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Review

The Role of Laser Technology in Urolithiasis: A Systematic Review of Clinical Outcomes and Technique

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Abstract

Urinary stone development (urolithiasis) is a common illness that presents substantial therapeutic problems. Laser technology has become a major breakthrough in the treatment of urolithiasis during the last few decades. An overview of laser treatment modalities is given in this abstract, with particular attention to their usefulness, safety, and position in contemporary urological practice. Treatment options catered to different kinds and sizes of stones have increased with the introduction of various laser technologies, such as the neodymium (ND), holmium (HO), and thulium lasers. In particular, laser has become widely accepted because of its greater capacity to efficiently break down both soft and hard stones. It breaks apart stones in the urinary tract because it works at a wavelength that water can readily absorb. By using a flexible fibre to administer laser energy endoscopically, the process targets stones directly while causing the least amount of tissue damage possible. Clinical research indicates that, in comparison to conventional techniques like extracorporeal shock wave lithotripsy (ESWL), laser lithotripsy delivers high rates of stone-free outcomes, decreased postoperative pain, and shortened recovery periods. Laser lithotripsy has drawbacks in spite of its benefits. It involves certain tools and knowledge, and there is a chance of consequences including bleeding or ureteral damage. Furthermore, accessibility may be impacted by financial factors and the requirement for additional training. In summary, laser treatment for urolithiasis offers improved precision and efficacy in stone management, marking a substantial development in urological care. It is projected that future research and technical advancements will further hone these methods, improving results and expanding their range of applications.

Keywords: Urolithiasis, Laser Lithotripsy, Endoscopic Surgery, ESWL, Current Laser Technology, Future Perspectives of Laser Treatment.

INTRODUCTION

When calculi are found in the kidney or any other area of the urinary tract, such as the ureters or the bladder, it is known as urolithiasis. These calculi can affect one or both kidneys. Calcium oxalate and phosphate make up about 80% of these calculi [1]. 12% of men and 6% of women will have urinary stone disease throughout their lives [2]. This intricate process, known as urolithiasis, results from an imbalance in the kidneys between promoters (calcium, sodium, oxalate, urate, cysteine, low urine pH, low urine flow), and inhibitors (citrate, magnesium, pyrophosphate, Tamm Horsfall protein, urinary prothrombin fragments, glycosaminoglycan osteopontin, and high urine flow).Up to 80% of the examined stone is composed of calcium oxalate (CAOX) [3]. A series of physicochemical phenomena, such as supersaturation, nucleation, growth aggregation, and retention within the renal tubules, culminate in the complex process of kidney stone development. Kidney stones can be treated using a non- invasive medical method called extracorporeal shock wave lithotripsy (ESWL). Kidney stones are broken up into smaller pieces that are more easily transported through the urinary tract by using shock waves [4]. Percutaneous nephrolithotomy back incision is made in order to remove bigger stones directly from the kidney during surgery. Although it is rarely performed these days, exceptionally large or complicated stones that cannot be treated with less invasive techniques may require open surgery [5]. The use of laser technology has transformed the management of urolithiasis, or kidney stones, by providing a very successful, less intrusive substitute for conventional surgical techniques. The development of laser lithotripsy, which offers a precise and effective method of stone fragmentation, has greatly improved patient results.

Principle

An electromagnetic radiation beam emitted by a laser is invariably coherent, collimated, and monochromatic. Lasers have a wide range of applications in clinical care and are made up of three major parts: an optical resonator, a stimulating energy source (pump), and a lasing medium (solid, liquid, or gas) [6].

Photo thermal Effect

Absorption: The stone and the surrounding fluid absorb the laser's energy and transform it into heat.
Heat Generation: The stone fractures as a result of thermal expansion brought on by the fast heating.
Vaporization: The stone substance can be vaporized by the laser at greater energy.

Effect of Photomechanical Light

Shock Waves: The stone is mechanically stressed by shock waves produced by pulsed laser radiation.
Cavitation Bubbles: The surrounding fluid experiences cavitation bubbles as a result of the laser's energy. These bubbles burst, creating forces that aid in the fracturing of stone.
Cracking and Fragmentation: The stone fractures into smaller, more manageable pieces as a result of both mechanical and thermal stress.

Types of laser used in urolithiasis

Kidney stones have been treated with a variety of laser types, each with specific properties that dictate their applicability and efficacy.

Holmium

Holmium, Yttrium, Aluminium, and Garnet 2100 nm is the laser wavelength [7]. Strong photo thermal effects are produced due to the high absorption by biological tissues and water. Because of this, it can effectively break up stones of any kind.
Benefits: Adaptable and efficient on stones of all shapes and sizes.
Precise and manageable, reducing harm to the tissues around it able to be applied to both fracture and vaporize stones.
Drawbacks: Needs certain tools and instructions.
Applications: The gold standard for percutaneous nephrolithotomy and ureteroscopy utilizing laser lithotripsy.

1. **Thulium laser Wavelength:** 1940nm

Mechanism: High absorption by liquids and tissues, similar to the Ho laser, which results in effective stone fragmentation [8]**.**
Benefits: Possibly quicker fragmentation in comparison to Ho and higher rates of stone ablation. Smaller, more pliable fibres that provide better access to hard-to-reach stones. Stone movement during fragmentation is known as lower retropulsion.
Drawbacks: Not as widely accessible as Ho, but with newer technologies. **Applications:** Becoming a potent substitute for the Ho laser, particularly in flexible ureteroscopy.

Mechanism of stone formation

1. **Supersaturation of Urine:** Generally speaking, kidney stones develop when the concentration of specific minerals, such as calcium, oxalate, phosphate, and uric acid, in the urine rises to an excessive level (supersaturated).When these compounds are out of proportion with the volume of urine that is available or with other variables that typically keep them in solution, supersaturation results.

2. **Nucleation:** Urine can form microscopic crystals if it reaches a supersaturated state. These crystals have the ability to form on the surfaces of the renal papillae or tubules, as well as in the urine itself.
3. **Crystal Growth:** If the urine's growth-promoting factors persist, crystals may enlarge over time. A number of variables affect this process, including pH, ion concentration, and the existence of chemicals known as promoters or inhibitors, which either encourage or prevent the formation of crystals.
4. **Crystal Aggregation:** Kidney stones are larger, solid structures made of aggregated crystals. The renal pelvis or kidney calyces may be the site of the aggregation.
5. **Stone Growth and Retention:** Stones may grow inside the kidney or pass through the ureter and into the bladder. Retention and growth of stones might be caused by anatomical differences, obstructions of the urinary tract, or reduced urine flow [9].

Current laser technology

Holmium: yag laser lithotripsy (λ = 2120 nm)

Laser wavelength

Because of its versatility in breaking up many types of stones (such as calcium oxalate, uric acid, cysteine, etc.), the Holmium: YAG laser is now the gold standard for lithotripsy. Water absorbs the holmium laser wavelength substantially, which is 2120 nm. Due to urine in the urinary system and continuous saline irrigation through the ureteroscope's working channel during the laser lithotripsy treatment, as previously discussed, there is water present in the pores and pockets along the stone surface. Moreover, when the water expands and vaporizes due to thermal expansion, this water absorbs IR laser energy, resulting in microexplosions. Together with direct IR laser absorption and thermal degradation of stone material, this mechanical phenomenon is important to the ablation mechanism [10].

Operation mode

Even though the holmium laser is a rather old technology, as it has developed in urology, little advancements have been made. In order to save space in the operating room, smaller, more compact, lower power (such as 20 W) holmium laser modules designed exclusively for laser lithotripsy have been created. These modules can be integrated with other ureteroscope components (such as monitors, illumination, and imaging systems). In addition, kidney stones can now be treated in "dusting" mode, which has low pulse energy (0.2–0.4 J) and high pulse rate (50–80 Hz), as an alternative to the traditional "fragmentation" mode, which has high pulse energy (0.6–1.0 J) and low pulse rate (5–10 Hz) [11]. This is made possible by operating at higher pulse rates.

Pulse shaping

Numerous temporal beam shaping techniques have been applied, such as extending the laser pulse up to approximately 1200 s, delivering trains of laser pulses in bursts, or modifying the laser pulse from its typical, short pulse length of 250–350 s up to 700 s by delivering two pulses together ("dual pulse mode") [12]. Reduction in stone retropulsion is achieved by using smaller fibers, lower pulse energies, and longer pulse durations. As an alternative, stone retropulsion has been decreased, and stone ablation rates have been raised by first delivering a short, low-energy pulse that forms a vapour bubble, followed by a longer, higher-energy pulse. In clinical literature, this mode is known as "Moses Tech" [13]. Reduced operation times may not be enough to offset the expensive cost of the laser and software, according to recent clinical studies [14].

Thulium: yag laser lithotripsy (λ = 2010 nm)

In urology, the 2010 nm wavelength Thulium: YAG laser has also been widely utilized, mostly for soft tissue applications in the management of benign prostatic hyperplasia (BPH). There are several diode-pumped commercial Thulium: YAG laser sources available with up to 200 W of output power for BPH. Only a small number of laboratory studies regarding the use of lithium have been published, though. Either a continuous-wave commercial laser tuned to operate in long-pulse mode or a flash lamp-pumped, short-pulse, Q-switched laser are used in this experimental research [15]. Before the usefulness of lithotripsy with Thulium: YAG lasers can be fully assessed, more research must be done.

Erbium: yag laser lithotripsy (λ = 2940 nm)

The solid-state, flashlamp-pumped Erbium: YAG laser has been used in several experimental laboratory experiments for lithotripsy [16]. Compared to the Holmium laser wavelength of 2120 nm, the Erbium:YAG laser wavelength of 2940 nm matches a greater water absorption peak in tissue, resulting in a substantially higher absorption of the laser energy A longer wavelength that results in both higher water absorption and stone absorption can lead to more effective laser ablation of kidney stones [17].

Laser technique

Laser Cutting
Method: The substance to be sliced is exposed to a strong laser beam, which causes it to melt, burn, or evaporate. To obtain exact cuts, a computer controls the procedure [18].
Applications: For cutting metal, plastic, and other materials in the manufacturing sector **Example:** laser cutting is used in the production of automobiles to create accurate body pieces.

Laser Engraving
Procedure: To create a design or pattern, material is removed from the surface using a laser beam. To get the desired result, the laser's focus, speed, and intensity are changed. **Applications:** Marks artwork, logos, and serial numbers on a variety of materials. **Example:** An illustration would be to engrave serial numbers on electronic parts.

Laser Welding
Procedure: A laser beam is used to melt the material, forming a joint between two components. The high energy of the laser allows for deep and narrow welds with minimal heat input. **Applications**: Widely used in the automotive and aerospace industries. **Example**: Welding components of a car body.

Laser Drilling
Procedure: A laser is used to create holes by vaporizing material in a localized area. This method allows for precise and clean holes with high aspect ratios. **Applications**: Used in the aerospace and electronics industries for drilling holes in components.
Example: Creating cooling holes in turbine blades.

Medical laser procedures
Laser Eye Surgery (LASIK)
Procedure: To treat refractive defects such as myopia, hyperopia, and astigmatism, the cornea is reshaped using a laser [19].
Applications: Correcting vision to lessen the need for glasses or contact lenses.
Example: Near-sightedness can be corrected with LASIK surgery.

Laser Skin Resurfacing
Method: To lessen wrinkles, scars, and imperfections, layers of skin are removed using a laser. The laser causes collagen to be produced, which results in skin that is tighter and smoother.
Applications: skin condition treatment and cosmetic enhancement.
Example: Laser acne scar therapy.

Laser Hair Removal
Method: A laser heats and damages hair follicles in order to prevent new hair growth. Long- lasting benefits may require multiple sessions [20].
Applications: Permanent hair reduction.
Example: Consider laser hair removal for undesirable facial hair.

Laser Lithotripsy
Method: Kidney stone fragments that can be passed via the urinary tract are broken up into smaller pieces using a laser during the procedure known as laser lithotripsy.
Applications: kidney stone therapy.
Example: One such treatment is laser lithotripsy for renal calculi.

Clinical outcome holmium laser
Efficacy
Stone-Free Rates: Holmium lasers are quite good at breaking up stones; for ureteral stones, the rates are between 85% and 95%, and for bigger renal stones, they are a little lower [21].
Versatility: It is a useful tool for urologists as it works well against a range of stone sizes and compositions [22].

Safety
Low Complication Rates: There aren't many complications reported after the surgery. Ureteral damage and surgical infections are possible side effects; however, they are not common [23].
Minimal Invasiveness: Holmium laser lithotripsy is less intrusive than open surgery, which lowers risks and speeds up recovery [24].
Recovery and Long-Term Outcomes

Fast Recovery: After a brief hospital stay, most patients are able to resume their regular activities in a few days [24].

Stone Recurrence: Although the treatment is successful in removing pre-existing stones, it does not stop the development of new stones; hence, continued observation and lifestyle modifications are required to stop recurrence [21].

Thulium Fibre Laser (TFL)

1. **Efficacy**
   Higher Stone-Free Rates: When compared to holmium laser, TFL has demonstrated greater stone-free rates. Stone-free rates were found to be 86.9% for TFL and 73.6% for holmium in a meta-analysis.
   Effective Stone Fragmentation: TFL is especially good at generating little, dust-like particles that are simpler to remove from the urinary tract [23].
2. **Safety**
   Low Complication Rates: TFL has a low rate of complications and a good safety record. Compared to holmium laser, it produces less thermal damage, which lowers the possibility of tissue damage.
3. **Recovery and Long-Term Outcome**

Shorter Operation Time

TFL frequently leads to shorter operation times, which can lower the total cost of the procedure and lower the chance of problems from longer surgery. Effective for various stone types: TFL is a versatile treatment option that meets a wide range of patient requirements. It is useful for a variety of urinary stone kinds [21].

Comparative results

Stone-Free Rates: While both lasers are efficient, TFL often exhibits faster stone fragmentation and higher stone-free rates.

Procedure Time: Compared to Holmium, TFL frequently has shorter operation times, which can result in higher patient throughput and fewer aesthetic risks. Complication rates are minimal for both lasers; however, TFL appears to have a marginal advantage in terms of lowering thermal injury [24].

Challenges and limitation

Cost and Accessibility

Expensive Equipment Requirements: Laser lithotripsy can be less accessible, particularly in environments with fewer resources, due to the cost of its equipment and ongoing maintenance.

Qualifications for Training: In certain healthcare settings, urologists may find it difficult to obtain the specific training required for the use of laser technology.

Stone Characteristics

The effectiveness of lasers on most stones is dependent on their size and composition. While most stones may be treated with one session, larger stones or those with complicated compositions may need to undergo further treatments, such as percutaneous nephrolithotomy.

Hardness of Stones: According to BioMed Central, some extremely hard stones, such as cystine stones, may be more difficult to completely remove using laser fragmentation.

Procedure-Specific Problems

Residual Fragments: Despite efficient fragmentation, tiny residual fragments fragments that are too small to be picked up and eliminated may still be present. These could result in future stone formation or necessitate further treatments.

Steinstrasse: According to Biomed Central, this is the term used to describe the build-up of stone pieces in the ureter following fragmentation, which can impede urine flow and result in problems.

Safety Issues

Thermal Damage: Despite improvements, there is still a chance that the surrounding tissues will sustain heat damage during the treatment, especially when using higher energy settings or for an extended period of time.

Ureteral Injury: During ureteroscopic laser lithotripsy in particular, there is a risk of ureter mechanical injury, such as strictures or perforations.

Patient Factors Anatomical Variations:

It may be difficult to employ laser lithotripsy effectively in patients with complicated urinary tract anatomies, such as strictures or severe hydro nephrosis.

Patient Comorbidities: According to laser on urolithiasis, patients who have specific comorbid diseases may be more vulnerable during the surgery and may need closer supervision and care.

Long-Term Effectiveness in Preventing Stone Recurrence:

Laser lithotripsy works well in removing current stones, but it is not a barrier against the creation of new stones. To lower their chance of recurrence, patients with recurrent stone illness need to modify their lifestyle and receive continuing care.

Technological Restrictions

Energy Distribution and Effectiveness: While improvements such as the MOSES technology in holmium lasers enhance energy delivery and efficiency, they may also raise the equipment's cost and complexity.

Advantages of laser technology on urolithiasis

High Efficacy: Stones of all sizes and materials can be broken up with great effectiveness using laser lithotripsy.
Precision: With minimum harm to surrounding tissues, the method enables exact targeting of stones.
Flexibility: Ho lasers are adaptable to various anatomical sites inside the urinary system and can be utilized in both rigid and flexible ureteroscopes.
Minimally Invasive: The technique is minimally invasive, generally conducted endoscopically, which minimizes recovery times and hospital stays.
Decreased Stone Migration: The chance of stone migration during treatment is decreased by the laser's exact control.

SUMMARY

Although laser treatment for urolithiasis is beneficial, there are still issues with cost, the nature of the stone, dangers associated with the surgery, patient considerations, and technology constraints. In order to address these problems, more research must be done, technology must evolve, and healthcare institutions must allocate resources and provide better training.

Future perspectives

1. **Improved Laser Technology**
   Thulium Fibre Lasers (TFL): These lasers have already demonstrated their potential. Compared to holmium lasers, TFL offers greater precision, superior stone dusting capabilities, and less thermal injury to surrounding tissues. Future advancements might make TFL the lithotripsy treatment of choice.
   Future-Stage Lasers: Systems that are even more efficient at breaking up stones with little negative consequences may be produced by further research into other kinds and wavelengths of lasers.
2. **Modification and Adaptability**
   Smaller Endoscopes: Developments in materials science and fiber optics will make it possible to make endoscopes that are more flexible and smaller. This would facilitate the access and treatment of stones in urinary tract areas that are challenging to reach. **Automation and Robotics:** Combining robotic technologies could improve results, lessen operator fatigue, and increase the accuracy of laser lithotripsy. Systems Assisted by Robots.
3. **Enhanced Imaging and Targeting**
   Real-time Imaging: When high-resolution imaging methods like enhanced ultrasonography or optical coherence tomography (OCT) are combined, stones can be seen in real time while receiving laser treatment. Both therapy efficacy and targeted accuracy may increase as a result.
   AI and machine learning: Artificial intelligence can be used to direct laser settings and evaluate imaging data to maximize stone fragmentation while minimizing tissue injury.
4. **Techniques that are semi-invasive and non-invasive Extracorporeal Laser Lithotripsy:**
   By studying non-invasive laser methods for breaking stones externally, intrusive procedures may not be necessary as often. This method would be comparable to extracorporeal shock wave lithotripsy (ESWL), with the added benefit of increased accuracy and efficacy from lasers.
   Percutaneous and Endoscopic Innovations: Potentially more advanced techniques for percutaneous and endoscopic procedures
5. **Customized Health Care**
   Analysis of the Biochemical Composition of Stones: State-of-the-art methods for determining the biochemical makeup of kidney stones can help determine customized laser parameters for more efficient fragmentation. Dietary and lifestyle suggestions for preventing recurrence can also be informed by an understanding of the makeup of the stone.
   Metabolic and Genetic Profiling: Treatment regimens tailored to individual patients' metabolic and genetic profiles may lead to better results and a lower recurrence rate. Based on the unique characteristics of each patient, different laser settings and treatment approaches might be used.
6. **Improvements in Efficacy and Safety**

Decreased Complications: To lower the danger of complications, including infections or ureteral injury, future laser systems might include improved safety features. Minimizing collateral damage can be achieved via precise targeting and better control over energy delivery.

Post-operative Care: Advances in postoperative care, such as laser scar therapy.

7. **Price and Availability**

Affordable Technology: A wider spectrum of patients will have greater access to innovative therapies as laser technology spreads and production prices come down.

Training and Education: Surgeons can benefit from improved training programs and virtual reality simulations to ensure high-quality care across various healthcare settings by improving the dissemination and standardization of laser treatment techniques.

All things considered, laser technology appears to have a bright future in the treatment of urolithiasis. New developments in technology and continuing research should improve patient results, lower procedure risks, and increase treatment accessibility.

CONCLUSION

The revolutionary and least invasive methods that laser technology offers for the treatment of urolithiasis greatly facilitate kidney stone management. Regardless of the size, makeup, or position of stones inside the urinary tract, laser lithotripsy in particular enables accurate targeting and fragmentation of the stones. This approach, as compared to conventional surgical alternatives, not only minimizes injury to surrounding tissues but also drastically shortens recovery durations and postoperative pain. With greater success rates and fewer side effects, laser technology has established itself as a mainstay in the management of urolithiasis, providing patients with a more effective and safe way to remove stones.

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