the prevailing standard in contemporary urologic interventions [4].

Although widely utilized in clinical practice, modern ureteral stents are not without complications. A significant proportion of patients experience what is termed "stent-related symptoms" or "stent syndrome," characterized by lower urinary tract symptoms such as dysuria, flank or bladder pain, increased urinary frequency, and hematuria. Additional complications include stent migration, mineral encrustation, biofilm formation, and urinary tract infections. Research shows that 70–80% of patients report substantial discomfort during the indwelling period. Furthermore, all current stent types necessitate timely removal due to the increasing risk of encrustation, occlusion, and the potential onset of urosepsis with prolonged implantation [5]. So-called "forgotten stents" pose a significant clinical challenge, often requiring invasive retrieval procedures [6].

With the global rise in urological surgeries and the growing incidence of urolithiasis, the relevance of ureteral stenting continues to increase [7]. Estimates suggest that more than 1.5 million ureteral stents are inserted annually worldwide, with approximately three-quarters following endoscopic procedures for urinary stones. This widespread usage contributes to a substantial burden on healthcare systems, considering the need for ongoing surveillance, stent exchanges, and management of associated adverse events [4]. Consequently, recent research efforts have focused on improving stent performance through the development of biodegradable devices that obviate the need for removal [8], incorporation of antimicrobial and antitumor coatings [9], and designs that mitigate patient discomfort and vesicoureteral reflux. Nonetheless, a universally optimal stent — one that achieves both maximal drainage and minimal side effects — remains elusive [10]. As such, continued innovation in stent materials, geometry, and clinical application is essential for advancing patient care in urology.

Objective. The main objective of this article is to review and analyze recent literature focused on the development of next-generation ureteral stents.

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2. Materials

A comprehensive analysis of the PubMed, EMBASE, Web of Science, and Cochrane Library databases was conducted up to May 2025.

3. Results

Ureteral stents are widely used in urology to ensure urinary drainage from the kidney to the bladder in cases of obstruction. The classic double-loop stent, known as the "Double J" (DJ) stent, was introduced into clinical practice in 1978 and became the standard due to its curled ends, which prevent stent migration [4]. However, despite its effectiveness in drainage, standard DJ stents frequently cause significant discomfort for patients. More than 80% of individuals with indwelling stents report flank pain, increased urinary frequency, urgency, and other symptoms related to bladder irritation [5]. Additionally, the presence of a stent disrupts the natural anti-reflux mechanism, often leading to vesicoureteral reflux (VUR) during urination, which may provoke flank pain episodes and increase the risk of pyelonephritis [11]. Infectious complications are also common — various studies indicate that 20–45% of patients develop urinary tract infections, particularly during prolonged stent placement [5]. These issues have prompted the active search for new ureteral stent designs aimed at improving tolerability, reducing complications, and enhancing patient quality of life [4].

The double-J stent is characterized by rounded "pig-tail" curls at both ends — the proximal end located in the renal pelvis and the distal end in the bladder. This configuration serves two primary functions: maintaining continuous urine drainage through the stent lumen and anchoring the stent in place, thereby preventing migration upward into the kidney or downward into the urethra [4]. Standard DJ stents are produced in various sizes (typically 4–7 Fr in diameter and 24–30 cm in length) and are inserted endoscopically for the treatment of urolithiasis, ureteral strictures, and following surgery or kidney transplantation. The introduction of dual loops effectively resolved the problem of stent displacement and eliminated the need for external fixation [3].

Nevertheless, double-loop stents are associated with multiple adverse effects collectively referred to as "stent syndrome." Patients frequently report renal-area pain that intensifies during urination due to vesicoureteral reflux, along with lower urinary tract symptoms (increased frequency, urgency, sensation of incomplete emptying), which are caused by irritation of the bladder trigone by the distal loop [12]. According to patient-reported outcome measures (such as the USSQ), over 70–80% of patients experience significant discomfort during DJ stent indwelling, negatively impacting their quality of life [5,12,13]. Additionally, due to the stent keeping the ureteral orifice open, the valve-like function is disrupted, and almost all patients with DJ stents exhibit both passive and voiding-induced reflux into the upper urinary tract [11,13]. This can lead to pyelonephritis, fever, and renal parenchymal damage if the stent remains in place for an extended period [14].

Moreover, the stent can serve as a substrate for biofilm formation and mineral encrustation, which increases the risk of infection and stone-like deposits with prolonged placement [14]. Thus, although DJ stents are widely used and generally effective, their minimally invasive nature is compromised by the high prevalence of associated symptoms and complications. These challenges have motivated researchers to modify stent designs with the goal of reducing contact with sensitive anatomical zones and mitigating the pathological effects of indwelling stents.

A single-loop (mono-loop) stent is a tube with a curl at only one end — typically the proximal end located in the kidney — while the distal end remains straight and does not form a loop within the bladder. Mono-J stents are designed with the intent that the absence of the lower loop may reduce bladder irritation and associated symptoms [15,16]. Essentially, the distal tip of such a stent is positioned within the ureteral lumen or hangs freely into the bladder without coiling. These stents are generally intended for short-term drainage — for instance, within the first few hours or days following ureteroscopy or surgery — as prolonged placement carries a higher risk of migration.

Short-term use of mono-J catheters (6 to 24 hours) after ureterolithotripsy has been examined in several studies [17]. In a prospective randomized trial, Moon et al. compared a standard DJ stent with an open-ended mono-loop catheter placed after endoscopic stone removal. No significant differences in pain or symptoms were observed during the first 24 hours, but the need for secondary interventions (e.g., due to obstruction or pain) was slightly higher in the mono-J group [18]. Another study stratified patients into two groups: those who received a classic DJ stent for 3–5 days and those who had a mono-J catheter removed six hours after surgery. The trial was discontinued early due to a trend toward more frequent complications in the mono-J group (repeat intervention required in 35.5% vs. 16.7% in the DJ group, $p > 0.05$). While urinary symptoms and pain levels were similar between groups at the 24-hour mark, patients in the mono-J group paradoxically reported more pronounced discomfort during the later postoperative period (3–5 weeks) [16]. This was likely due to unplanned repeat stenting in some mono-J patients following obstruction and pain.

Thus, while mono-loop stents may initially reduce bladder irritation, the risks of migration and incomplete drainage limit their broader use. To address dislodgement, certain technical solutions have been proposed — for example, attaching the free end of the mono-J to a Foley catheter in the bladder — but such stents are rarely used in routine practice. Currently, mono-loop designs are primarily regarded as short-term inpatient drainage catheters (lasting less than 24 hours), enabling temporary urinary diversion without significant bladder symptoms and allowing timely removal without cystoscopy [18].

Multi-loop stents are those in which two or more loops are formed at one or both ends. These additional curls can be

designed as two small rings instead of one large loop or as sequential spiral coils. The goal of such modifications is to improve stent retention while simultaneously reducing the pressure a single loop may exert on organ walls. For example, a dual-loop configuration has been developed for the bladder end of the stent: two smaller loops replace one larger loop in order to reduce contact with the bladder trigone, thereby decreasing irritation [13]. Multi-loop designs also include stents with three or four coils (usually at the renal end) to provide enhanced anchoring in cases of large renal pelvises or mobile kidneys. A commercial example is the Polaris™ Loop (Boston Scientific), which features two small loops at the bladder end [19]. The combined material volume of these loops is approximately 69% less than that of a standard single loop. This design was hypothesized to reduce bladder irritation and associated symptoms. Clinical trials have shown some reduction in pain, urinary frequency, and analgesic use in patients with Polaris-type stents compared to standard DJ stents [13]. However, in many cases, these differences were not statistically significant or consistently reproducible [20].

A randomized study by Lee and Kim (2015) compared the tolerability of three different stent models and found no clear advantage for the double-loop design in terms of reducing irritation-related symptoms [21]. Nonetheless, some patients subjectively reported better tolerability with multi-loop variants, supported by trends in symptom score reductions (e.g., ~21% lower scores on urinary symptom scales for so-called "tail-stents" that lack a bladder loop) [13]. From a migration prevention perspective, additional coils at the renal end may improve retention within the renal pelvis, especially when it is markedly dilated. Overall, multi-loop designs are viewed as an evolution of the standard stent, aiming to reduce the volume of foreign material in the bladder while maintaining effective anchoring. Although they do not provide a definitive solution to stent-related symptoms, these stents — including double-loop models — have been adopted in clinical practice and offer a useful alternative for patients experiencing significant bladder discomfort [20].

Vesicoureteral reflux (VUR) caused by the presence of a stent is considered one of the main contributors to flank pain during urination and a risk factor for ascending infections [11,13]. Consequently, the development of an anti-reflux stent that prevents backflow of urine into the ureter has become a logical objective. Implementing such a design is technically challenging, as the stent lumen must allow unobstructed urine flow from the kidney while simultaneously blocking retrograde flow from the bladder. One of the earliest solutions involved valve membranes located at the distal end of the stent. For instance, the Finney anti-reflux membrane is a thin silicone pouch secured around the stent's exit holes. It inflates to allow urine passage during antegrade flow and collapses to block flow during retrograde pressure from the bladder. Clinical trials demonstrated that this valve reduced the degree of reflux and related symptoms. In a study by Ecke et al. (2010), standard DJ stents were compared with stents equipped with a membrane valve: the anti-reflux group experienced significantly fewer episodes of VUR, less intense voiding pain, and better overall tolerability [13,22].

However, other studies have not definitively confirmed improvements in quality of life. For example, Ritter et al. (2012) found no significant difference in symptom scores (USSQ) between standard and anti-reflux stents, even though imaging revealed considerably less reflux in the group with valves [23]. This suggests that addressing reflux alone may not completely resolve discomfort, and other factors — such as direct irritation of the bladder wall by the stent material — likely play a role [13].

Another design — the polymeric flap valve — was proposed by Park et al. It is manufactured using 3D printing from an elastic material and consists of two thin leaflets attached to the outlet of the stent [24]. When bladder pressure increases, the leaflets close and block the lumen, while under normal pressure, they remain open. In a porcine model, this valve significantly reduced the degree of reflux compared to a standard stent [25]. However, complete prevention of urine backflow was not achieved: peristent reflux persisted, with urine flowing around the outside of the stent through the ureter, as the presence of any stent keeps the ureteric orifice partially open [13]. Even with the valve, about 18% of cases showed low-grade vesicoureteral reflux in pigs [25]. Thus, membrane and leaflet valves effectively block retrograde urine flow inside the stent lumen but cannot eliminate reflux around the stent when it traverses the ureteric orifice into the bladder.

Anti-reflux stents have evolved from prototypes to clinical testing. Recently published data have confirmed real clinical benefits of such stents. In a randomized controlled trial conducted in 2023, 51 patients with anti-reflux stents were compared with 56 patients receiving standard stents after stone removal. The group with valve-equipped stents demonstrated a significant reduction in flank and suprapubic pain, a decrease in dysuric symptoms, and a higher quality of life index according to the SF-36 scale. No differences were observed between groups in terms of infection rates, hydronephrosis, or renal function impairment, confirming the safety of the new design [26]. A 2023 meta-analysis (Adhoni et al.) combining several RCTs showed that anti-reflux stents significantly reduced pain and stent-related symptoms compared to standard models [27]. Therefore, implementing valve mechanisms at the distal end of ureteral stents is one of the most promising directions for minimizing painful reflux and improving stent tolerability without compromising drainage function.

Short (intraureteral) stents. Short stents generally refer to devices whose distal end does not extend deeply into the bladder cavity. This category includes so-called tail-stents with a straight tip instead of a loop, as well as intraureteral stents without a bladder loop — the distal end is either anchored in the terminal portion of the ureter or remains entirely within its lumen. These stents are sized such that the distal tip reaches the ureteral orifice or slightly protrudes into the bladder without forming a bulky coil. A commercial

example is the Tail Stent by Boston Scientific, which tapers from 7 Fr to 3 Fr toward a straight tip with no curl [28]. Thanks to the reduced diameter and absence of a bladder loop, the volume of foreign material within the bladder trigone is reduced by approximately 70% [13]. Similarly, the Buoy Stent (Cook Medical) has a thin straight tail, while its proximal end is reinforced (up to 10 Fr) to enhance drainage following endopyelotomy [29].

Reducing the length of the stent within the bladder is intended to minimize irritation. Results have been encouraging: in a randomized trial, Dunn et al. compared the traditional DJ stent with the shortened tail-stent and found a 21% decrease in lower urinary tract symptoms (frequent urination, urgency) in the group with the short stent [28]. However, pain scores and bladder mucosal inflammation did not differ significantly, indicating that the issue is only partially addressed. Still, for patients with severe bladder discomfort, tail-stents may be preferable due to the absence of a "floating" loop that continuously irritates the bladder trigone.

A specific subclass of short stents includes fully intraureteral stents, in which the entire structure is located within the ureter, with no component entering the bladder. To prevent migration, alternative anchoring methods have been developed — ranging from narrowed distal segments to specialized self-anchoring elements. For example, the BraidStent® features a standard loop at the renal end and a distal double spiral "whisker" that unfolds within the terminal ureter and anchors the stent in place [30]. The stent body is a flexible braided mesh approximately 3 Fr in diameter, without an internal lumen, which further reduces its volume. In animal studies, this design completely prevented vesicoureteral reflux (VUR did not occur even under elevated bladder pressure) and caused significantly less mucosal injury at the ureteral orifice compared to conventional stents [13,30]. Targeted drainage of only the affected ureteral segment using an intra-luminal stent did not impair healing; on the contrary, animal studies show that localized stenting without affecting healthy regions promotes better tissue recovery and reduces proximal ureteral dilation above the stent [31].

Fully intraureteral stents are already undergoing clinical trials. Yoshida et al. (2022) conducted a randomized study on patients after ureteroscopy, comparing a conventional stent with a shortened stent whose tip was fixed at the ureteral orifice using internal anchoring with threads and a micro-spiral [32]. In the group receiving intraureteral stents, the incidence of dysuria and pain was significantly lower than in patients with traditional DJ stents, and the need for analgesics was minimal [32]. Thus, the "short" approach — whether a straight tail or a stent that does not extend into the bladder — clearly reduces bladder irritation and the associated discomfort. However, these benefits come with the potential risk of migration and obstruction, especially with prolonged indwelling times. For example, in a case series by Vogt et al. involving "ultra-short" JFil® stents without a distal loop, approximately 20% experienced stent migration [33]. While most of these displacements were distal (into the bladder), around 7% were proximal and required endoscopic removal of the filamentous stent from the kidney [34]. As a result, intraluminal stents are typically equipped with removal aids — thin threads extending into the bladder (as in MiniJFil®) or magnetic tips (as in Black-Star®) that allow extraction without cystoscopy [35]. In any case, reducing stent length within the bladder is a promising direction that has already shown positive clinical outcomes.

Modified stent designs encompass a range of technical improvements to conventional stents that do not fall into other categories. Many of these innovations aim to facilitate stent placement and removal, as well as to tailor stent characteristics to various clinical scenarios.

One such approach involves variation in stiffness across different segments of the stent. Dual-durometer stents have been developed, with a stiffer proximal segment (to ease advancement over a guidewire through a narrowed ureter) and a softer, more flexible distal segment (to minimize bladder irritation) [4,19,36]. This is achieved via co-extrusion of different polymers, creating a seamless transition in material properties along the stent. In addition, some stents feature tapered or conical tips that facilitate passage through strictures and reduce trauma during insertion [36].

Another modification includes widened lumens or the absence of an inner partition (as seen in the braided BraidStent), which enhances drainage while minimizing the external diameter [30]. Certain models are also equipped with additional lateral drainage holes at specific zones — for example, to better drain the upper calyx — representing another structural enhancement of the basic stent design [9,13].

Traditionally, ureteral stents are removed cystoscopically, a process often associated with patient discomfort. To address this, various modifications have been developed to enable non-invasive stent removal. The simplest method involves an external retrieval string attached to the distal end of the stent and extending outside the urethra (common in women and pediatric patients). By pulling the string, the physician can extract the stent without a cystoscope. However, this string may cause discomfort and even serve as a source of infection during extended use [37].

A more advanced solution is the magnetic stent. An example is the Black-Star® system, in which a tiny magnet is embedded in the bladder coil of the stent, and a specialized magnetic retrieval catheter is used for extraction [38]. A randomized trial in 2017 demonstrated that magnetic stents could be successfully removed in an outpatient setting without anesthesia in 100% of cases. Patients — particularly men — reported significantly less pain compared to traditional cystoscopic removal [37]. Complications were minimal, although in cases of heavy encrustation, the magnetic retrieval mechanism may fail. Overall, the magnetic tip is a notable example of a design upgrade that enhances patient experience, and these stents are already in use for short-term indications (2–4 weeks) [13].

Specialized stents for specific clinical scenarios can also be considered part of the broader category of stent

modifications. For example, a stent with an enlarged proximal diameter (10 Fr), such as the Buoy stent, is designed for both drainage and simultaneous dilation of the ureteropelvic junction after incision of a stricture. Its use in pig models demonstrated effective drainage, appropriate healing of the incision, and less trauma to the ureteral orifice compared to conventional stents [29].

In pediatric practice, miniature stents with reduced diameter and length, as well as increased flexibility, are used — an adaptation tailored to children's anatomical features. Other examples include dual-lumen stents, which have two parallel channels — one for urine drainage and the other for instrumentation or contrast injection [39]. These are especially relevant when repeated interventions are required through an indwelling stent (e.g., for stone fragmentation).

Moreover, several improvements are often combined within a single device. The previously mentioned Polaris Loopintegrates a dual-loop design, hydrophilic coating, and a dual-durometer polymer structure [19]. Together, these modifications aim to facilitate both stent placement and patient tolerance, although each feature individually may yield only partial benefits.

Mesh (metallic) stents refer to stents made not from solid polymer cylinders but from braided wires or mesh — typically metallic (nitinol or stainless steel alloys). These stents are usually self-expanding and structurally resemble vascular stents: inserted in a compressed form via a guidewire, they expand upon placement, pressing against the ureteral wall.

One example is the Allium™ Ureteral Stent, a large-caliber (up to 30 Fr expanded) nitinol mesh tube with a polymer coating. It lacks traditional pigtail loops; instead, it features flared ends that anchor in the renal pelvis and bladder lumen to prevent migration [40]. Another example is the Resonance® stent (Cook Medical), a tightly wound metallic spiral resembling a spring [41-44]. Essentially, Resonance is also a mesh-type device if the spiral coils are viewed as a continuous mesh.

Metallic mesh stents are primarily designed for long-term use (months to years) in cases of chronic obstruction — for instance, inoperable ureteral strictures, malignant compression, or recurrent stenosis post-reconstruction. Their advantages include a large internal lumen and high resistance to external compression. Studies have shown that in patients with refractory ureteral strictures (not manageable with conventional stents), self-expanding metal stents provided sustained drainage with reduced need for frequent replacement [44].

For example, Gao et al. (2021) compared Resonance and Allium stents in patients with benign but severe ureteral strictures. Both devices maintained ureteral patency in the majority of cases and reduced the need for repeat procedures, ultimately proving more cost-effective despite higher initial costs [45]. The average indwelling time for Allium stents without replacement reached up to 22 months [40], whereas conventional DJ stents required replacement every 3–6 months.

Metal stents are also less prone to encrustation due to their hydrophobic coatings and smooth surfaces, which hinder salt deposition. However, the primary drawback of mesh stents is migration. The lack of anchoring loops compromises fixation: even with the flared ends of the Allium stent, around 27% of patients experienced migration within the first seven months [40]. Migration may occur downward into the bladder or upward out of the renal pelvis. If a stent migrates too far, it may re-obstruct the ureter and require another surgical intervention.

The Resonance stent, being a spring, offers slightly better fixation (its ends also rest against the bladder and renal pelvis walls), and migration is less frequently reported. However, its rigid design makes it poorly adaptable to body movements. Many patients report significant discomfort or pain due to constant pressure on the ureteral and bladder walls. In one study, 47% of patients were unable to tolerate the Resonance stent beyond 3 months, despite adequate drainage function [43].

In summary, metallic mesh stents represent a niche solution: they provide long-term drainage in complex obstructions and reduce the need for repeated stent changes — but at the expense of patient comfort. Their use is justified primarily in patients with malignant or recurrent strictures, where quality of life is already compromised by the underlying disease, or in situations where repeat replacement of plastic stents is technically challenging.

Spiral stents are devices shaped like a coiled spring along a significant portion of their length. Unlike the conventional Double-J (DJ) stent, which is a straight tube with loops only at its ends, a spiral stent may have a helical configuration throughout its body or in a critical segment. One example is the aforementioned metallic Resonance® stent, which essentially consists of a tightly wound metallic spiral [41]. There are also known prototypes made of biopolymers designed as helical springs without a central lumen.

The spiral shape gives the stent increased elasticity and radial expansion force. This is particularly useful in cases of external ureteral compression: the spiral stent is better able to resist external pressure compared to a hollow tube. Additionally, the gaps between the coils of the spiral allow urine to flow through them (similar to fluid passing between spring segments), potentially reducing the risk of lumen obstruction by clots or sediment. The spiral design may also enhance ureteral peristalsis: studies suggest that the helical surface more effectively transmits peristaltic waves, aiding urine flow and preventing atrophy of the ureteral smooth muscle [46].

One of the most illustrative studies was conducted in Finland by Lumiaho et al. (2011), who tested a biodegradable spiral stent in an animal model. The stent was a short (10 cm) self-expanding coil made of polyglycolic material that gradually dissolved in the body. In dog experiments, the spiral stent provided adequate urine drainage and, most notably, significantly reduced vesicoureteral reflux (VUR) compared to a standard DJ stent [47]. Hydronephrosis and elevated renal pressure during bladder filling were minimal,

whereas conventional stents led to significant retrograde urine flow.

Thus, the short spiral stent demonstrated superior drainage and anti-reflux properties compared to the double-looped stent in experimental settings. This effect was attributed to the spiral's positioning in the lower ureter, which does not open the ureteral orifice as much as a long tube and may even act as a valve-like structure due to its shape. Another potential benefit of the spiral design is the reduction of bladder symptoms, as it lacks a long, floating tail inside the bladder. It was observed that animals with spiral stents had fewer signs of inflammation and histological damage to the bladder wall compared to those with DJ stents [48].

In clinical practice, spiral stents are still used only to a limited extent. The metallic Resonance stent is relatively common for malignant obstructions, but its spiral structure is paired with significant rigidity, making it unsuitable for long-term comfortable wear in most patients. Polymeric spiral stents, especially biodegradable ones, are currently in experimental phases. Their appeal lies in the fact that they may dissolve after restoring ureteral patency, thus eliminating the need for removal [49].

However, it should be noted that a spiral stent without anchoring loops still requires fixation to avoid migration. In the aforementioned Lumiaho study, the spiral stents were short and designed to degrade before migration could occur [47]. For long-term use, a spiral stent would need to combine its shape with other fixation mechanisms (e.g., flared ends). Overall, the spiral design has already demonstrated its effectiveness in reducing reflux and resisting compression but requires further refinement for safe human use.

Stent displacement from its intended position is one of the complications affecting all designs, especially with prolonged indwelling. Despite having anchoring loops, approximately 5–10% of standard DJ stents may shift over time: proximal migration can lead to the stent dislodging from the kidney, while distal migration may result in prolapse into the urethra. This can cause recurrence of obstruction or trauma to the urinary tract. The risk of migration increases with incorrect stent length selection, high physical activity, marked diuresis, etc. Nonstandard designs without conventional anchoring loops (e.g., short or mesh stents) are particularly vulnerable.

All engineering solutions aimed at maintaining the stent in situ are categorized as retention mechanisms. The most basic include the loops themselves, historically developed for this exact purpose [3]. Another is the use of expanding elements—for example, the Allium stent features flared ends that anchor into the walls of the urinary tract to prevent migration. However, as previously mentioned, this is not always sufficient, and Allium stents often migrate nonetheless [40,45].

A different approach is the use of self-anchoring spirals or barbs, as in the BraidStent, which features a double spiral at the distal end [30]. Tests showed that this design remained in place within the ureter without additional support: animal studies reported no significant migration during a 25-day observation period [40]. Similarly, an experimental intraluminal stent by Shilo et al., with expanding “Yoti spirals” at both ends, demonstrated stable positioning in the ureter of pigs, remaining unmoved until euthanasia on day 25 [50]. These promising results suggest that intramural anchors (spirals, hooks, flaps) may be as effective as traditional loops while avoiding entry into the bladder.

Another method is external fixation. Temporary stents are sometimes tied to a urethral catheter or connected to a string secured externally with adhesive tape. This guarantees the stent won’t migrate upward but is only suitable for short-term use due to discomfort and infection risks.

Looking ahead, high-tech solutions are being considered—for example, bioadhesive coatings that temporarily "stick" the stent to the mucosa, or miniature deployable anchors that can be expanded on command after insertion [11,13]. Some of these ideas exist in patents but haven’t yet reached mass production.

Nevertheless, existing designs already perform quite well: with the correct choice of stent length and diameter, double-looped stents typically remain in place until planned removal, and newer models (e.g., spiral or mesh) are gradually approaching this level of retention reliability.

Thus, retention mechanisms are not a distinct stent type but rather a feature common to all modern stents in varying forms. Future developments place increasing emphasis on this aspect, as loss of positioning nullifies the therapeutic benefits of stenting.

Modern research continues to propose original forms and operating principles for ureteral stents. Some are still in preclinical testing, while others are undergoing initial clinical trials. Stents made of biodegradable materials are being developed to dissolve after a predetermined period. The goal is to eliminate the need for removal procedures and avoid the issue of “forgotten stents.” Prototypes made of polyglycolic acid (e.g., Uriprene™) have effectively drained urine in animal models for 6–10 weeks before being absorbed [51]. However, early generations were too soft and difficult to insert, so work is ongoing to create reinforced biodegradable compositions. Such stents can also have nonstandard shapes—such as the previously mentioned spiral—since they do not require subsequent removal [8,30,52]. In Spain, researchers have developed the BraidStent-H, a braided stent with valve function, made from a resorbable material and coated with heparin to prevent biofilm formation. In pig experiments, this design showed lower bacterial colonization and no reflux, with drainage performance comparable to a standard stent. This direction combines several innovations at once: material, geometry, and coating.

Reports are emerging of stents equipped with sensors or active components. For instance, researchers are exploring stents capable of measuring renal pelvic pressure and transmitting data externally for real-time monitoring of patency. Another approach involves stents with vibration or heating capabilities to disrupt early encrustation or biofilm formation, though these concepts have only been demonstrated in laboratory settings so far. Additionally, the idea of a dynamic stent—one that adjusts to ureteral peristalsis and

minimizes interference—has been proposed [13]. Although "active" stents have not yet reached clinical application, interest in them is growing rapidly.

3D printing is already being used to prototype valve structures [24], and in the future, it may be applied to the fabrication of entire stents, custom-tailored to the patient's unique anatomy. This would allow clinicians to modify length, diameter, and loop configuration based on an individual patient's ureteral dimensions, potentially reducing both migration and symptom burden.

Overall, there is a clear trend toward highly specialized stent designs for specific clinical scenarios. It is likely that in the near future, there will be no single "universal" stent model. Instead, physicians will be able to select from a variety of options: one stent for reflux prevention in a young patient with stones, another for long-term drainage in cases of malignancy, a third for pregnant women, and a fourth for pediatric patients, and so on. Experts are already forecasting this shift [9]. Naturally, all these experimental solutions must still undergo thorough validation for safety and efficacyin large-scale clinical trials. However, progress in this field is evident: over the past 10–15 years, numerous new designs have emerged, some of which have already improved patient outcomes. Ongoing research and innovation give reason to believe that future ureteral stents will be better tolerated, while maintaining their therapeutic functions.

4. Conclusions

The evolution of ureteral stent design reflects a clear effort to minimize side effects and improve patient quality of life, while ensuring reliable urinary drainage. Despite their widespread use, traditional double-J stents are associated with significant discomfort, vesicoureteral reflux, and infection risk. This has prompted the development of alternative designs: single-loop, multi-loop, short (tail), intraluminal, and mesh stents. One of the most promising directions is the anti-reflux stent with valve mechanisms, which has shown effectiveness in reducing symptoms and urinary backflow.

There is ongoing innovation in biodegradable, spiral-shaped, and "smart" stents with pressure monitoring capabilities, as well as in customized solutions enabled by 3D printing. However, no single design is universally optimal. The future lies in a personalized approach, where stent selection is based on anatomical characteristics and the specific clinical indication. The systematization of innovations, their clinical validation, and the standardization of indications are key steps toward further advancement in this area.

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