

Ureteral Stent Encrustation: Epidemiology, Pathophysiology, Management and Current Technology



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Abbreviations and Acronyms

CT = computerized tomography
FECal = Forgotten, Encrusted, Calcified
KUB = kidney, ureter and bladder

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Purpose: Encrustation is a common phenomenon that can occur following placement of a ureteral stent into the urinary tract, and it can lead to serious complications. The following review addresses the mechanism of encrustation, the management of these stents and the newest technology developed to mitigate this issue.

Materials and Methods: We performed a comprehensive literature search on stent encrustation including peer-reviewed publications, public product listings, and material on current and future stent technology.

Results: The mechanism of encrustation is complex and multifaceted, including dwell time, patient specific risk factors, conditioning film formation, biofilm formation and mineral deposition. Several technological developments in stent materials and coatings may have a role in reducing the risk of stent encrustation. It is important to identify the extent of stent encrustation and plan treatment strategies accordingly. We propose a novel treatment algorithm for the management encrusted ureteral stents.

Conclusions: The ubiquity of ureteral stents in urology practice mandates updated knowledge about the prevention of stent encrustation, identification of high risk patients and preparedness for removal using multimodal techniques.

Key Words: ureter, stents, ureteral obstruction, urine, risk factors

URETERAL stents are important urological tools that can stabilize the ureters and assist outflow of urine from the kidney to the bladder.¹ Stents are inserted to decompress ureteral obstruction, to dilate the ureters to aid instrumentation, to prevent occlusion following procedures and to provide a scaffold for healing.² However, stent placement can be a double-edged sword, potentially causing side effects and complications. Introduction of a foreign object into the urinary tract can result in discomfort, infection, and encrustation of the surface and/or lumen of a stent.³ These issues not only impact the quality of care, but

can also exert a significant economic toll. Multiple additional procedures may be required to remove an encrusted stent, and up to 16% of endourology lawsuits are related to retained stents.⁴

Encrustation is the deposition of mineral crystals onto the surface and lumen of a ureteral stent. This can create serious problems, especially for chronically indwelling stents or forgotten/retained stents, which can occur in up to 13% of cases.⁵ When stents become encrusted, they become calcified and brittle and lose their tensile strength, raising the risk of stent fracture or ureteral avulsion during removal. Crystal deposition

can obstruct drainage through the stent lumen and can also interact with the urothelial lining of the ureters, leading to ureteral trauma.⁶ Additionally prolonged retention of ureteral stents has been shown to confer an increased risk of chronic kidney disease and hospitalization for urinary tract infection or sepsis after stent removal.⁷

The following is a review of the most recent literature regarding stent encrustation and management. First, the risk factors and mechanisms of encrustation are explored. Next, current stent technology and strategies for prevention are reviewed. Then, clinical guidelines for diagnosing and managing encrusted stents are summarized. Finally, emerging areas of research are discussed.

RISK FACTORS

Encrustation occurs when minerals from the urine deposit on the surface of an indwelling stent. Risk factors include duration of stent indwelling time, bacterial colonization, patient specific factors and physical characteristics of the stent.

The key risk factor for development of encrustation has been shown repeatedly to be the duration of stent indwelling time. A 1991 study by el-Faqih et al evaluated polyurethane stents removed from patients at a single institution and reported that 9% of stents showed signs of encrustation by 6 weeks, 48% by 6 to 12 weeks and 77% after 12 weeks.⁸ A 2012 study by Kawahara et al similarly reported encrustation rates of 27%, 57% and 76% at equivalent time intervals.⁹ Moreover, 30% of stents retrieved before 12 weeks showed evidence of luminal encrustation but only 4% of patients had clinical symptoms of stent obstruction.⁸ While the ideal indwelling time is not strictly known for many urological procedures, the temporal risk of encrustation is clear.

Bacterial biofilm may also have a critical role in encrustation. A commonly cited study from 1996 showed that 90% of ureteral stents retrieved from patients had colonized pathogens and 55% had adherent biofilms.¹⁰ An analysis of bacterial colonization performed by Shabeena et al found that duration of catheter placement was linearly related to colonization rates, with 90% of stents colonized by 120 days.¹¹ Major pathogens included *Escherichia coli*, *Streptococcus* and *Pseudomonas*. However, the clinical significance of bacterial colonization and biofilm formation on ureteral stents is poorly understood—there is no consensus on which specific pathogens, if any, increase risk of encrustation. Additionally it is unclear how biofilm formation on the surface of the stent may precipitate minerals and trigger encrustation. Furthermore, new understanding of the urinary microbiome may

implicate commensurate bacteria instead of these uropathogenic strains.¹²

Conditions that increase susceptibility to bacteriuria and urinary lithiasis predispose patients to encrustation as well. Recurrent urinary tract infections, diabetes mellitus and chronic renal failure are conditions that can increase urinary bacterial load, and may increase the risk of stent encrustation.¹³ Pregnant patients are similarly high risk—possibly secondary to absorptive hypercalciuria and hyperuricosuria associated with pregnancy—and are encouraged to undergo frequent stent changes every 4 to 6 weeks to avoid encrustation.¹⁴ Other well-known patient specific risk factors include history of urolithiasis, diet, malabsorptive disorders and cancer, all which exert pro-encrustation effects by increasing urinary concentrations of calcium, oxalate and uric acid. Finally, low health literacy and poor patient compliance naturally increase the risk of chronically retained stents.^{9,13}

Risk of encrustation is also related to the stent's physical characteristics. Kawahara et al evaluated 330 stents placed at a single institution and found that, while stent length and patency did not correlate with risk of encrustation, stent caliber did, with catheters smaller than 6Fr exhibiting significantly higher rates of encrustation and those 7Fr or larger exhibiting significantly lower rates.⁹ Furthermore, as will be discussed in more detail below, stent material composition can significantly influence the risk of encrustation, with different compounds and polymer blends facilitating or hindering stone formation on the stent surface. In the future identifying optimal materials for different types of stone formers may allow for more personalized decision making in the management of urological conditions requiring stent placement.

MECHANISM OF ENCRUSTATION

The mechanism of encrustation is complex and multifaceted. Once a stent is inserted, it is immediately coated with a conditioning film made up of glycoproteins specific to the patient's tissue and urinary composition, after which one of 3 potential outcomes can occur: 1) the stent can remain unchanged, 2) the stent can be further coated with a bacterial biofilm (predisposing the patient to urosepsis) or 3) the stent can develop encrustation (fig. 1).^{15,16} An analysis by Wollin et al used x-ray photoelectron spectroscopy to evaluate the surface composition of indwelling stents in 64 patients, finding that 100% of stents had been coated, to some degree, by a conditioning film.¹⁷ Further analysis of these stents showed that 47% had developed some encrustation on the surface and 13% had been coated by a bacterial biofilm.

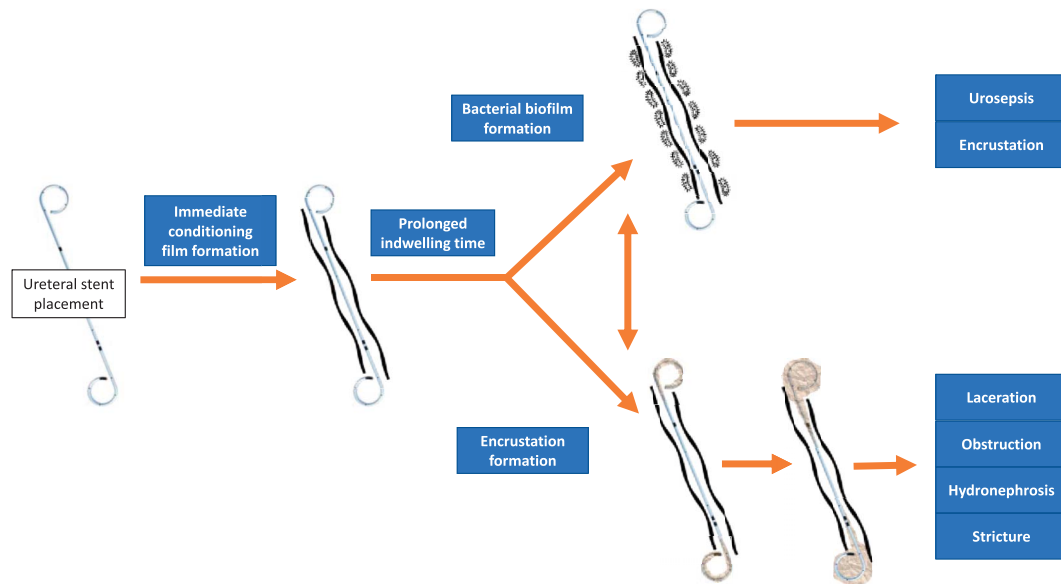


Figure 1. Mechanism of stent encrustation

Stent encrustation is invariably due to the deposition of minerals on its surface. Encrustation can occur spontaneously due to the presence of elevated levels of minerals in the urine (eg calcium, oxalate, phosphorus) or it may be catalyzed by the presence of urease producing organisms, similar to the mechanism of urolithiasis formation. The urease producing organisms (*Proteus*, *Pseudomonas*, *Klebsiella* etc) cleave urea into ammonia, elevating the pH of the urine and allowing for the precipitation of struvite ($\text{NH}_4\text{MgPO}_4 \cdot 6\text{H}_2\text{O}$) on the stent surface.¹⁸

The relationship between encrustation and bacterial biofilm formation is poorly understood. Bacterial biofilms may facilitate precipitation of crystals, allowing for encrustation. Conversely encrustation may serve as a nidus for bacteria and bacterial biofilm formation, which can cause urosepsis in patients with indwelling stents.¹⁹ Nevertheless, any material coating a stent changes its inherent physical characteristics (ie a protein conditioning film or bacterial biofilm) and may allow for the deposition of crystals on the stent surface. Furthermore, the longer the indwelling time of the stent, the more time there is for the surface characteristics to change and crystallization to develop.

CURRENT STENT TECHNOLOGY AND ENCRUSTATION PREVENTION

The design and technology of ureteral stents, as well as their market, have advanced dramatically. According to a recent analysis, the global market for ureteral stents in 2018 was about \$360 million and it is forecasted to surpass a global valuation of \$564 million by 2026.²⁰ Since a key component in the

development of urosepsis and encrustation is bacterial colonization, previous and current research has focused on developing materials and/or stent coatings that inhibit this process. However, this has proven difficult as bacterial adhesion is a complex process. Organisms exhibit a variety of adhesion mechanisms that vary between species, making it challenging to pinpoint a universal treatment. Furthermore, urinary components can alter the biological activity of surface coatings and reduce anti-adhesive properties.²¹ Nevertheless, a variety of different technologies have been developed to reduce the burden of stent encrustation (Appendixes 1 to 4).

Most stents in use are made of polymer blends with encrustation reducing properties that may or may not be coated with bioactive compounds (Appendix 1).²² These blends are often proprietary but are generally based on polyurethane. Other polymer combinations also exist, such as hydrogel plus urethane/silicone/polyvinyl chloride (*Aquavene*®), styrene/ethylene-butylene/styrene block copolymers (*C-Flex*®) and polyester (*Silitek*®).²³ Products like *Silhouette*®, *Bardex*® and *Tecoflex*® are all examples of stents comprised of proprietary copolymer mixtures that report polyurethane as the primary composite material.

Recently there has been renewed interest in developing silicone based ureteral stents, with research by Tunney et al demonstrating silicone's ability to deter encrustation *in vitro*.¹⁰ In this study ureteral stents comprised of 5 different biomaterials—silicone, polyurethane (with and without hydrogel coating), *Percuflex*™ and *Silitek*®—were placed in an artificial urine solution for 14 weeks to assess for differential

rates of encrustation. Using scanning electron microscopy to measure rates of stent surface coverage, the silicone stents demonstrated 69% coverage at 10 weeks, while all other materials showed 100% surface coverage within a similar interval. Concurrent compositional analysis of the surface depositions using atomic absorption spectroscopy found that silicone stents were least susceptible to both calcium and magnesium deposition over a 14-week indwelling period.^{10,23} Another study by Bouzidi et al prospectively analyzed 658 encrusted stents and found that, compared to polyurethane stents, silicone stents demonstrated a 20% lower rate of biofilm formation and a 35% lower rate of mineral deposition.²⁴ Popular silicone based stents include the black silicone stent (Cook Medical, Bloomington, Indiana), Imajin®, Double-J® and UroGuide™ (Appendix 2). A new combined approach is Heparius®, which is a polyurethane based stent that is treated with a silicone coating surface, thereby minimizing biofilm formation and reducing encrustation.

Many leaders in ureteral stent development have opted to make products comprised of proprietary copolymer mixtures, for which there is little detailed, publicly available information regarding the material composition. Products include Percuflex, C-Flex, Sof-Flex®, Universa®, InLay® and Lubri-Flex®.²⁵ Furthermore, there are almost no head-to-head data comparing encrustation susceptibility of these new materials. Although many companies advertise maximal indwelling times upward of 3 months, there is little evidence validating these claims. As such, this gap in the literature poses a unique challenge for urologists who hope to optimize ureteral stent selection for their patients. Ultimately while polymer stents have properties that may reduce the rates of encrustation, the existing literature suggests that prolonged stenting will most likely result in an encrusted stent, regardless of stent composition.

Patients with malignant obstruction requiring long-term stenting pose a unique challenge. One method that has been explored for improving ability to withstand extrinsic compression and reducing encrustation is the use of metallic stents (Appendix 3). The Silhouette stent has a standard polyurethane external surface and a lumen reinforced with a metallic coil. Furthermore, when the Silhouette was compared head-to-head with the Amplatz urethane ureteral stent (Cook Medical) in assessing resistance to external radial compression, the flow rate of the Amplatz dropped 4 times faster than that of the Silhouette, indicating superior stent patency.^{23,26}

Resonance® is a fully metallic stent comprised of a proprietary nickel-cobalt-chromium-molybdenum alloy. In a retrospective analysis of 92 patients

with malignant extrinsic ureteral obstruction Resonance was shown to provide superior 1-year patency when compared with a standard polymeric stent.²⁷ An analysis of 13 patients who underwent long-term Resonance placement for benign ureteral obstruction (mean indwelling time 11.6 months) revealed a 43% reduction in average annual stent maintenance costs in comparison to traditional polymer stent, amounting to \$10,362 per patient annually.²⁸ Yet this study is limited by both its small sample size and its broader clinical applicability regarding the number of patients with benign ureteral obstruction requiring yearlong stenting. A separate study of the Resonance revealed similar concerns regarding encrustation; on removal of the stents following an indwelling time ranging from 8 to 14 months, encrustation was macroscopically detectable on 12 of 54 stents (22%) and microscopically detectable on all studied stents.^{29,30} An *in vitro* study of the Allium® URS—a nitinol stent coated with a proprietary polymeric biomaterial—demonstrated up to 80% surface coverage with encrustations consisting of calcium and magnesium phosphate after 5 weeks of bathing in an artificial urine solution.³¹ Other fully metallic stents include the Memokath™051 and Uventa™.

Another avenue for reducing encrustation rates is through coating stent surfaces with various materials that inhibit bacterial adhesion or mineral deposition. One option has been hydrogel, a polymer network of hydrophilic gels that can swell and retain water and are thought to diminish bacterial adhesion and therefore reduce stent encrustation.³² Some companies have produced proprietary hydrogel solutions, like HydroPlus™ and AQ®. One company, Q Urological, converted this hydrogel technology into a novel stent material, which it is marketing with its Aguamedicina™ stent, although this product is not yet approved by the U.S. Food and Drug Administration and has little available public information.

Attempts have been made to develop drug coated or drug eluting stents that can prevent the encrustation process. A study of silver nitrate and ofloxacin coated copolymer stents placed in rabbit urethras preliminarily demonstrated decreased rates of biofilm formation and stent encrustation when compared with uncoated stents.³³ However, this treatment failed to yield similar results in subsequent clinical trials. Antibiotic infused catheters have also been studied over the years but these products proved unsuccessful due to antibiotic resistance and the ability to infuse only 1 drug on a single catheter.³⁴ Watterson et al found that coating of stents with oxalate degrading enzymes significantly decreased the rate of stent encrustation, although these have never been taken to market.³⁵

A potentially fruitful opportunity for reducing stent encrustation emerged through treating stents with glycosaminoglycan coatings. Heparin—a naturally occurring glycosaminoglycan commonly used as an anticoagulant—exhibits anti-adhesive properties that could theoretically reduce bacterial adhesion on the stent itself, thereby preventing biofilm formation and encrustation.³⁶ However, the data supporting this hypothesis remain inconclusive. In a case study of 5 patients with bilateral obstructions Cauda et al placed 1 heparin coated and 1 uncoated polyurethane stent in each obstructed ureter for 1 month, after which the composition and extent of encrustation were analyzed using electron microscopy, spectroscopy and spectrophotometry.³⁷ The layer of encrustation found on the uncoated stents was, on average, both thicker (17.0 μm vs 8.5 μm) and more extensive (86% vs 67% stent coverage) when compared to the heparin coated stents. Riedl et al performed a similar prospective randomized study in which 20 uncoated and 20 heparin coated polyurethane stents were placed in patients for an indwelling period of 2 to 6 weeks; subsequent microscopic analyses of encrustation revealed significantly decreased encrustation burden in the heparin coated stents.²¹ Conversely Lange et al found that heparin coating did not significantly decrease bacterial adherence to stents.³⁸ Currently the only stent that utilizes this technology is Endo-Sof® Radiance®, whose proprietary material is comprised of covalently bonded heparin mimetic molecules. That this technology occupies a small share of the stent market may reflect the conflicting nature of the literature.

As mentioned previously, elevated urinary pH can promote crystal deposition and cause encrustation. Thus, researchers postulate that increasing fluid intake and citrate supplementation can alter urinary chemistry and prevent encrustation similar to urolithiasis.³⁹ This is supported by a 2016 retrospective study, which found that citrate supplementation decreased the incidence of ureteral stent encrustation, thought to be secondary to citrate's effect on increasing the urinary nucleation pH (ie pH at which crystals deposit out of urine), thereby making it harder for encrustation to form.⁴⁰ Despite these promising results, a prospective trial would be necessary to draw more definitive conclusions on the efficacy of this prevention strategy.

Finally, perhaps the best option for preventing stent encrustation is to avoid placing a stent altogether, with some urologists advocating for increased adoption of stentless ureteroscopy in select patients. However, in a 2019 systematic review comparing postoperative outcomes of patients who did vs did not receive a stent following

uncomplicated ureteroscopy no high quality evidence-based conclusions could be drawn. As such, further high quality research is required to optimize patient selection and define associated risks and benefits of foregoing stent placement after ureteroscopy.⁴¹

DIAGNOSIS AND MANAGEMENT

While the majority of stents can be removed without prior imaging, in patients with risk factors for encrustation imaging is useful to evaluate the severity and location of encrustation along the stent (fig. 2). Standard KUB x-ray is often sufficient to diagnose the extent of encrustation. However, ultrasound or CT may be necessary to more definitively evaluate the extent of encrustation and develop a strategy for extracting an encrusted stent.⁴²

After defining the extent of encrustation on imaging several grading systems exist to define the extent of pathology and predict surgical complexity for stent removal. One system proposed by Acosta-Miranda et al, the FECal (“Forgotten, Encrusted, Calcified”) system, classifies encrustation on a scale of 1 to 5 depending on the size, location and degree of encrustation.⁴³ Another system, proposed by Arenas et al, is the KUB system, which grades each portion of the stent individually on a scale of 1 to 5 based on encrustation extent.⁴⁴ The proximal renal coil (“K” score), the ureteral shaft (“U” score) and the distal bladder coil (“B” score) are combined to form a cumulative KUB score (maximum score 15). In an analysis of 110 retained encrusted stents higher KUB scores correlated with increased risk of stone formation following stent removal, while total KUB score 9 or higher was associated with an approximately fourfold increase in risk of requiring multiple surgeries for stent removal. Importantly the authors propose 2 metrics for distinguishing mild vs moderate/severe pathologies, ie less than 50% stent coverage of encrustation and a cutoff encrustation diameter of 5 mm.⁴⁴

In an effort to integrate the clinical applicability of the FECal system treatment algorithm with the criteria defined in the KUB system we propose a new treatment algorithm (fig. 3). Using KUB, CT or ultrasound imaging, encrustation should be evaluated for a diameter of 5 mm or larger anywhere along the course of the stent. If encrustation burden does not exceed 5 mm and covers less than 50% of the stent, then the burden is classified as mild and cystoscopic stent removal should be attempted initially. If encrustation burden is 5 mm or greater anywhere along the stent and/or if extent of encrustation exceeds 50% stent coverage, then the pathology is classified as severe, at which point

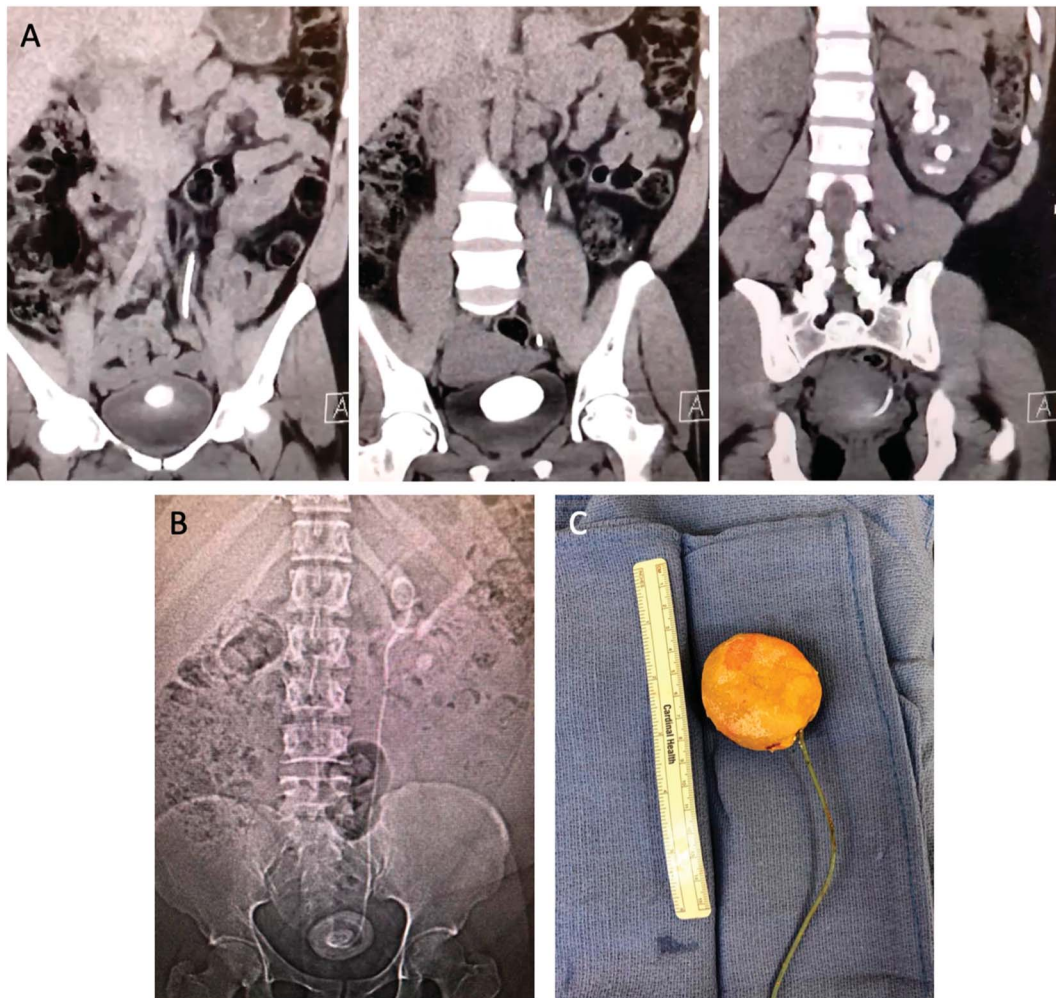


Figure 2. Stent retained for 3 years shows significant encrustation and associated bladder calculus. *A*, coronal view of abdominal CT demonstrates left encrusted ureteral stent, bladder calculus and staghorn renal calculus. *B*, abdominal x-ray reveals retained stent. *C*, gross image of extracted stent and bladder stone removed via robotic pyelolithotomy and cystolithotomy. Reproduced with permission.³²

surgical management should be pursued following the proposed algorithm. If encrustation spans less than 1.5 cm, consider an initial extracorporeal shock wave lithotripsy, and if encrustation spans 1.5 cm or more, escalate directly to percutaneous nephrolithotomy.⁴⁵

FUTURE RESEARCH

As companies continue to expand their product lines and introduce new stent technology, further research will be needed to elucidate the roles of these stents in urology. Furthermore, comparative effectiveness studies and cost analyses are required to clarify the best options for patients.

A currently fertile area of research is that of biodegradable stents, which theoretically offer an economical upside by eliminating both the need for a second procedure to remove the stent and the opportunity for stents to be forgotten/retained

(Appendix 4). Another potential edge toward hindering encrustation is the constantly changing shape of the stent surface, which could prevent bacterial adhesion.⁴⁶ A 2013 in vivo study of Uriprene™ showed favored physiological responses in comparison to Polaris™ but the study did not comment on differential rates of encrustation, nor did it show statistically significant differences in rates of positive urine cultures (thought by the researchers to be related to encrustation rates).⁴⁶ Currently a biodegradable stent by HydrUSStent (Guimaraes, Portugal) is marketed as an alternative to the traditional stents, although there is limited research available supporting this claim.

The need to prevent urosepsis and encrustation have driven researchers to explore new opportunities for preventing bacterial adhesion and biofilm formation. In response to concerns of bacterial resistance to antibiotic eluting stents, some have

Stent Encrustation Management Pathway

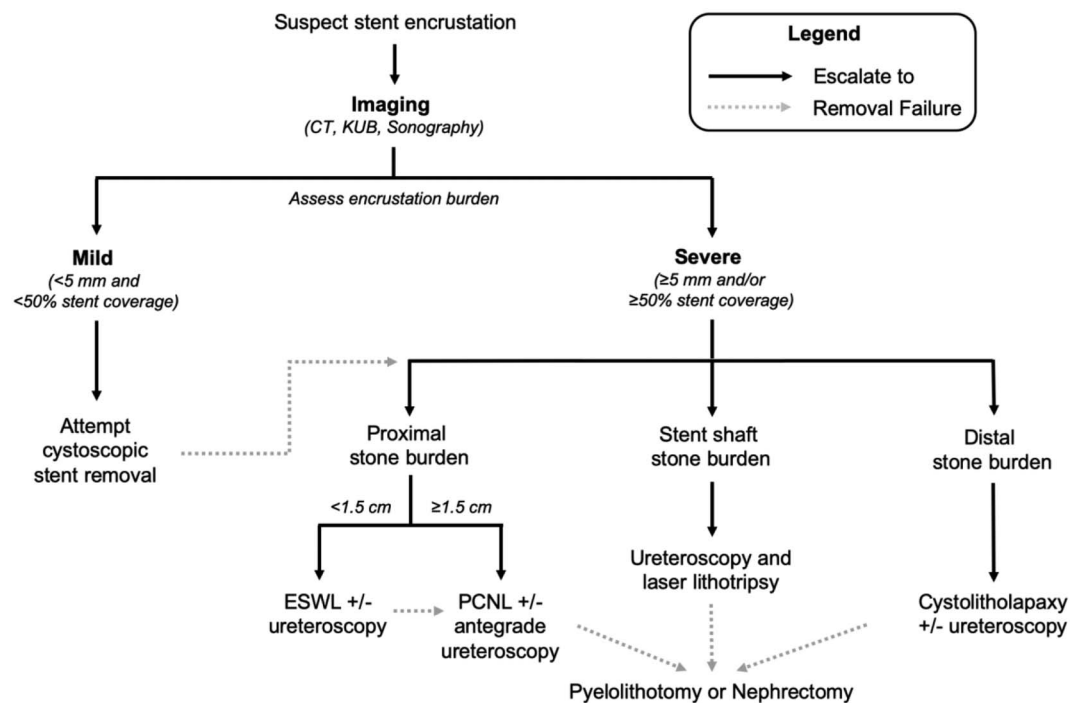


Figure 3. Diagnosis and treatment algorithm. *ESWL*, extracorporeal shock wave lithotripsy. *PCNL*, percutaneous nephrolithotomy.

explored coating stents with biomaterials such as antimicrobial peptides, bacteriolytic enzymes and essential oils.⁴⁷ A novel study by Hazan et al showed that, when placed in male rabbit urethras, Foley urinary catheters attached to low energy sound wave generators maintained urine sterility for up to 7 days longer than control animals, with further electron microscopy confirming the decreased biofilm burden on the treatment catheters.⁴⁸ However, the clinical utility of these strategies has not yet been elucidated. One series of 10 patients with recurrent, heavy encrustation burdens reported no crystalline biofilm formation in vivo after ureteral stents coated in diamond-like carbon coatings (mean indwelling time 97 days), although the power of this study is limited given the cohort size and disease burden described.⁴⁹

Companies are also exploring new coating substances to complement their existing stent technologies that specifically target inhibiting mineral deposition or bacterial adhesion. pHreeCoat coating, which is offered with the InLay Optima® ureteral stent, is marketed as a pH stabilizing solution that inhibits urinary calcium salt accumulation. Meanwhile, Boston Medical's recently announced PercuShield™ technology will be available with the upcoming line of Tria™ ureteral stents. The PercuShield inner and outer coatings are hydrophobic and claim to significantly reduce urinary calcium and

magnesium adhesion and deposition. The design of the Tria is also geared toward reducing risk of encrustation, as the stent features hydrophobic outer and inner surfaces to reduce calcium and magnesium salt adhesion.

Finally, in lieu of pursuing novel stent technologies, some researchers are exploring opportunities to reduce the indwelling time of the ureteral stents. One proposed solution was to create a national stent registry where all stent placements are logged and reminders are sent to providers to contact patients who need stent removal to reduce the rate of forgotten stents leading to encrustation.⁵⁰ Unfortunately this registry failed to gain traction and has not been deployed on a large scale. A mobile application, the Ureteral Stent Tracker app (Visible Health Inc., Austin, Texas and Boston Scientific Corp, Boston, Massachusetts), was created to track stent placement at the point of care but, despite its preliminary successes, the app was discontinued.⁵

CONCLUSIONS

While ureteral stent placement is meant to alleviate symptoms and complications associated with various urological conditions, stent encrustation is a serious complication that can adversely impact patient quality of life and safety, particularly in those who require long-term stenting. The development of

new ureteral stent technology is a rapidly growing field that offers an arena for clinicians, researchers and medical device manufacturers to collaborate in order to minimize encrustation and improve patient outcomes. The current ureteral stent market offers a variety of products available that allow providers to tailor stent selection in order to optimize and personalize the management of each patient. Moving forward, future research will center on defining the pathophysiology of stent encrustation, opti-

mizing biomaterial propertie, and understanding the role of the urinary microbiome. Such research will enable physicians to prevent encrustation and make it a problem of the past.

ACKNOWLEDGMENTS

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Appendix 1. Current polymer stent models

Company	Product Name(s)	Stent Composition	Coating Composition	Maximum Indwelling Time	Notable Features
Boston Scientific	Contour (SL, ML), Percuflex, Percuflex Plus, Polaris Ultra, Polaris Loop, Retromax	Percuflex	HydroPlus (proprietary)	365 days	Pliable Percuflex material softens at body temperature, maximizing comfort and biocompatibility. Large inner lumen offers improved Inner Diameter/Outer Diameter ratio
Boston Scientific	Stretch VL Flexima	Flexima	HydroPlus (proprietary)	90 days	
Boston Scientific	Tria	Proprietary polymer blend	PercuShield (proprietary)	365 days	PercuShield technology on inner and outer surfaces protect against urinary Ca and Mg salt deposition. Reduction in stiffness at body temperature
Becton Dickinson (+ Bard)	Bardex double pigtail soft	Polyurethane		Not specified	
Becton Dickinson (+ Bard)	InLay ureteral (SL, ML)	Proprietary polymer blend	Hydrophilic coating	365 days	Hydrophilic coating maximizes patient comfort. Softens up to 50% at body temperature
Becton Dickinson (+ Bard)	InLay Optima ureteral (SL, ML)	Proprietary polymer blend	Proprietary pHreeCoat coating (stabilizes pH level on stent surface)	365 days	Biocompatible and ultra smooth for patient comfort. Softens up to 49% at body temperature. pHreeCoat offers superior prevention of urinary Ca salt deposition vs. leading competitive stents
Coloplast	Polyurethane double loop	Polyurethane		Not specified	Offered as soft or rigid
Cook	C-Flex double pigtail (SL, ML)	C-Flex		6 months	
Cook	Endoureterotomy ultrathane	Ultrathane		2 months	
Cook	Endo-Sof Radiance	Endo-Sof		12 months	Softens at body temperature. Heparin-bonded stent that reduces bacterial adhesion, slowing stent encrustation
Cook	Sof-Flex, Kwart Retro-inject double pigtail (SL, ML)	Sof-Flex		6 months	
Cook	Universa with/without hydrophilic coating (SL, ML; with or without tether)	Universa	AQ Hydrophilic Coating	6-12 months	Offered as soft or firm formulation. Softens up to 42% at body temperature
Olympus America	Classic double pigtail, Lithostent, Multi-Flex, Quadra Coil ML, Sof Curl	Tecoflex	Hydrophilic coating	Not specified	Softens at body temperature
Olympus America	Lubri-Flex	Lubri-Flex	Hydrophilic coating	Not specified	Softens at body temperature

Appendix 2. Current silicone stent models

Company	Product Name(s)	Stent Composition	Maximum Indwelling Time	Notable Features
Becton Dickinson (+ Bard)	Fluoro-4 silicone (SL, ML)	Silicone/tantalum formulation	Not specified	The insertion advantages of urethane stents with the biocompatibility of silicone stents. Highly radiopaque
Coloplast	ImaJin silicone ureteral stent kit	Silicone	12 months	Greater patient comfort. Improved encrustation resistance compared to polyurethane
Coloplast	Silicone double loop ureteral stent	Silicone	12 months	Compromise of patient comfort and tolerance. Less prone to encrustation
Cook	Black silicone double pigtail	Silicone	Not specified	
Olympus America	Double-J, UroGuide	Silicone	Not specified	Provides maximum patient comfort while minimizing stent encrustation

Appendix 3. Current metallic and reinforced stent models

Company	Product Name(s)	Stent Composition	Coating Composition	Maximum Indwelling Time	Notable Features
Allium Medical	Allium URS	Nickel-titanium alloy (nitinol)	Proprietary polymer coating	3 years	Excellent patient comfort. Self-expanding. Coated in non-permeable, biocompatible polymer to prevent tissue ingrowth and early encrustation
Applied Medical	Silhouette (Pediatric, comfort, XtraFlo, Scaffold; SL, ML)	Polyurethane with metal-coil reinforcement	With/without hydrophilic coating	Not specified	Superior compression resistance with exceptional patient tolerance. 30% larger inner lumen with increased inner diameter/outer diameter ratio
Coloplast	Tumor stent	Undisclosed internal reinforcement layer		12 months	Internal layer of the stent is reinforced for compression resistance
Cook	Resonance metallic	Proprietary nickel-cobalt-chromium-molybdenum alloy		12 months	Maintains patency under severe extrinsic compression. Prolonged indwelling time reduces stent changes, decreasing infection risk
PNN Medical	Memokath-051 metallic	Nickel-titanium alloy (nitinol)		Not specified	Protective inner titanium oxide layer to prevent nickel allergy.
Taewoong Medical Co.	Uventa ureteral	Metallic stent with polytetrafluoroethylene and nickel-titanium alloy (nitinol) inner membrane		Not specified	

Appendix 4. Other stent models

Company	Product Name(s)	Stent Composition	Coating Composition	Notable Features
HydrUStent	HydrUStent	Biodegradable material		Offers 60% reduction in medical treatment cost. Avoids bacterial infections and need for a second surgery
Q Urological Stent	Structural hydrogel ureteral	Proprietary Aquamedicina hydrogel		Proprietary structural hydrogel promotes patient comfort and reduces encrustation via natural antifouling qualities
UROMED Kurt Drews KG	Heparius	Polyurethane	Hydroxiorganofunctional polydimethylsiloxane (silicone) copolymers	Reduced bacterial adherence. Encrustation-reducing additive. Lower strain on patient due to reduced number of surgeries
UROMED Kurt Drews KG	Hydropur	Aromatic polyurethane		Manufacturing procedure and stent material causes low encrustation rates

Maximum indwelling time is not specified for any of the stents listed.

REFERENCES

- Mosayyebi A, Vijayakumar A, Yue QY et al: Engineering solutions to ureteral stents: material, coating and design. *Cent European J Urol* 2017; **70**: 270.
- Zhao J, Cao Z, Ren L et al: A novel ureteral stent material with antibacterial and reducing encrustation properties. *Mater Sci Eng C Mater Biol Appl* 2016; **68**: 221.
- Dyer RB, Chen MY, Zagoria RJ et al: Complications of ureteral stent placement. *Radiographics* 2002; **22**: 1005.
- Duty B, Okhunov Z, Okeke Z et al: Medical malpractice in endourology: analysis of closed cases from the State of New York. *J Urol* 2012; **187**: 528.
- Small AC, Thorogood SL, Shah O et al: Emerging mobile platforms to aid in stone management. *Urol Clin North Am* 2019; **46**: 287.
- Cao Z, Zhao J and Yang K: Cu-bearing stainless steel reduces cytotoxicity and crystals adhesion after ureteral epithelial cells exposing to calcium oxalate monohydrate. *Sci Rep* 2018; **8**: 14094.
- Ibilbor C, Grand R, Daneshfar C et al: Impact of retained ureteral stents on long-term renal function. *Urol Pract* 2019; **6**: 107.
- el-Faqih SR, Shamsuddin AB, Chakrabarti A et al: Polyurethane internal ureteral stents in treatment of stone patients: morbidity related to indwelling times. *J Urol* 1991; **146**: 1487.
- Kawahara T, Ito H, Terao H et al: Ureteral stent encrustation, incrustation, and coloring: morbidity related to indwelling times. *J Endourol* 2012; **26**: 178.
- Tunney MM, Keane PF, Jones DS et al: Comparative assessment of ureteral stent biomaterial encrustation. *Biomaterials* 1996; **17**: 1541.
- Shabeena KS, Bhargava R, Manzoor MAP et al: Characteristics of bacterial colonization after indwelling double-J ureteral stents for different time duration. *Urol Ann* 2018; **10**: 71.

12. Zampini A, Nguyen AH, Rose E et al: Defining dysbiosis in patients with urolithiasis. *Sci Rep* 2019; **9**: 5425.
13. Beysens M and Taily TO: Ureteral stents in urolithiasis. *Asian J Urol* 2018; **5**: 274.
14. Evans HJ and Wollin TA: The management of urinary calculi in pregnancy. *Curr Opin Urol* 2001; **11**: 379.
15. Gristina AG: Biomaterial-centered infection: microbial adhesion versus tissue integration. *Science* 1987; **237**: 1588.
16. Lange D, Bidnur S, Hoag N et al: Ureteral stent-associated complications—where we are and where we are going. *Nat Rev Urol* 2015; **12**: 17.
17. Wollin TA, Tieszer C, Riddell JV et al: Bacterial biofilm formation, encrustation, and antibiotic adsorption to ureteral stents indwelling in humans. *J Endourol* 1998; **12**: 101.
18. Gleeson MJ, Glueck JA, Feldman L et al: Comparative in vitro encrustation studies of biomaterials in human urine. *ASAIO Trans* 1989; **35**: 495.
19. Tieszer C, Reid G and Denstedt J: XPS and SEM detection of surface changes on 64 ureteral stents after human usage. *J Biomed Mater Res* 1998; **43**: 321.
20. Coherent Market Insights: Ureteral Stents Market Analysis. 2019. Available at <https://www.coherentmarketinsights.com/market-insight/ureteral-stents-market-2172>.
21. Riedl CR, Witkowski M, Plas E et al: Heparin coating reduces encrustation of ureteral stents: a preliminary report. *Int J Antimicrob Agents* 2002; **19**: 507.
22. Forbes C, Scotland KB, Lange D et al: Innovations in ureteral stent technology. *Urol Clin North Am* 2019; **46**: 245.
23. Venkatesan N, Shroff S, Jayachandran K et al: Polymers as ureteral stents. *J Endourol* 2010; **24**: 191.
24. Bouzidi H, Traxer O, Doré B et al: Caractéristiques des incrustations des endoprothèses urétérales chez les patients lithiasiques. *Prog Urol* 2008; **18**: 230.
25. Mardis HK, Kroeger RM, Morton JJ et al: Comparative evaluation of materials used for internal ureteral stents. *J Endourol* 1993; **7**: 105.
26. Miyaoka R, Hendlin K and Monga M: Resistance to extrinsic compression and maintenance of intraluminal flow in coil-reinforced stents (Silhouette Scaffold Device): an in vitro study. *J Endourol* 2010; **24**: 595.
27. Asakawa J, Iguchi T, Tamada S et al: Treatment outcomes of ureteral stenting for malignant extrinsic ureteral obstruction: a comparison between polymeric and metallic stents. *Cancer Manag Res* 2018; **10**: 2977.
28. López-Huertas HL, Polcari AJ, Acosta-Miranda A et al: Metallic ureteral stents: a cost-effective method of managing benign upper tract obstruction. *J Endourol* 2010; **24**: 483.
29. Kallidonis PS, Georgiopoulos IS, Kyriazis ID et al: The full metallic double-pigtail ureteral stent: review of the clinical outcome and current status. *Indian J Urol* 2015; **31**: 8.
30. Liatsikos E, Kallidonis P, Kyriazis I et al: Ureteral obstruction: is the full metallic double-pigtail stent the way to go? *Eur Urol* 2010; **57**: 480.
31. Shaheen T, Edirisinghe T, Gabriel M et al: In vitro encrustation of a semi-permanent polymer-covered nitinol ureter stent: an artificial urine model. *Urolithiasis* 2014; **42**: 203.
32. Ahmed EM: Hydrogel: preparation, characterization, and applications: a review. *J Adv Res* 2015; **6**: 105.
33. Multanen M, Tammela TL, Laurila M et al: Biocompatibility, encrustation and biodegradation of ofloxacin and silver nitrate coated poly-L-lactic acid stents in rabbit urethra. *Urol Res* 2002; **30**: 227.
34. Singha P, Locklin J and Handa H: A review of the recent advances in antimicrobial coatings for urinary catheters. *Acta Biomater* 2017; **50**: 20.
35. Watterson JD, Cadieux PA, Beiko DT et al: Oxalate-degrading enzymes from *Oxalobacter formigenes*: a novel device coating to reduce urinary tract biomaterial-related encrustation. *J Endourol* 2003; **17**: 269.
36. Al-Aown A, Kyriazis I, Kallidonis P et al: Ureteral stents: new ideas, new designs. *Ther Adv Urol* 2010; **2**: 85.
37. Cauda F, Cauda V, Fiori C et al: Heparin coating on ureteral Double J stents prevents encrustations: an in vivo case study. *J Endourol* 2008; **22**: 465.
38. Lange D, Elwood CN, Choi K et al: Uropathogen interaction with the surface of urological stents using different surface properties. *J Urol* 2009; **182**: 1194.
39. Pearle MS, Goldfarb DS, Assimos DG et al: Medical management of kidney stones: AUA Guideline. *J Urol* 2014; **192**: 316.
40. Idweini Y: Alkaline citrate medication to prevent stent encrustation in urolithiasis therapy. *J Urol Nephrol* 2016; **2**: 1.
41. Ordonez M, Hwang EC, Borofsky M et al: Ureteral stent versus no ureteral stent for ureteroscopy in the management of renal and ureteral calculi. *Cochrane Database Syst Rev* 2019; **2**: CD012703.
42. Vanderbrink BA, Rastinehad AR, Ost MC et al: Encrusted urinary stents: evaluation and endourologic management. *J Endourol* 2008; **22**: 905.
43. Acosta-Miranda AM, Milner J and Turk TM: The FECal Double-J: a simplified approach in the management of encrusted and retained ureteral stents. *J Endourol* 2009; **23**: 409.
44. Arenas JL, Shen JK, Keheila M et al: Kidney, ureter, and bladder (KUB): a novel grading system for encrusted ureteral stents. *Urology* 2016; **97**: 51.
45. Borboroglu PG and Kane CJ: Current management of severely encrusted ureteral stents with a large associated stone burden. *J Urol* 2000; **164**: 648.
46. Chew BH, Paterson RF, Clinkscales KW et al: In vivo evaluation of the third generation biodegradable stent: a novel approach to avoiding the forgotten stent syndrome. *J Urol* 2013; **189**: 719.
47. Glinel K, Thebault P, Humblot V et al: Antibacterial surfaces developed from bio-inspired approaches. *Acta Biomater* 2012; **8**: 1670.
48. Hazan Z, Zumeris J, Jacob H et al: Effective prevention of microbial biofilm formation on medical devices by low-energy surface acoustic waves. *Antimicrob Agents Chemother* 2006; **50**: 4144.
49. Laube N, Kleinen L, Bradenahl J et al: Diamond-like carbon coatings on ureteral stents—a new strategy for decreasing the formation of crystalline bacterial biofilms? *J Urol* 2007; **177**: 1923.
50. Lynch MF, Ghani KR, Frost I et al: Preventing the forgotten ureteral stent: implementation of a web-based stent registry with automatic recall application. *Urology* 2007; **70**: 423.