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TECHNOLOGICAL INNOVATIONS FOR MANAGEMENT OF KIDNEY STONE

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ABSTRACT: The kidney is an important organ in waste filtration, plays a central role in maintaining body homeostasis. The management of kidney stones includes several techniques over the period of time which involve Percutaneous Nephrolithotomy (PCNL), Shock wave lithotripsy (SWL) and Ureteroscopy (URS). Ureteroscopy has undergone considerable innovations over the last few decades. Laser technologies have further advancement for kidney stone removal that is Holmium fiber laser technique and thulium fiber laser technique. Holmium laser technique removes the stone by dusting and fragmenting it. The selection of technique depends on stone type, size and location. Thulium fiber laser has higher precision and efficiency due to its shorter wavelengths and continuous-wave emission characteristic. These technological advancements have resulted in more positive patient outcomes due to reduction in recovery times and fewer complications. This review provides complete overview of the physiology of the kidney, composition of kidney stone, factors affecting on their formation and the management techniques with focusing on the development of ureteroscopy and the latest laser technologies for kidney stone removal.

INTRODUCTION:

Physiology of Kidney: The kidneys are complex organs that play a central role in keeping the body functioning properly. They primarily work by regulating fluid, electrolytes and acid-base balance of body as well as providing a stable environment for all cells and tissues. They achieve this by managing water and solutes flows, excreting waste products, preserving nutrients and regulating acid-base balance.

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The human body comprises about two-thirds water is stabilized by the renal (urinary) system, which consists of two kidneys, two ureters, bladder and urethra, which helps to keep everything in balanced state. The kidneys are reddish brown in color with beanlike shapes that filter the blood. These are located behind the abdominal organs, in connection with the 12th thoracic and 3rd lumbar vertebrae.

The right-side kidney is little bit lower than the left because of the position of liver. A layer of fat cushions the kidneys and protects them from injury. The ureters, which are bilateral thin tubes about 27 to 30 cm long and 1 to 5 mm wide, transmit urine from the kidneys toward the bladder through waves like motion. The bladder, located at the back of the pelvic bone and acts as storage tube and stores

urine until it is ready to be excrete from the body. Every kidney has an outer layering called the cortex and an inner layer known as the renal medulla, which is divided into triangular sections named 'Renal pyramids' that connect to the renal calyces [1, 2, 3, 4].

Theory of Stone Formation:

Natural History: The genesis of Nephrolithiasis originates. Nephrolithiasis, also called kidney stones, begins as microscopic crystals in the kidneys are named as calculus. These particles form when certain urinary components, such as calcium or oxalate, reach a high concentrated level beyond saturation. Over time, the crystals develop into larger stones, in some instances the kidney is almost occupied, with the whole spreading form of a stone called a staghorn calculus.

The stone remains in the kidney and keeps growing, but however, it may migrate and move down the ureter, which is the duct that connects the kidney to the bladder. In general, smaller stones- less than 5 millimeters in diameter size can easily pass out of the body through the urinary tract without making any disturbance but once larger stones enter the ureter, they get fixed on there and can cause an obstruction of urine flow. This is referred to as ureteric colic. Also, it may be severely painful and is mostly associated with nausea and vomiting. When the stone enters the bladder, it may continue to grow; in a few cases, it can obstruct the urethra, thereby causing painful inability to urinate or urinary retention [2].

Chronic Kidney Disease: What is chronic kidney disease (CKD)? Chronic Kidney Disease (CKD) is a disorder characterized by continuous and irreversible decrease in kidney function over time. Chronic kidney disease (CKD) is defined by the National Kidney Foundation as evidence of kidney damage that persists for three or more than three with or without decrease in glomerular filtration rate kidney. Kidney damage is a condition characterized by Development of Structural and function abnormalities in kidney such as cysts. Blood tests or urine tests that show high levels of waste products like creatinine at abnormal levels, or protein in the urine [6].

Composition of Renal Stones: Kidney stones are varied in form of composition and how they develope. It's important to study the chemical makeup and structure of kidney stones is crucial because of composition of the stone elements and their functions are vary based on the stone type, thus basic features of different kind of kidney stone are discussed in next part [4, 8, 13, 14, 26].

TABLE 1: COMPOSITION OF KIDNEY STONE, CAUSES, % OF FORMATION OF STONE, RADIODENSITY AND CRYSTAL SHAPE OF THE SAME

Sr. no.	Composition of stone	Cause	Total percentages of stone formation	(X-ray characteristics or Radiopacity)	Crystal shape in urine[4]
1.	Calcium Oxalate	Acidic urine	80-85%	Radio-opaque	Envelope
2.	Uric acid	Acidic urine	5-10%	Radio-lucent	Diamond or barrel
3.	Struvite	Kidney infection	2-20%	Radio-opaque	Coffin-lid
4.	Cystine	Genetic	1%	Slightly Radio-opaque	Hexagonal
5.	Calcium phosphate	Alkaline urine\ Hyper-parathyroidism	Rare%	Radio-opaque	Amorphous

Note: Pure Uric acid and Indinavir stones don't show up on X-rays because they are radiolucent. Cystine stones, on the other hand, are radiopaque, meaning they can be seen on X-rays due to their sulphur content [4, 6, 7, 8, 12, 13, 15].

Kidney Stones Detection Techniques: To learn all, there is to fully inform about kidney stone formation. There is need to know about variation in stone composition. Evalution of kidney stone is important for the therapy and preventive care of residual and repetitive stone. Here are some common methods used to analyze kidney stones:

Chemical Analysis: Identifying the chemical nature of the stone.

Thermogravimetry: To Measure weight changes as the stone is heated to see its composition.

Polarization Microscopy: To observe the structure of stone under the microscope by using specialized light.

Scanning Electron Microscopy: Used for more detailed images of the stone's surface [12].

Powder X-ray Diffraction: Analyzing how X-rays scatter off powdered stone to determine its composition.

Spectroscopy: To Study the interaction of light with the stone to get more detailing of stone formation [5, 13, 15].

Factors Affecting the Formation of Stone: There are many predisposing factors to stone formation. Some of these are listed below. These factors mainly categories into two parts i.e Intrinsic factors and Extrinsic factors. In essence the cause of urinery stone is supersaturation of urine with one or more of the components which forms stones [13].

Intrinsic Factors:
Age: Peak incidence 20 - 50 years age.

Sex: In Males stones are developed rapidly than females (1.5 times more). i.e Ratio of formation of stone in Male: female (1.5 :1) [12].

Male: Testosterone can increase the production of oxalate that resulting in formation of calcium oxalate stones.

Female: In female there is more citrate in their urine, which helps to prevent formation of calcium oxalate stones, but they are more prone to urinary tract infections (UTIs), that leads to increasing the risk of struvite stones.

Genetics:

- Increased Risk in caucasian and asian populations
- Family history of stone.
- Familial renal tubular Acidosis (calcium phosphate stones)
- Cystinuria (Cystine stone)
- Primary Hyperoxaluria (Ca+ Oxalate stone) in this case excess 45mg/day oxalate is excreted from urine.
- Hypercalcuria [8]
- Hyperthyroidism (As the increase in the resorption of bone resulting hyperparathyroidism condition, may leads to recurrent stone formation) [2].

Anatomical Abnormalities:

- Horseshoe/ duplex kidney [8]
- PUJO
- Anything that causes obstructions in urinary function/or delayed emptying of bladder.

Certain kidney shapes (like horseshoe or duplex kidneys) and blockages (like PUJO) can cause urinary stasis, leading to stone formation.

Urinery Track Infection: Infections (Urease hydrolysis) can increase pH of urine by breaking down urea into ammonium, promoting formation of stone.

Medication: Some medications like loop diuretics, steroids, chemotherapy drugs, and certain anti-epileptics, can increase the risk of stones.

Extrinsic Factors:
Geography:

- Western lifestyle
- Hot climate [8]

Fluid Intake: < 1.2 L/day is a risk. Drinking less than 1.2 liters of water a day increases the chance of forming stones.

Occupation:

- Sedatory lifestyle may result this condition.
- Working on hot environment e.g. kitchen.

Diet:

- **High Protein:** High protein diets can lead to excess uric acid, causing uric acid stones.
- **High Salts:** High salt intake can increase calcium levels in urine. That condition is called Hypercalcuria.
- **Law Calcium:** higher risk of calcium stones, which I agree is not as you would expect.

- **Malabsorptive disease:** Hyperoxaluria (reduced binding of calcium = increase absorption of oxalate) [4, 11, 13, 26].

Management of Stone/ Techniques:

1. Conservative management.
2. Extracorporeal stockwave lithotripsy (ESWL) [20].
3. Urethroscopy and Stone Fragmentation.
4. Percutaneous Nephrolithotomy.
5. Open nephrolithotomy.
6. Medical dissolution therapy.

Conservative Management: Often stone may pass by their own depending on their Size, especially if they are less than 4 mm in size. In fact, there's more than 80% chance that a stone this size will pass within 30 days. In such cases the patient will require analgesia, reassurance and a follow up scan to check whether the stone is passed a few weeks later or not. Sometimes alpha blockers drugs such as tamsulosin may be given for ease of stone passage. Patients must be given safety netting advice. If they developed the sign and symptoms of an infected obstructed kidney [8].

Extracorporeal Stockwave Lithotripsy (ESWL): This procedure is done in a specialized clinical procedure with analgesia. We use stock waves to fragment stones into smaller pieces through which the patient will hopefully be able to pass stone naturally [20].

Urethroscopy and Stone Fragmentation: The procedure Performed under an anesthetic condition. A very long but thin endoscope is passed *via* the urethra into the bladder then up into the ureter and into the kidney. With this endoscope we can use a number of devices such as lasers to fragment the stone. We can then remove the fragments with a small basket which can easily pass through the scope [8].

Percutaneous Nephrolithotomy: Percutaneous Nephrolithotomy is still a minimally invasive procedure which can be perform by giving a small cut in the skin, but it can be remove larger stones from kidney. Under radiological guidance a tube is pass through the skin into the kidney. This tube can be used to insert a scope into the kidney and fragment the stone and also for removing fragments [16].

Open Nephrolithotomy: This process rarely performed now in countries with endoscopic equipment available which is applicable for large staghorn stones in some specialized cases [8].

Medical Dissolution Therapy: This technique best suited during surgery of uric acid stones having aim to make the urine alkaline nature and Cystine stones with aim to alkalinse the urine and also reduce delivery intake [5, 8, 13]

Uretheroscopy Techniques:

History of the Advancement in Ureteral Endoscopy: Human endoscopy technique developed for clear visualization of internal body cavities. In urology, the primary focus has been on examining the bladder, a highly focused area for diagnosing a variety of medical issues. The bladder lies just a few centimeters beneath the surface in females, while in males, it is accessed through a longer urethra. Specialized Endoscopic tools designed for the urinary passage, from the urethral opening to the renal apex, share several fundamental design and functional features and aimed at providing access to and visibility of these internal structures for diagnostic and therapeutic purposes.

Scope must have:

1. The endoscope must have a way to show a clear view at the tip of the shaft for proper imaging
2. It's included illumination possibly by several different sources
3. There should system with procedure for irritating to distend the cavity being entered and inspected
4. To improve the endoscope's function, it needs a channel to pass tools through for performing procedures.

Note: Now a day's flexible endoscopes become available, for clear deflection.

History: In 1806 'Brozzinis Lichtleiter' developed a device for visualization within the body. This device consists of a tube together with mirror and illumination candle.

Purpose: its main motive to visualize pharynx but it can also be applicable for examination of pelvic organ. (Actual model was at American college of surgeons in Chicago).

New Designs in 19th Century:

1. An early device for examining the male urethra was designed by 'Desormeaux' (1815-1882) in Paris It was a long metallic tube together with mirror that illuminated from a petroleum lamp. Its tip had an angled beak, like wise previous design. However, it had a major drawback it became very hot during use, hence is not practicable.
2. In the USA, a design developed based on emitted light from an opthalmic mirror which main focus to looking a tube of bladder.
3. It had sharp nib. A major drawback of this technique is it only got hot like the previous design but had some limits for visualization.
4. Nitzwith Leiter' Austrian instrumenta creator, introduced first cell microscopy in 1878. Device contains a wire of tungsten filament for light emission, but it generates heat.
5. Another improvement was' Mignon bulb by electronic surgical instrument a small light bulb designed for cytoscope in Rochester, New York Although these bulbs didn't overheat, but it could burn out, and it may cause temporary working problems.
6. In 1910 A improved version in scopy design by Buerger in New York. On the basis of this model Tilden Brown cystoscope discover. Over the 50 years the 'Brown-Buerger cystoscope' still in working.
7. In 2016, 'LithoVue' from Boston Scientific was introduced as a fully flexible, disposable electronic ureteroscope. It had a shaft with dimensions of 9.6 F and a 3.6 F channel [15].

This Cytoscopehad:

- Interchangeable telescopes.
- A channel for irrigation and instruments.
- The ability to accept the Albarran deflector this system used no of thin lenses, same as that of optical lenses.

Characteristics of Ideal Ureteroscope: Over the past decade, we haven't yet developed the ideal flexible ureteroscope.

1. Small rigid ureteroscope have shown to more reliable and longevity.
2. Both the terms durability and continuous production should be maintained.
3. Size must be remained at 7 F or less so it can easily inserted.
4. Visualization of structure can be improved with very fine optical fiber bundle or micro- chips.

Features for Flexible Urethroscopes:

1. Workings length = 65 to 70.
2. Shaft size =< 7.5F.
3. Channel: Smaller in size, about 3.6 F.
4. Weight = lighter in weight.
5. Handle = Ergonomically design for comfort.
6. Imaging = High resolution video.
7. Cost = Available at affordable price [15].

Basics of Laser: Laser word stands for 'Amplification of light by excited emission of electromagnetic Radiation'. Laser is concentrating light beam form by the source of electromagnetic waves.

The main parameters related to the laser are:

1. Pulse time
2. Energy per pulse, the wavelength, and
3. Number of pulses per burst [9]

Construction:

1. Laser contains current generating device used to energies atoms and produce light in medium.
2. A cavity of resonator consisting of pair of mirrors to reflect light back allow to pass through active region. A beam of laser is formed when part of amplified light is escape from the resonating space.

Laser Fiber: The use of low hydroxyl silica optical fibers that are inherently robust, durable and inexpensive fiber use in Ho: YAG laser. These are varied in diameter and core size. It consist of three components:

1. Core
2. Cladding
3. Jacket

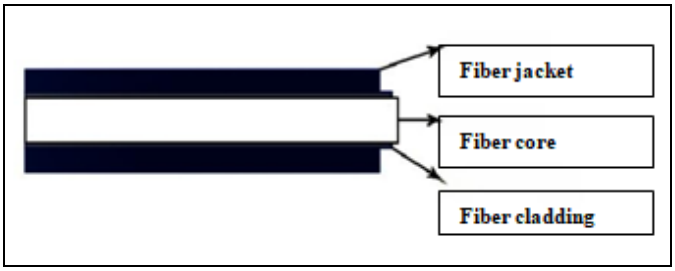

FIG. 1: STRUCTURE OF LASER FIBER

- **Silica Glass Core:** This is core fiber through which laser light travel easily
- The core is surrounded by cladding by the process of reflection of energy with efficient energy transfer.
- Cladding is the outer layer of fiber help in energy reflection in core.
- The jacket or outer coating surrounds core and cladding which provide protection to glass component of fiber [15, 22].

Important Points:

Ho: YAG Laser to Fragments Stones Involved Important Points such as:

1. Laser technique in stone removal procedure has more systematic yielding stone free rate of 92% in review of 21 patients.
2. It can target stones located anywhere within urinary tract however optimum efficacy is noted with calyceal stones treatment.
3. This laser works well with Cystine stone and calcium oxalate monohydrate stones and many other types of stones even in cases in which holmium or thulium laser treatment have previously been attempted.

Choice of Techniques Based on Stone type [3, 13, 20]:

For Renal Stone:

1. Extracorporeal shock wave lithotripsy (ESWL) technique [17].
2. Percutaneous Nephrolithotomy (PCNL) technique.
3. Flexible urethroscopy [20].
4. Active surveillance.

Proximal Ureteric Stone:

1. Extracorporeal shock wave lithotripsy(ESWL) technique.
2. Rigid urethroscopy.
3. Conservative management.
4. Distal ureteric stone.

Conservative Management:

1. Extracorporeal shock wave lithotripsy (ESWL) technique.
2. Rigid urethroscopy [16, 17].

Classification Ureteroscopy:

1. Thulium fiber laser technique.
2. Ho: YAG fiber laser technique.

A. Dusting

B. Painting

C. Chipping

D. Popcorning

E. Fragmentation[19, 23]

Physical Characteristic of HO: YAG Laser and Thulium Fiber Laser: The nucleus of Holmium and thulium atoms consist of 67 and 69 protons respectively. Which make this elements unique from other elements. In periodic table classifies them are rare earth elements. Holiumis a chemical element that was isolated from erbia by swiss chemists '*marc delafontain'* and *Jacques lauissoret* in 1878 and was originally called as 'Element X'. The Swedish chemist *'per theodorcleve'* was working with Erbium oxide in 1879 and found two Different coloured compounds that is brown and Green which further named as holmium and thulium respectively. Both these lasers are the best version which usually presents with trivalent ions and specially used in medicines and lithotripsy [15, 18].

Thulium Fiber Laser Technique: A chemically doped thulium fiber laser is an advanced tool that uses specifically designed thin and long silica fiber that are extremely thin, about 10-20 micrometer in core diameter and long in length. This fiber chemically doped by Thulium ions [19]. Several diode lasers employed for laser pumping in order to excite the Thulium ions. Laser beams are designed to emit 1940nm wavelength, which can perform either continuous mode or adopt a pulsed action in different range of frequency, pulse shape and energy. Based on the study TFL required more time than holmium fiber laser for lithotripsy. And efficiency is accurate due to spectral emission laser diode which matches with absorption line of Thulium fiber [18, 21, 27].

Properties of Thulium Fiber:

- Minimum noise produced by this process.
- TFL has a near single mode beam profile.
- Ability to deliver Pulse energy between 0.025-6 J.
- Power output of this technique up to 500 W.
- A Weight approximately 30 kg.
- Possibility of operating on standard power outlet.
- Its contain an air cooling system.
- A diode source for power.
- Pulse width approximately 200-1100us.
- The ability to operate at frequencies upto 2400 Hz [21].

Advantages:

- It contains a simple cooling system.
- It has a smaller fiber diameter.
- It may reduce irrigation property and enhance visibility of stone.
- Reduced retropulsion.
- It may Increase absorption in water.
- This is the most suitable technique for all kind of stones.
- It's also potential for large stone.
- It may operate at a higher frequency rate.
- Low pulse energy required.
- This may cause little damage to surrounding tissue.
- Shorter lithotripsy time.
- Its required less heat dissipation.
- Can potentially operate at high power > 50W.
- Can operate at high frequency range (upto 2000Hz with forced Air) [21, 28, 29].

Disadvantages:

- There is a insufficiency clinical studies.
- Uncertain cost effectiveness.
- Undefined optimal setting [18, 21].

HO: YAG Laser (Holmium:Yag Laser Lithotripsy): The Ho:YAG laser has been widely accepted has a valuable noninvasive technology for urolithiasis management. There have been utilized lithotripsy method due to simplicity and its

availability hence, The Ho:YAG laser considered as gold standard for intracorporeal lithotripsy over past few decades [19,12, 13].

Key Features of HO: YAG Laser:

1. The Lasers are diplomatic in nature because fragmented all types of stones and allow use of other techniques of lithotripsy
2. Wide margin of safety as compared to other techniques

This laser being operated at a wavelength around 2140 nanometer nearby. It's ideal in an aqueous environment because is absorbed greater energy in water.

Dusting and Fragmentation: Traditional stone fragmentation technique uses higher energy setting (0.6 to 1 J) combining with low frequency (6- 15 Hz).

In this method usually break stones in larger pieces which can then remove easily with basket. Recently however, there has been growing interest in techniques that called dusting uses lower energy (0.2- 0.4J) and higher frequency around (50 -80 Hz) to break the stones into tiny, dust like particles [19].

Goal of dusting:

1. To remove all the fragments to avoid the need to basket Stone.
2. Urethral excess Sheath might be excluded in this case because multiple in /out passage to the kidney is not required.

Advantages of Dusting:

1. This process takes less time and reduces the risk of uretheral injury.
2. Produce small fragments during operation.
3. Avoid continues use of UAS thus reducing risk of urethral trauma.
4. Operated with short intervals of time.
5. No need for an assistant.
6. Avoid continues Post operative standing.
7. It's can offer best therapy in cases of failure of UAS insertion.

Disadvantages:

1. There may increase a chance of further formation of stones if some fragments remain in the body.
2. There is Requirement of alpha generation laser system (Not affordable) inappropriate for hard stones. (eg. Calcium oxalate monohydrate).
3. The percentage of patient who become free from stone is totally depends on skill of physician.
4. Its resulting drainage of fragments in certain cases. *i.e.* spinal cord injury
5. No fragments remain for further evalution [18, 19, 24, 25].

Fragmentation Active Removal: Using fragmentation along with extraction can result to more complete removal of the kidney stone from the start.

Advantages:

1. Use low power consumption in this system (reduce the investment cost required for capital).
2. Ability to withdraw all stone fragments in non-complicated cases.
3. Best option for harder stones.
4. Can send fragments for further analysis.

Disadvantages:

1. Produce large fragments.
2. More time required.
3. Difficult to dispose of because of higher cost involved in disposed.
4. Skilled person required.
5. Chances of ureteral injury from using UAS.
6. Routine urethral standing if using excess health [19, 24].

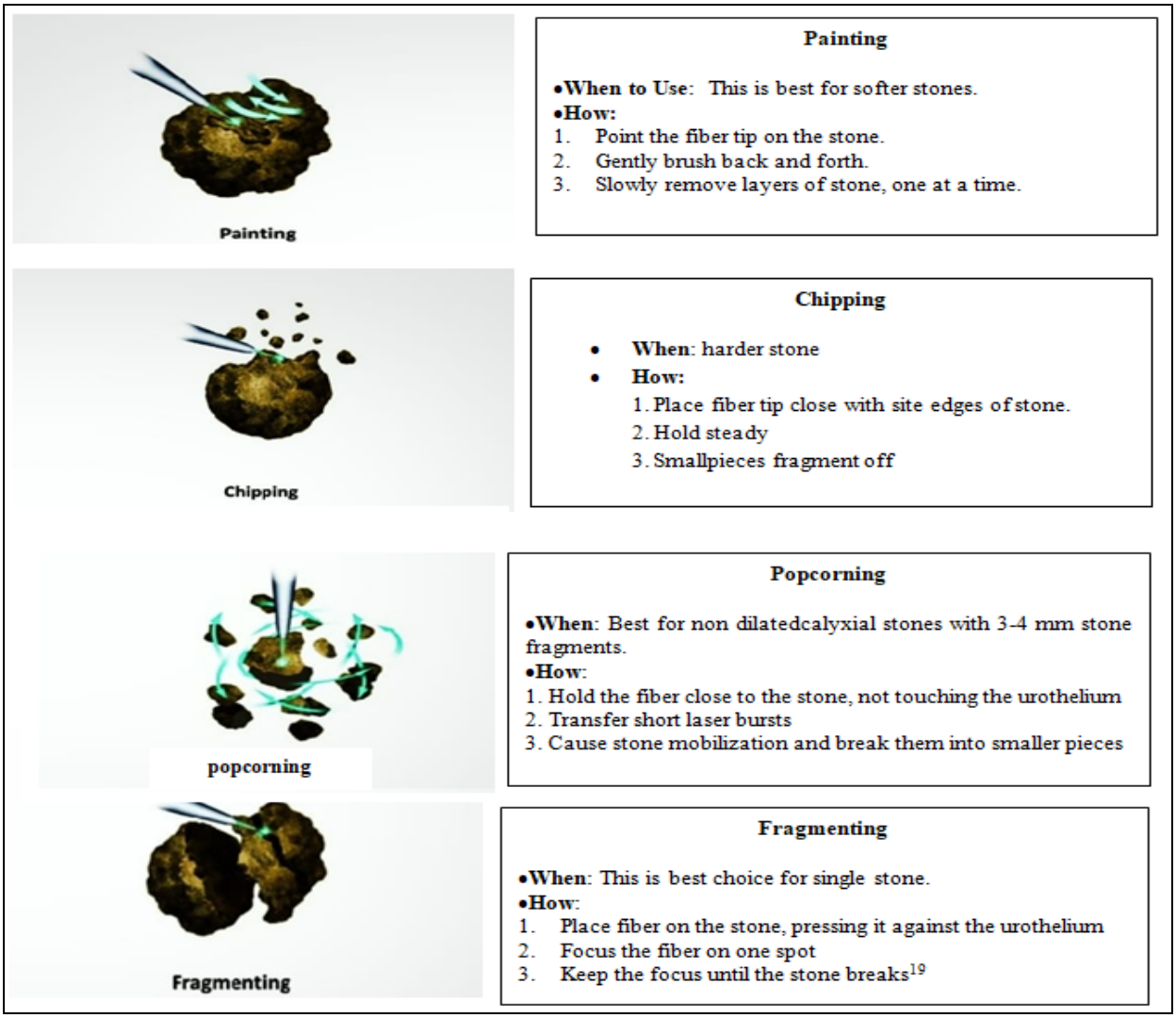

FIG. 2: COMPREHENSIVE STUDY OF STONE REMOVAL TECHNIQUES

TABLE 2: SELECTION OF TECHNIQUE [23]

Stone formation site	(Suitable technique) Fragmentation v\s Dusting	Time interval	Energy setting
kidney	Fragmentation	Short duration	Energy: 0.6 to 1.0 J Frequency:6 to 10Hz
	Dusting	Long or pulse modulation mode	Energy: 0.2 to 0.4 J Frequency:40 to 80 Hz
Bladder	Mixed (residual piece clear with elikevacuator)	Long or pulse modulation mode	Energy: 1.5 to 2.0 J Frequency: 50 Hz
Ureter	Fragmentation	Long or pulse modulation mode	Energy: 0.6 to 0.8 J Frequency: 6 to 8 Hz

TABLE 3: DIFFERENCE BETWEEN HO:YAG LASER TECHNIQUES AND THULIUM FIBER TECHNIQUE [18, 19, 21, 28, 29]

Sr. no.	Ho:YAG laser technique	Thulium fiber technique
1.	Ho:YAG laser can Emit light of Wavelength-approximately- 2100nm or between range of (2090 to 2120) [8]	Light Emitted by TFL's has wavelength tunable between 1810 to 2100nm by fiber laser design
2.	Ho:YAG laser energies are highly absorbed by water radiationat 2900nm wavalengh and absorption coefficient of $\alpha = 31.8 cm^{-1}$	TFL radiation at the 1940 nm wavelength is nearer to absorption peak of water has an absorption coefficient $\alpha = 129.2 cm^{-1}$
3.	Water optical penetration depth is 0.314mm	Water optical penetration depth is 0.077mm
4.	High power Ho:YAG laser consumes 8000-10000 W of electrical power.	TFL consumes about 10 time less with maximum consumption of 800-1000 W hence its more environment friendly.
5.	Maximum pulse frequency is about 120Hz	Maximum pulse frequency is about 2000Hz

CONCLUSION: Due to technological innovations, especially with the introduction of lasers like Holmium and Thulium fiber lasers significant advancements has seen in kidney stone management. These lasers have improved the precision and effectiveness of stone treatment, allowing for minimally invasive procedures which are more efficient and reduce patient recovery time. Holmium lasers have traditionally been founded in kidney stone management due to their stones fragment ability depending on compositions. However, Thulium fiber lasers have recently come into focus due to greater efficiency at lower energy levels and produce finer dust fragments. These technologies not only enhance the precision and efficiency of treatment but also potentially decrease the overall time required for procedures. Techniques like chipping, painting, fragmentation and popcorning have been developed which maximize the effectiveness of the laser treatments also these approaches help to minimize damage to surrounding tissues and reduce the risk of stone recurrence and fine stone particles can pass out naturally. Combining Holmium and Thulium fiber lasers with these advanced techniques greatly improves kidney stone treatment. These lasers allow for more precise and effective stone removal and making the process safer by reducing the risk of stones recurrence. In future we can develop regenerative hydrogel solutions which can encapsulate targeted stones for easier eliminaton of stone or prevent further recurrence of stone formation and also can developed AI monitored smart wearable devices that moniter hydration level in body along with stone composition that helps to user to take preventing action before initiation of stone.

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