Endourologic Disease Group for Excellence (EDGE)

Mitchell R. Humphreys

Ureteroscopy for stone disease
I consider it a great honor and privilege to be able to present this special publication from the Endourology Disease Group for Excellence (EDGE). The EDGE group is an international multi-institutional research consortium comprised of dedicated individuals that endeavor to ask and answer some of the most pressing questions in endourology and stone disease today. This effort has culminated in the current special edition that covers all facets of retrograde intrarenal surgery for stone disease. The evolutions of technology and techniques have drastically altered how physicians and surgeons think about and treat nephrolithiasis. Keeping up with those changes and how they impact outcomes is an important endeavor. The goal of limiting patient morbidity while maximizing outcomes in an efficient way is desired by all, and the information contained within will become an important tool in your armamentarium. To understand where we are with diagnosis and management one has to look to the history of retrograde intrarenal surgery and ureteroscopy to put the modern advancements in context, these chapters will do that and more. Everything anyone needs to be on the forefront of this field and to provide a resource, answers and a guide to special clinical situations and complication management are within.

I am deeply grateful to those individuals that have taken the time from their busy clinical practices and research to contribute to this publication. Their expertise and knowledge are vast and are the main reason this has become such a standout publication. I truly hope you enjoy it as much as we have in preparing it!

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Minimally invasive endoscopic surgery has become a cornerstone in both the diagnosis and management of many benign and malignant disorders of the upper urinary tract. While fundamental to modern urology, endoscopic treatment of the upper urinary tract did not become fully established until the 1980s. Although the first ureteroscopy was reported in 1912, it would be many years before the potential of this technology would begin to be fully realized. The rapid advances in ureteroscopic equipment and techniques starting in the mid-20th century have transformed the manner in which the modern urologist approaches disorders of the upper urinary tract. Herein, we review the development of ureteroscopy. For the sake of clarity, the development of rigid, flexible, and semi-rigid ureteroscopy are addressed separately, but one can readily appreciate that advances in each modality were interwoven during this period of rapid advancement in urologic endoscopy.

## Rigid Ureteroscopy

### Origins

In 1912, Hugh Hamptom Young performed the first reported ureteroscopic procedure on a pediatric patient with posterior urethral valves. Young was able to advance a long pediatric cystoscope up the widely dilated ureter to the level of the renal pelvis. Though unable to “identify the renal papillae and jets of urine which are supposed to come from the urinary tubules,” it was clear that Young was aware of the massive potential that endoscopy represented.\(^1\) It would be almost half a century however before any significant progress in the field was seen.

Advancement in ureteroscopy was dependent upon a critical advancement first applied to cystoscopy: the rod-lens system. In 1959, Professor Harold H. Hopkins filed a patent for his innovative rod-lens system for rigid endoscopy. The traditional optical arrangement employed a series of precisely spaced glass lenses separated by air. The rod-lens system, however, consisted of a series of elongated, contoured and polished glass rods separated by short segments of air which acted as air lenses. Of primary importance, this system allowed for markedly improved transmission of light as well as a wider viewing angle, ultimately delivered through a smaller diameter endoscope. Manufacturers initially showed little interest in the system until shortly after Professor George Berci introduced Hopkins to medical instrument manufacturer Karl Storz in 1965. Cystoscopes incorporating the system were put into production by his company in Tuttlingen, German. Karl Storz would later combine the rod-lens system with fiber optic bundles for illumination forming the foundation for modern cystoscopy and its eventual adaptation into rigid ureteroscopy.\(^2\)

Even with the introduction of the rod lens system into rigid endoscopy, flexible fiber-optic ureteroscopy was the predominant focus of the literature in the 1960’s. It was not until 1977 when Goodman reported the functional use of rigid ureteroscopy that the focus shifted. At the time, flexible ureteroscopy was mainly used to assist in diagnosis of upper urinary tract pathology, often employed *via* an open ureterotomy. In Goodman’s early reports, an 11-Fr pediatric cystoscope was advanced transurethrally up to 3 cm of the distal ureter in two patients.\(^3\) In one patient a ureteral tumor was electrocoagulated in what was the first reported case of an endoscopically treated ureteral tumor.\(^4\)

### Urolithiasis

Lyon *et al.* described the routine use of transurethral ureteroscopy first in women in
1978, followed by men in 1979.5,6 Lyon utilized a flexible probe with dilating tips for dilation of the ureteral orifice in men up to 16 Fr. After dilation a 13-Fr juvenile cystoscope was used to enter the ureter with inspection limited to the most distal 3 cm to 4 cm of the ureter. For resection of ureteral tumors the authors reported the use of a 14.5-Fr juvenile resectoscope. In many cases the level of ureter inspected was limited by the length of the instrument.6

An early demonstration of the ureteroscope’s unique utility in the treatment of ureteral stones was reported by Das in 1981. Facing an obstructing distal ureteral stone not amenable to blind stone basketing, he maneuvered an 11-Fr pediatric cystoscope 4 cm proximal to the ureteral orifice and, with 4-Fr stone extractor, retrieved a 5x7-mm ureteral stone under direct vision.7 Endoscopically visualized stone retrieval offered several proposed advantages to a blind approach, including the ability to more accurately and safely engage stones. However, initial studies of stone retrieval under direct vision demonstrated stone retrieval rates similar to those seen in blind stone manipulations. Huffman reported the ureteroscopic treatment of distal ureteral stones in 15 patients. In the study, 5 patients required eventual open ureterolithotomy, due to either failure of the ureter to accommodate the 14.5-Fr sheath or failure of the scope to reach more proximal stones.8 Improvements in ureteroscopic equipment were clearly needed before ureteroscopy could become an accepted treatment modality for ureteral calculi.

**Urothelial lesions**

Development of rigid ureteroscopy also led to advancements in the treatment of urothelial cancer of the upper urinary tract. Before ureteroscopy, tumors of the upper tract were characterized by cytology, brush biopsy, and radiographic imaging. The introduction of ureteroscopy allowed for direct visualization – as well as biopsy, fulguration, and in select cases, resection of lesions and suspected tumors. The added information gained from ureteroscopy allowed for improved surgical planning or in many cases permitted endoscopic treatment and surveillance, thus avoiding open surgical resection.9

As with stones, early ureteroscopic applications of urothelial lesions were set in the distal ureter. In order to address lesions of the proximal ureter and renal pelvis, refinements in ureteroscopic instrumentation was required.

**Emergence of dedicated rigid ureteroscopes**

A significant step towards extending ureteroscopic domain beyond the distal ureter was realized in 1980 by Perez-Castro with the design of a ureteropyeloscope manufactured by the Storz Company. The prototype, designed after a cystoscope, was 50 cm long with an 11-Fr sheath and included a 4-Fr working channel and irrigating system. The scope utilized Hopkins’ rod-lens system with 0° and 70° viewing angles. The extended length of the ureteropyeloscope allowed for passage of the instrument to the level of the renal pelvis. A report of its use in 12 patients was published in 1982. The ureteropyeloscope provided several advantages over flexible fiber-optic fiberscopes for use in the upper urinary tract. Rigid ureteroscopes were more affordable and durable compared to their fiberscope counterparts. In addition, they provided improved image quality and the rigid design and large working channel allowed for more interventional possibilities.10

After the initial introduction of the ureteropyeloscope, Huffman and colleagues reported the use of a ureteropyeloscope which was 41 cm long with a caliber ranging from 10 Fr to 12 Fr. The reduced caliber allowed easier transurethral passage into a pre-dilated ureter to the level of the renal pelvis. The 11.5-Fr and 12-Fr scopes included a working channel which could accommodate various flexible instruments up to 5 Fr. The authors demonstrated the ability of the ureteropyeloscope to biopsy and fulgurate urothelial tumors in the ureter and renal pelvis. Renal and proximal ureteral calculi were successfully treated in several cases with the assistance of an ultrasonic lithotripsy transducer introduced through the ureteropyeloscope. In one case, a 1.6x0.9 cm calculus in the renal pelvis was effectively treated with ultrasonic disintegration thus avoiding open surgery. The authors reported a complication rate of 10% over 110 cases of ureteroscopy or ureteropyeloscopy, mostly from mucosal disruptions.11
The advent of techniques for ureteroscopic lithotripsy is arguably the primary force behind the rapid emergence and durability of ureteroscopy in the urologic armamentarium. However, Huffman’s use of lithotripsy for ureteral calculi was not the first employment of this technique. In fact, ureteral lithotripsy significantly predated ureteroscopy, but the limitations of this approach clearly underscored the need for ureteroscopic application of this technology. In 1973, Roger Goodfriend demonstrated the first successful disintegration of a ureteral calculus by ultrasound. Goodfriend utilized a fine wire ultrasonic probe introduced through a ureteral catheter to treat a patient with a 5-mm distal ureteral stone which had failed various other attempts at retrieval. The position of the ultrasonic probe was not confirmed by direct vision but instead by X-ray leading to questions over its ability to accurately and safely engage stones.

Other techniques of ureteral lithotripsy were described by Reuter et al. who designed an electrohydraulic lithotripsy (EHL) device for use in the ureter similar to those used in the bladder. Reuter’s design included a 2 mm probe with electrodes that generated hydraulic impulses for stone destruction. The device was successfully used in 11 of 17 patients with both proximal and distal ureteral calculi. The complication of urinary extravasation from a damaged ureter was observed in this study and later human and animal studies of electrohydraulic lithotripsy. While popular in percutaneous surgery of the kidney, the inability to focus the energy of electrohydraulic lithotripsy demonstrated increased risk of perforation when used in the ureter.

While improved lithotripsy technology made the prospect of endoscopic treatment of upper urinary tract stones appealing, blind passage of a lithotripsy probe had obvious drawbacks. Beyond that fact that ensuring probe contact with the stone was technically challenging, the inability to accurately focus the probes energy meant there was almost no way to prevent collateral injury to the surrounding tissue. It was obvious that before upper tract lithotripsy could reach widespread application, ureteroscopes would have to catch up to the rapid advances in lithotripter technology made in the 1970’s and early 1980’s. Ureteroscopic technology in the 1970’s, which mostly relied on flexible non-steerable fiber optic devices with working channels, was unable to accommodate lithotripsy probes. The aforementioned development of rigid ureteroscopes allowed for greater precision in the control of instruments within the ureter, setting the stage for the introduction of modern ureteroscopic ureteral lithotripsy.

Early use of ureteroscopic assisted ureteral lithotripsy was performed by Huffman and colleagues, as previously discussed. Huffman did not deploy the ultrasonic lithotripsy device under direct vision, but instead engaged a calculus in a basket under direct vision and then removed the telescope from the ureteropyeloscope sheath. The ultrasonic transducer could then be introduced into the sheath and blindly make contact with the stone with the assistance of the basket.

In 1984, Goodfriend introduced a technique for lithotripsy of ureteral calculi under direct vision. Goodfriend utilized a 9-Fr ureteroscope with a 5-Fr working channel which accommodated a fine flexible ultrasonic probe. The use of a smaller caliber ultrasonic probe allowed for constant visual surveillance during fragmentation. The technique proved successful in one patient with a 1.2-cm ureteral stone, which was adequately fragmented in just five seconds.

Reports of electrohydraulic lithotripsy under direct vision soon followed. In 1985, Green et al. demonstrated nine successful cases of ureteral stone removal utilizing the assistance of electrohydraulic lithotripsy. The authors employed a 5-Fr EHL probe introduced through at 9.5-Fr ureteroscope with minimal complications. With the use of direct vision the operator ensured the stone was not too tightly impacted and could accurately focus the electrode tip on the stone. Combining direct vision with lower voltage settings allowed the authors to avoid previously reported complications associated with the technique.

While shown to be effective in the treatment of large ureteral stones, lithotripsy technology such as ultrasound and EHL carried appreciable risk of injury to the urinary tract. The search for lithotripsy energy sources which could be well
controlled and allow for smaller instrumentation within the urinary tract were desired. The development of lasers for use with ureteroscopy in the mid-1980’s paved the way for state of modern urology.

Early experimentation with lasers in urology used continuous wave lasers which vaporized stones as opposed to fragmenting them. While these lasers were effective in ablating stones it was felt their use within the ureter could be dangerous due to the significant thermal energy created by the devices. The development of a pulsed dye laser in the mid 1980’s by the Candela Corporation in Natick, Massachusetts, sought to address this shortcoming. They designed a pulsed dye laser that emitted one-microsecond pulses of 504-nm green light through a 250-micron quartz fiber. The laser was referred to as a dye laser because it utilized coumarin dye to produce the desired wavelength. The formation of plasma at the tip of the laser fiber fragmented stones without noticeable damage to the ureter. In 1986, Watson et al. reported use of the pulsed dye laser in the treatment of 37 urinary calculi with an average diameter of 7.9 mm. The laser fiber was introduced through a 6-Fr catheter that allowed for continuous irrigation around the fiber. The authors reported every stone accessible by ureteroscopy was successfully fragmented. They also concluded the laser fiber was more easily controlled than an electrohydraulic probe and reported no evidence of damage to the ureter.

With advances in laser technology it was felt timely and safe lithotripsy of larger stones would eventually be feasible. Use of holmium:YAG laser lithotripsy was reported as early as 1993 and demonstrated unique versatility due to its ability to work on soft tissue as well as the hardest of stones. Laser lithotripsy continues to evolve. Although earlier lasers such as the candela have been largely replaced by neodymium:YAG holmium lasers, the most generally accessible modifications involve technique as opposed to hardware. In particular, there has been increasing adoption of the “dusting” technique, using lower joules at higher pulse frequencies with a goal of generating innumerable small fragments to leave for later passage as opposed to active fragment extraction. The relative merits of these two techniques are under continued evaluation.

Soon after the development of the first endoscope specifically designed for ureteroscopy in 1980, a rapid expansion occurred in the number of devices available to urologists. By 1986, several manufacturers offered ureteroscopic instruments including ACMI, Olympus, Wolf, and Storz. The different ureteroscopes offered by manufacturers varied by several technical specifications. Ureteroscopes were designed as short scopes (27-34 cm) or long ones (40-45 cm). The scopes came in diameters ranging from 9.5 Fr to 13.5 Fr with most containing either one or two 5-Fr working channels. The working channels could be accessed through either straight operating ports to allow the passage of rigid instruments, or oblique ports that required flexible instruments. In order to accommodate straight operating ports the telescope was offset from the instrument.

The telescopes involved the rod-lens system that provided excellent picture quality. The main drawback of the rod-lens telescope was the intolerance of the rod lens to flexion of the scope. Upon progressive bending, an increasingly obscuring crescent-shaped obstruction of the transmitted image is noted. Some authors at the time concluded the most useful of all the options available were short ureteroscopes with offset telescopes and straight working channels. It was felt longer ureteroscopes were unnecessary because upper ureteral and renal stones could be more effectively treated with shock wave lithotripsy or percutaneous techniques, while lower ureteral stones could be managed effectively by short ureteroscopes and rigid operating instruments.

FLEXIBLE URETEROSCOPY

While rigid ureteroscopy allowed access to much of the upper urinary tract, variable tortuosity of ureteral anatomy may leave many areas inaccessible. The advent of fiber-optics allowed for images to be transmitted through flexible fibers and greatly expanded the boundaries that the urologist could explore through endoscopy. Fiber optics relies on internal reflection of light within an optical fiber to transmit light from
fiberscopes, the authors reported the use of 5 and 6 mm fiberscopes that included the first reported channel for irrigation.24

Early refinements

Early flexible ureteroscopes were controlled in the urinary tract by passive deflection. If the operator wanted to change the orientation of the tip they could push the tip of the scope against a surface to obtain a new viewing angle. In 1971, Takagi introduced a fiberoptic pyeloureteroscope that included a 25-mm section at the tip which allowed the operator to actively control deflection.23 In the early application of fiberscopes, insertion of the device into the ureter via a transurethral approach provided added difficulty. During entry into the ureter the device could many times become stuck in ureteral orifice and increased applied forces on the device damaged the glass fibers. Early techniques to address this obstacle were developed by Takayasu et al. who developed a specialized cystoscope lever and guide tube system to ease passage of their pyeloureteroscope into the ureter.25

In order to negotiate the advantages and deficiencies of flexible and rigid instruments, early attempts were made to combine the technologies and maximize their capabilities. In 1983, Bagley introduced a flexible fiberscope into the sheath of a rigid ureteropyeloscope in place of its telescope. This arrangement permitted pas-
sage of the fiberscope through difficult ureters and its actively deflecting tip could extend past the end of the sheath and thoroughly inspect the renal pelvis. The rigid sheath was also used to provide a means of irrigation and the introduction of operating instruments as the fiberscope did not own these capabilities.26

**Emergence of therapeutic flexible ureteroscopy**

In 1985, Bagley introduced the use of a 3.6 mm flexible ureteropyeloscope provided by the Olympus Corporation that included a 1.2-mm working channel which could be used for irrigation or the introduction of small caliber working instruments. The inclusion of a working channel allowed the flexible scope to be used in a therapeutic manner. Bagley utilized the ureteropyeloscope to introduce a guidewire across an obliterated ureteropelvic junction and perform a ureteropyelostomy with the assistance of rigid percutaneous nephroscopy. In this instance, the flexible ureteropyeloscope was able to access and intervene in an area of the ureter inaccessible by rigid devices.27

As interest in flexible ureteroscopy began to grow, more devices became available to the endourologist. In 1987, Bagley presented the use of three flexible, deflectable, ureteroscopes developed by the Olympus Corporation. Alterations in the design of these devices included decreased diameter of the ureteroscopes and their working channel. Successful passage of the ureteroscopes into the kidney was achieved in 88% of cases. While the utility of the flexible devices was still in the diagnosis of hematuria, specifically the evaluation of filling defects, the therapeutic range was expanded when the author used a 3-Fr electrode passed through a flexible ureteroscope to fulgurate a renal hemangioma.28

**Flexible ureteroscopic lithotripsy and the emergence of modern flexible ureteroscopy**

The application of flexible ureteroscopy expanded further with the integration of electrohydraulic lithotripsy. In 1988, Begun et al. reported the use of a prototype 3-Fr EHL probe in 9-Fr and 13-Fr flexible ureteroscopes. While the probe was successful in the treatment of several cases of ureteral calculi, several obstacles were encountered. Narrow caliber steerable ureteroscopes available at the time were not strong enough to adequately deflect the tip of the scope with the electrode in place. Alternatively, wide caliber 13-Fr steerable ureteroscopes could be used to ensure accurate control of the probe but these ureteroscopes required significant dilation to be introduced into the ureter. In addition, electrohydraulic lithotripsy had a well-recognized risk of ureteral damage.29

Reports of laser lithotripsy with flexible ureteroscopy began as early as 1988 when Voges et al. reported using a 9-Fr flexible ureteroscope with a 1-mm neodymium-YAG laser probe to disintegrate two ureteral stones after failure of SWL therapy.30 Flexible ureteroscopic laser lithotripsy was also advocated by Higashihara et al. in 1990, successfully treating 14 of 16 upper ureteral stones. Not surprisingly, the stones failing retrograde treatment both measured greater than 1.8 cm.31 The study represented an important shift in the management of upper ureteral stones. Before flexible ureteroscopy, endoscopic instruments could not consistently treat upper ureteral stones, leaving SWL as the default favored modality.32 However, at the time treatment of upper ureteral stones with SWL commonly employed a pre-SWL retrograde endoscopic “pushback” of proximal ureteral stones. The introduction of flexible ureteroscopy and laser lithotripsy to retrograde techniques provided a streamlined management strategy.31

With improvements in technology and increased operator experience flexible ureteroscopy would prove to be effective in many facets of endourology. In 1992, Abdel-Razzak et al. reported the use of actively deflectable flexible ureteroscopes in 290 procedures. Use of the flexible ureteroscope ranged from management of urolithiasis to evaluation of hematuria. The study revealed an overall success rate of 95.5%. Most impressive, the flexible ureteroscope was able to perform successful lithotripsy in 74 of 77 cases. The most commonly used ureteroscope was a 9.8-Fr instrument that required dilation of the ureter.33

To ease access to the upper urinary tract however, slimmer flexible ureteroscopes were
required. In 1994, Grasso and Bagley reported the use of 7.5-Fr actively-deflectable flexible ureteroscope developed by Karl Storz endoscopy. The small caliber device maintained a 3.6-Fr working channel which could accept a wide variety of operating instruments. The tip of the instrument had two-way active deflection capabilities with 170 and 120 degrees of deflection as well as passive deflection permitting consistent access to the lower pole calix. Improvement in fiber-optic technology allowed for miniaturization of the device without sacrificing the working channel. The 7.5-Fr distal tip of the ureteroscopic could be passed into the ureter over a guide wire without need for dilation. The instrument firmly established the flexible ureteroscope as a therapeutic device with the ability to treat calculi and urothelial tumors throughout the entire upper urinary tract. A new wave of modern flexible ureteroscopes would soon follow with many of these novel design principles incorporated. By 1997, several different small caliber actively deflecting flexible ureteroscopes were available from various manufacturers with dimensions as low as 6.2 Fr. Other strategies to improve the utility of flexible ureteroscopes include the inclusion of two working channels in traditional fiber optic ureteroscopes in order to increase their capacity for irrigation.

**SEMI-RIGID URETEROSCOPY**

The superior optics of the rigid scope and the improved maneuverability of the early flexible endoscopes were complementary, but left each technique lacking in critical ways.

While fiber optic image transmission was essential in flexible ureteroscopes, its adoption into rigid ureteroscopes was slow to occur due to its inferior image quality compared to the rod lens system. However, the flexible nature of fiber optics would allow preservation of the viewed image in spite of bending of the scope. Reports of rigid fiber optic ureteroscopes came as early as 1986 with the Rigiflex ureteroscope by ACMI. The scope was 12 Fr in diameter with a triangular cross section and an 8 Fr working channel. Though the inclusion of fiber optics avoided the crescentic image distortion found in the rod lens system, the scope did not achieve a narrow caliber and its documented use in the literature is limited.

The introduction to the modern semi-rigid ureteroscope occurred in 1989. The ureteroscope was 47.3 cm long and measured 11.9 Fr at its proximal aspect and tapered to 7.2 Fr over its distal 11 cm. The instrument contained two 2.1-Fr working channels allowing for passage of irrigation, wires, or laser fibers. The inclusion of a fiber optic bundle for image transmission allowed the ureteroscope to be flexed 5 cm from its axis without and distortion in the transmitted image. The instrument could be passed into the ureter without dilation with the help of a pre-placed guidewire. The instrument was initially used in 50 patients to treat all levels of the ureter. It was particularly useful in women with successful passage of the ureteroscope in 26 out of 27 patients. Passage of the ureteroscope was more difficult in men with successful passage in the mid and upper ureter in only 6 out of 13 cases. The small working channels of the instrument were able to accommodate 250-micron laser fibers that permitted the fragmentation of ureteral calculi in several cases. At the time, narrow stone baskets were not available to pass through the 2.1-Fr working channel thus larger ureteroscopes were used in the event that stone fragments required basketing.

By 1993, several manufacturers produced versions of semi-rigid ureteroscopes with fiber optic imaging. Semi-rigid ureteroscopes ranged from 6 to 9.5 Fr and included one or two working channels ranging from 2.1 Fr to 5 Fr. Further miniaturization of operating instruments added to the versatility of semi-rigid scopes with various graspers, baskets, electrohydraulic probes, and laser fibers all available at under 2 Fr. The major drawback from the use of fiber optic imaging was decreased image resolution compared to standard rod lens systems. Even so, the small caliber and the ability of semi-rigid ureteroscopes to maintain a field of vision when flexed allowed for higher success rates and lower complication rates compared to conventional rigid ureteroscopes.

While our current fleet of semi-rigid ureteroscopes allow previously unimaginable visualization and access, their size still limits accessibility to some regions of the ureter. In