Light Amplification by Stimulated Emission of Radiation (LASER)

Editors:

Jessica H. Hannick, MD, MSC

Authors:

Alexander K. Chow, MD; Parth Patel, MD

Last Updated:

Wednesday, February 15, 2023

Keywords:

Laser, energy, holmium, KTP

Summary

- Laser describes the concept of using an external energy to stimulate an active medium that generates emitted photons and buildup of energy.
- Laser effect on a target can vary by adjusting settings including energy (J), frequency (Hz), power (W), power density (W/cm2) and the distance of its delivery to the target tissue
- The photothermal effect on tissue is dependent on the temperature created by laser. Coagulation occurs between 60-100 degree Celsius whereas Vaporizing/Cutting occurs at 150 degree Celsius.
- Most common operator injury are eye injuries (proper eye protection is important) while common patient adverse effects include perforation of urinary tract, mucosal bleeding and skin burns.

1. PHYSICS/INTRODUCTION

Stimulated Emission

The term "laser" refers to a specific type of energy. There are multiple lasers available, all of which have some difference in the way they create and deliver energy, and treat tissue, which is relative to their specific atom. However, they all share similar physics - which must be understood by clinicians as the different laser energies may be better suited, or contraindicated, for each disease state.

The outermost electrons of most atoms are in a resting state. When external energy (i.e. electricity) is delivered to the electrons, they are raised to the next higher energy level. If the external energy is increased even further, the electrons can go to even higher states. As the electron spontaneously returns to its resting state, it emits a photon of energy and wavelength characteristic of the emitting atom (i.e. holmium, neodinium, etc). If the emitting photon strikes another atom already at a higher state, stimulated emission occurs (**Figure 1**). As each of the struck atoms return to their resting states, they emit photons with the same properties of the first and the process continues until the external energy (electricity) is discontinued.

The initiating energy can be electrical, optical, or chemical. Most medical lasers use electricity to create a bright light, which stimulates the active medium. Emission occurs in the active medium of the laser, which is contained within the laser resonator (the laser "box"/unit). The active medium can be solid (Nd:YAG), gas (CO2), liquid (dye), or semiconductor (diode). The laser resonator contains two parallel mirrors-one allows transmission of light (generally opened via a foot pedal) and another that reflects the atoms and stimulated electrons back into the resonator, causing continued stimulated emission and buildup of energy (**Figure 2**). Energy is released in a controlled fashion, generally either in a continuous or pulsed mode depending on the mechanics of the laser unit.

Laser light is delivered one of three ways through a laser resonator (**Figure 3**):

I. Collimated/Nondivergent (always in parallel)
II. Monochromatic (same wavelength)
III. Coherent (waves travel in phase)

Laser characteristics
The effect of Laser energy on a target is dependent upon several characteristics: energy, frequency, power and power density. In addition, how far or close the delivery device is to the target can affect target response, however, this can vary depending on the laser properties.

- Energy: The capacity to do work, expressed in joules (J).
    - 1 watt for 1 sec = 1 joule
- Frequency: the cycles of laser energy delivered over a period of time, expressed in Hertz (Hz)
- Power: The rate at which energy is delivered, expressed in watts (W)
    - J x Hz = watts (i.e. 2J x 50 Hz = 100 watts)
- Power Density: Watts/cm2 (at target surface)

Laser-Tissue Interactions (**Figure 4**)

Laser light can reflect backwards, scatter, transmit or be absorbed. It is the photons that are absorbed that raise the tissue temperature and destroy cells.

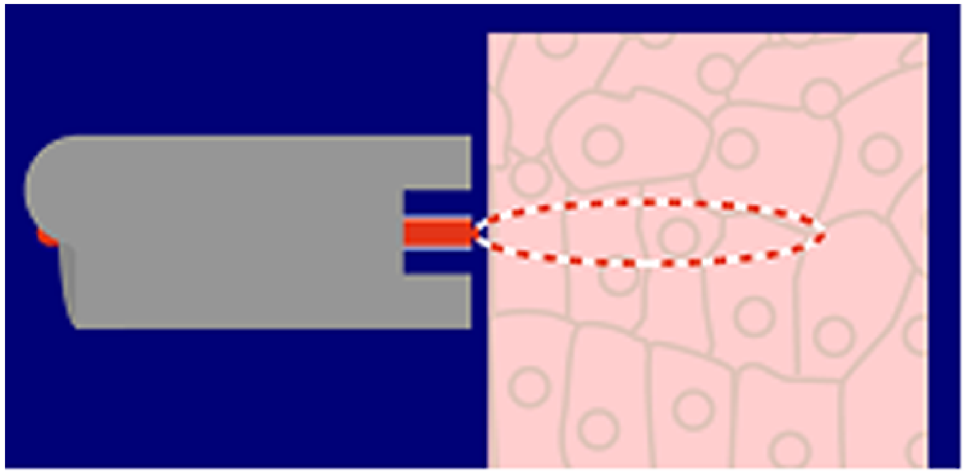
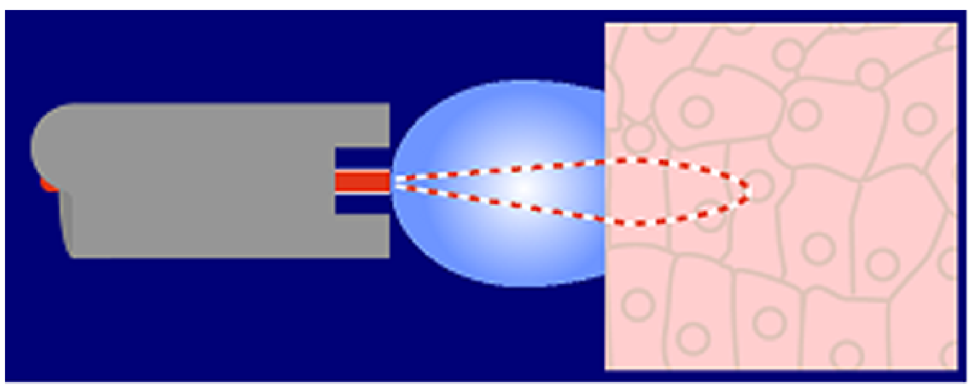
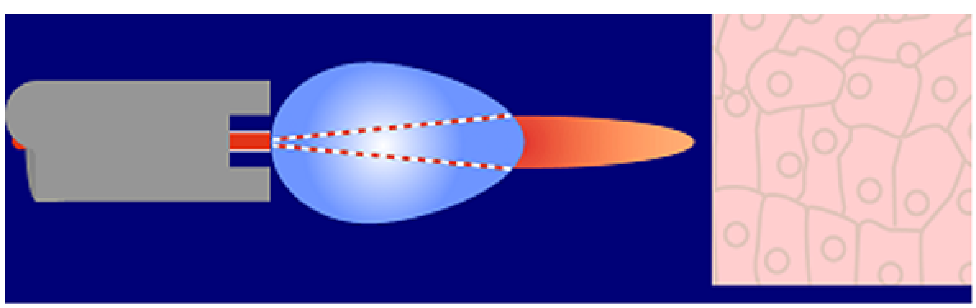
The depth of penetration is the distance in which 90% of laser energy is deposited and is what is generally used to define how "deep" a particular laser can heat tissue. However, dependent upon the chromophore of the laser (the entity which absorbs the energy), 10% may travel deeper than the "zone of penetration".

As stated, the goal is to heat the tissue. How hot the tissue gets will affect the results (**Figure 5**). For example, in order to vaporize tissue, the temperature must reach 150 degrees Celsius. See **Table 1** for biological effect of tissue with varying temperature generated by Laser.

Table 1: Photothermal Effects	
Temperature Threshold	**Biological Effect**
37° C	Body Temperature
45° C	Hyperthermia
60° C	Coagulation†
100° C	Vaporizing/Cutting‡
150° C	Carbonization
300° C	Melting

† *Near Tissue Contact*
‡ *In contact with tissue*

Table 2: Photothermal Effects

Description	Image
Closer to target = more cutting effect	 Table Image 1: Closer to target = more cutting effect.
Farther away results in coagulation	 Table Image 2: Farther away results in coagulation.
Outside penetration zone = no effect	 Table Image 3: Outside penetration zone = no effect.

The wavelength of laser photons affects tissue interactions (**Figure 6**). Tissue has different absorption coefficients for each wavelength. Important tissue characteristics that affect absorption include hemoglobin, pigmentation content and chemical composition. Laser energy travels to its "chromophore" - i.e. water, blood cells, dark pigment. Once at its chromophore, the energy is absorbed and the tissue heats up.

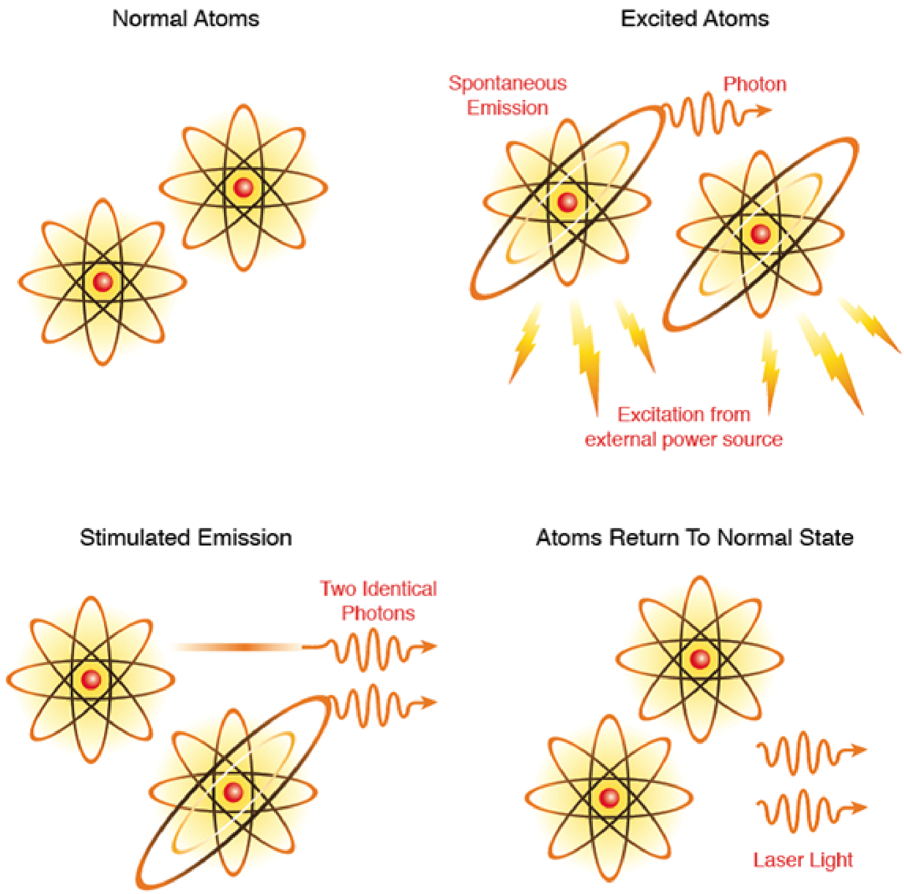


Figure 1: Stimulated Emission.

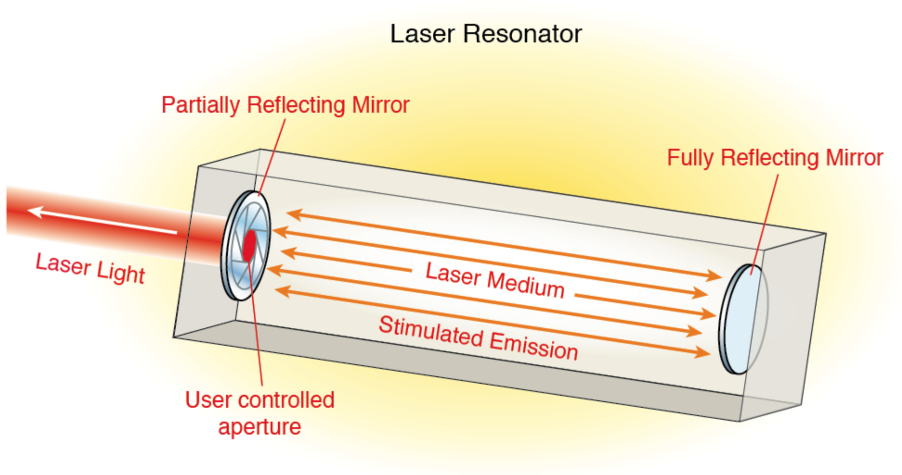


Figure 2: Laser Resonator.

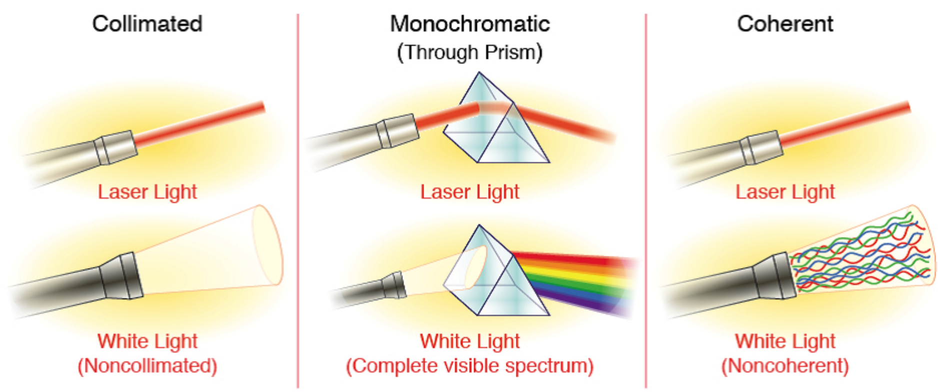


Figure 3: Laser Light Characteristics.

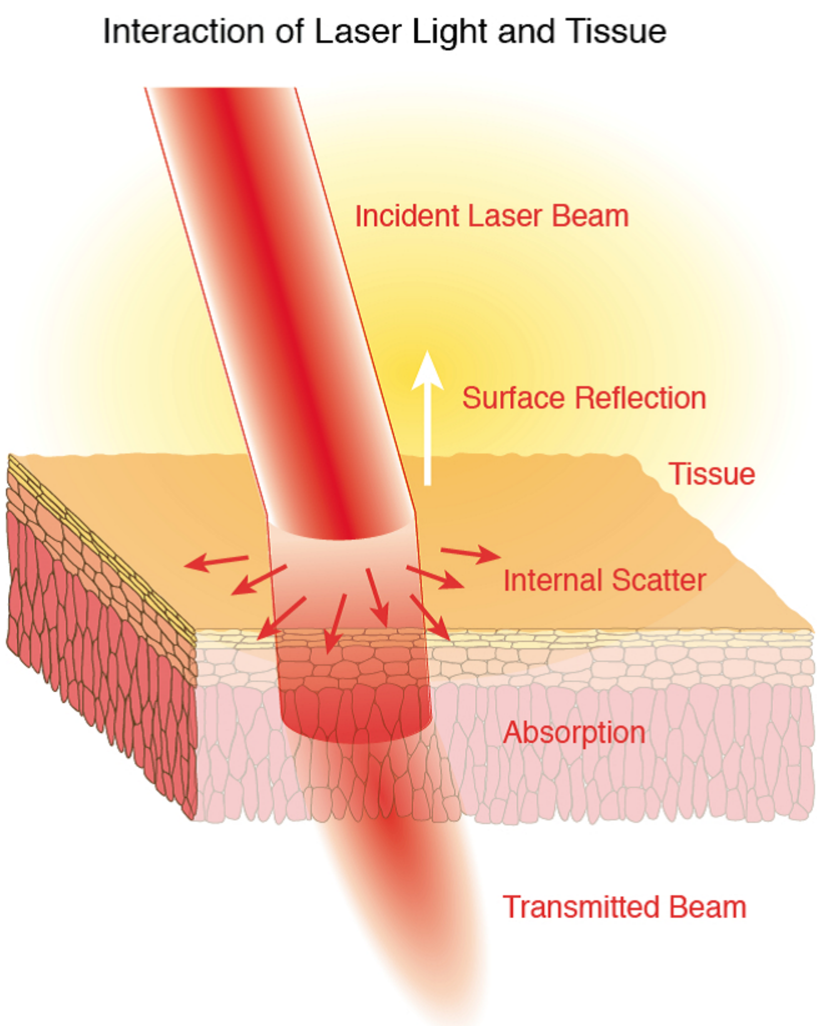


Figure 4: Laser light interactions on tissue.

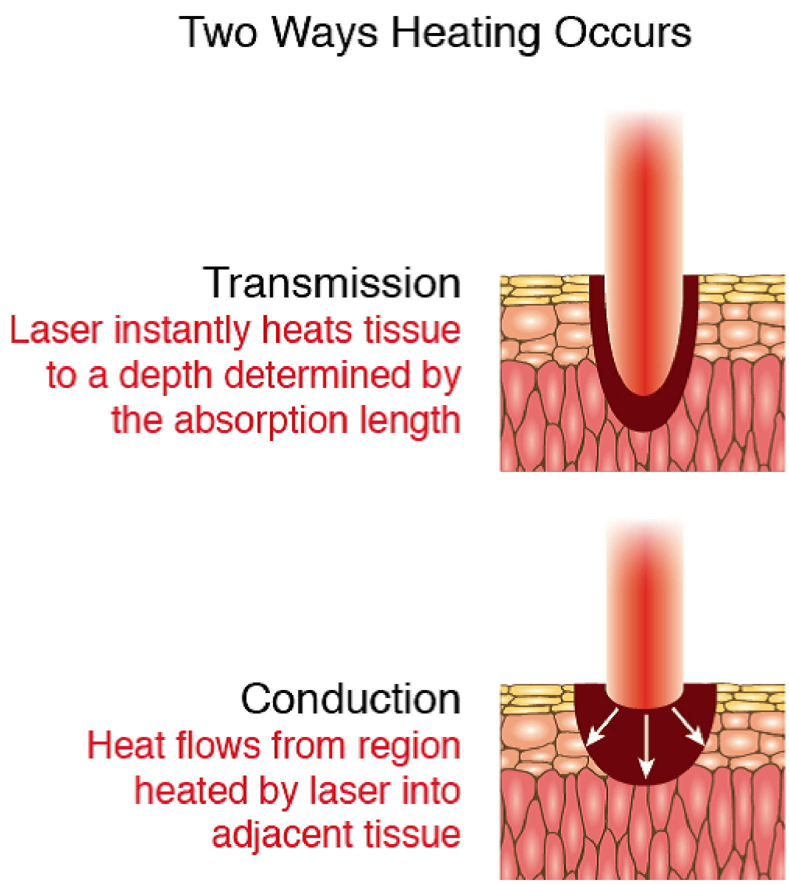


Figure 5A: Heating of the target (Two Ways Heating Occures).

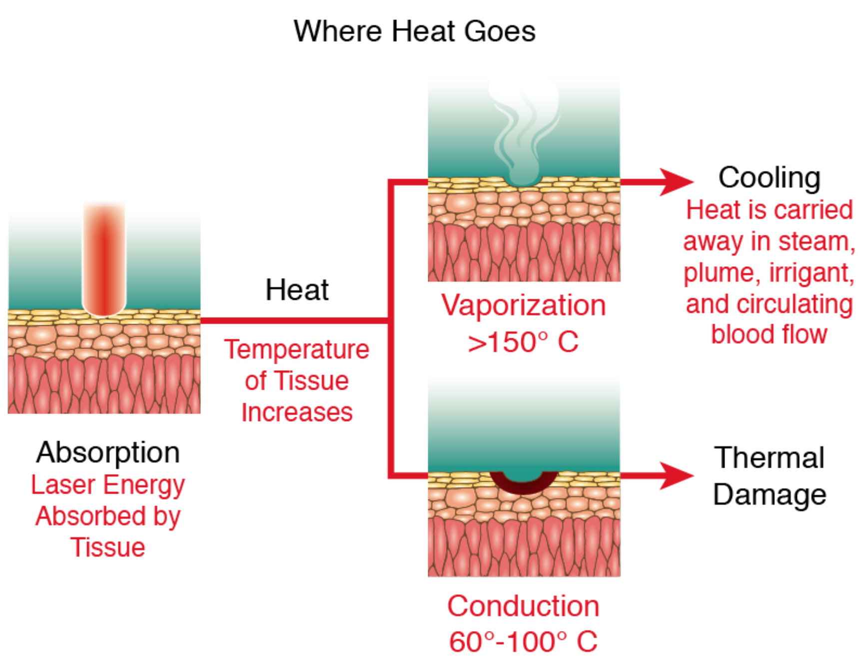


Figure 5B: Heating of the target (Where Heat Goes).

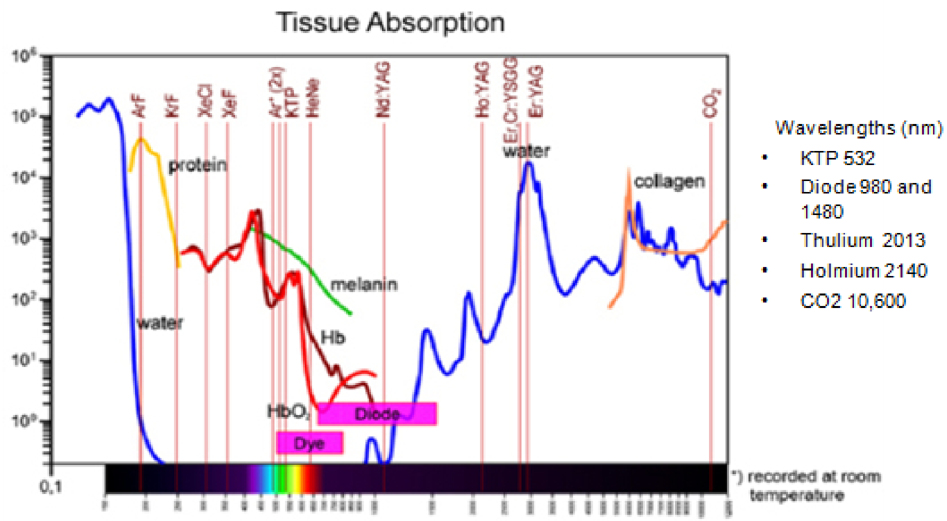


Figure 6: Wavelengths of typically used urologic lasers

2. MECHANISM OF DELIVERY

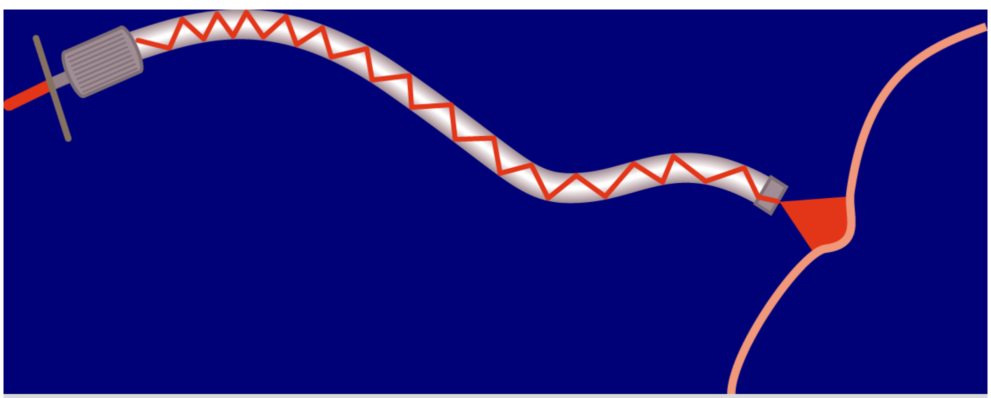


Figure 7: Laser energy "bouncing" down the fiber.

Energy is delivered via laser fibers. These can be either end fire, where the energy is emitted through the tip, or side firing, where the energy is discharged at an angle. Fibers come in different sizes, which vary by device. Energy is stored and released in a pulsed or continuous fashion (again dependent upon the specific laser device), controlled by a foot pedal. Energy travels along the laser fiber through internal reflection that "bounces" the energy down the fiber (**Figure 7**). The surgeon controls precision and tissue effect by directing the laser energy where they wish it to go.

3. SAFETY

Improper use, lack of safety equipment, and device failure can all result in adverse events (AEs). AEs can affect the surgeon, patient, operating room personnel, and/or endoscopic equipment. Eye injuries, contact skin burns, electric shock, and injuries related to fires have all been reported consequent to the use of medical lasers. Any of these adverse perioperative events should be reported to either the FDA's Manufacturer and User Facility Device Experience (MAUDE) database, or to the Rockwell Laser Industries (RLI) Laser Accident Database.

Protective, wavelength-specific eyewear for the operating physician and those working with the fiber is recommended. For the patient, having the eyes closed, or blocked by a sheet, is sufficient. Most machines are key controlled and easy to use. Regular inspection and maintenance is essential to ensure proper functioning. Lasers contain different internal protective devices that lead to automatic powering down of the laser if it isn't working or cooling properly. For those lasers that contain blast shields, replacements should be kept in stock. The laser unit/resonator should be kept in a cool environment and free of moisture. For water based lasers, internal steam/condensation can lead to absorption of energy and lead to blast shield disruption.

Several societies have specific guidelines for laser safety, including: American National Standards Institute (ANSI); American Society for Lasers in Medicine and Surgery (ASLMS); Laser Institute of America (LSA); National Fire Protection Association (NFPA); National Institutes of Health (NIH); National Institute for Occupational Safety and Health (NIOSH); and Occupational Safety and Health Administration (OSHA).

4. DEVICES- Most commonly utilized urologic lasers

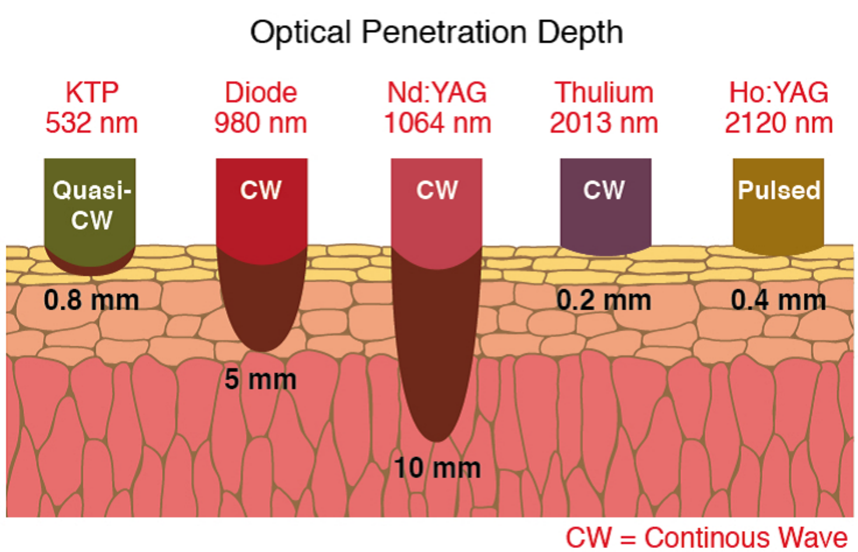


Figure 8: Optical Penetration Depth of Commonly Utilized Lasers in Urology.

1. *KTP- Potassium titanyl phosphate*
    - 532 nm wavelength
    - Visible (Green) light

- 80/120/180 watt units available
- Absorbed by hemoglobin
- Low absorption by water
- Optical penetration 0.8 mm
- Coagulation depth 1-2 mm
- Continuous wave delivery of energy
- Side fire laser fiber
- Generally used to ablate the prostate, but has also been described for bladder tumors and hemorrhagic cystitis by experienced urologists.

2. *Diode*
   - 980 and 1470 nm wavelength
   - Absorbed by water and hemoglobin (higher wavelength more water than hemoglobin)
   - Maximum power output 200 watts
   - Depth of penetration 5 mm
   - Continuous and pulsed energy delivery
   - Side fire contact or bare fiber
   - Mostly used for ablating prostate
3. *Nd:YAG*
   - 1064 nm wavelength (near infrared)
   - Absorbed by oxyhemoglobin
   - Deepest penetration amongst clinical lasers (depth 5-10 mm)
   - Continuous or pulsed
   - Unpredictable zone of coagulation
   - Rarely used today in urology, but could be used for a large hemorrhagic prostate
   - Highest risk of potential adverse effects to operators (eye injuries) and patients.
4. *Thulium*
   - 2013 nm wavelength
   - Diode pumped solid state laser (DPSS)
   - Revolix 50W, 70W, 120W, 200W
   - Revolix Junior 15W, 30W
   - Absorbed by water
   - Penetration depth 0.2 mm
   - Continuous wave or pulsed mode energy release
   - End or side fire fibers
   - Used in the prostate
   - Increasing popularity in treatment of urolithiasis with higher efficiency for stone dusting when compared to Holmium laser.[1]
   - Compared to Holmium:YAG
     1. Thulium operates with a smaller laser fiber (50-150 µm core diameter),
     2. Thulium has a four fold higher absorption coefficient in water, lower energy per

pulse, and higher maximal pulse repetition rate. This translates to 1.5-4x faster stone treatment in multiple in vitro studies.[2]

5. *Holmium:YAG*
    - 2140 nm wavelength (non visible/infrared)
    - High absorption in water and fluid is useful for endourology; must be in contact, or very near target, to have an effect.
    - Penetration depth 0.4 mm
    - Safe > 0.5 mm from target in fluid environment
    - Pulsed energy release
    - Works via the Moses Effect - Because Holmium laser energy is well-absorbed in water, when it is released in a water-filled environment (like endourology) it creates a vapor bubble in the water. This is known as the "Moses Effect" since the water is parted by the bubble that forms.
    - End fire or side fire options
    - Multiple applications for Holmium in urology, such as prostate, stones (the current gold standard), strictures, bladder tumor.
    - Cuts, coagulates and fragments all stone compositions via its pulsed mode
6. *Carbon Dioxide*
    - 10,000+ nm wavelength
    - 15 and 25 watt systems
    - Absorbed by water
    - Very shallow penetration at 0.1 mm
    - Continuous wave, pulse, and super pulse operation modes
    - Articulating arm with end fire energy delivery
    - Used for skin lesions, such as genital warts

5. CLINICAL USE/PROCEDURES

- Prostate Reduction (KTP, Holmium, Nd:YAG, Diode, Thulium)
    - Ablation/Coagulation (KTP, Holmium, Thulium)
    - Enucleation (Holmium, Thulium)
- Bladder Tumors (KTP, Holmium, Diode, Thulium, Nd:YAG)
- Upper Tract Urothelial Carcinoma (Holmium, Nd:YAG, Thulium)
- Radiation Cystitis (Holmium, Nd:YAG)
- Ureteral/urethral strictures (Holmium, Thulium)
- Infundibular stenosis (Holmium, Thulium)
- Stones: Bladder, Ureter, Kidney (Holmium, Thulium)
- Genital warts (CO_2)

Please refer to the following Core Curriculum chapters for additional information on clinical application of LASER:

- **Surgical Stone Disease (section 9.1)**
- **Surgical BPH (section 4.1-4.3)**

6. COMPLICATIONS

Injuries can result from equipment failure, errors in technique, and an inadequate understanding of the properties of the particular laser being used. Althunayan et al (2013) looked at all the reported complications relevant to urology in the RLI and MAUDE databases; the former represents primarily research-related AEs from 1964-2005 while the latter is only clinically related AEs from 1992-2012. Of the 433 AEs reported, 46% were due to generator failure or tip breakage-for example, small bore (200μ -272μ) laser fibers fired within flexible ureteroscopes at severe deflection angles. The Nd:YAG, which is rarely used in the modern era, accounted for 48% of the events. However, there were 164 eye injuries to the laser operator ranging from corneal abrasion to blindness due to inadequate or improper eye protection associated with Nd:YAG, KTP and diode but not Holmium lasers. This may be due to the fact that Holmium laser energy is absorbed by water whereas the others are absorbed by oxyhemoglobin. Finally, 8.3% of the AEs represented harm to the patient including 7 mortalities directly related to laser use. Four were due to air emboli generated from the Nd:YAG (from 1987-1990), however 3 were due to ureteral perforation by the Holmium laser causing intractable retroperitoneal bleeding (from 2003-2005). Other intraoperative injuries included bladder perforation, skin burns and significant mucosal bleeding.

Proper education and knowledge of the differences between the various laser energies is essential in order to reduce risk of complications. Movement of laser fibers (slow vs fast) varies depending on the laser wavelength and chromophore, meaning that techniques are different when applying different energies. Improper use can lead to under/over treatment of tissue and potentially lead to injury (long dwell times for certain lasers can cause deep tissue damage/injury).

Commonly reported long-term complications associated with lasers include:

1. Prostate reduction surgery: incomplete tissue removal which may require retreatment, severe irritative symptoms, sexual dysfunction, incontinence and bladder neck contracture (due to excessive coagulation). These are likely related to technical errors. Damage to the ureteral orifices has also been reported.
2. Upper Tract Urothelial Carcinoma/Stones: Aggressive lasering within the ureter can result in ureteral damage leading to scarring, fibrosis and stricture formation. Pulsed modes and cool irrigation fluid may reduce collateral thermal damage.

Videos

Presentation Video 1

Presentations

References

1 Panthier F , Doizi S, Berthe L, et al. In vitro comparison of ablation rates between superpulsed thulium fiber laser and ho:YAG laser for endocorporeal lithotripsy. 2020 European Association of Urology Virtual Congress. July 17-26, 2020. Abstract PT131.

2 Traxer O, Keller EX. Thulium fiber laser: the new player for kidney stone treatment? A comparison with Holmium:YAG laser. World J Urol. 2020 Aug;38(8):1883-1894.

3 Althunayan AM, Elkoushy MA, Elhilali MM, Andonian S. Adverse events resulting from lasers used in urology. J Endourology 2014. PMID:24074324.

4 American Society for Laser Medicine and Surgery: Procedural Skills for Using Lasers in General Surgery. http://www.aslms.org/public/standardpsgs.shtml. Accessed September 28, 2013.

5 Association of Surgical Technologists: AST Recommended Standards of Practice for Laser Safety. http://www.ast.org/pdf/Standards_of_Practice/RSOP_Laser_Safety.pdf. Accessed September 28, 2013.

6 Grasso M, Fishman AI, Moscowitz EJ, Green DA. Lasers in Urology (Medscape). http://emedicine.medscape.com/article/445722-overview. Accessed September 24, 2013.

7 Hermann TR, Liatsikos E, Nagele U et al. EAU guidelines on laser technologies. Eur Urol 2012; 61: 783.

8 Johnson DE, Cromeens DM, Price RE. Use of the holmium:YAG laser in urology. Lasers Surg Med 1992; 12: 353.

9 Nazif OA, Teichman JM, Clickman JM et al. Review of laser fibers: A practical guide for urologists. J Endourology 2004; 18: 818.

10 Pierce JS, Lacey SE, Lippert JF et al. An assessment of the occupational hazards related to medical lasers. J Occup Environ Med 2011; 53: 1302.

11 Teichmann HO, Hermann TR, Bach T. Technical aspects of lasers in urology. World J Urology 2007; 25: 221.

12 Rockwell Laser Industriesâ€”Laser Accident Database: http://www.rli.com/resources/accident.aspx. Accessed October 4, 2013.

13 US FDA: MAUDE - Manufacturer and User Facility Device Experience. http://www.accessdata.fda.gov/scripts/cdrh/cfdocs/cfmaude/search.cfm. Accessed October 3, 2013.