Basic Principles of Laser for Prostate Surgery

Jin Wook Kim, Du Geon Moon

Department of Urology, Korea University Guro Hospital, Korea University Institute of Regenerative Medicine, Seoul, Korea

= Abstract =

Recent advances in laser technology have provided a varied arsenal for endoscopic treatment of benign prostatic hyperplasia. Laser is a collimated coherent radiation of photons generated by stimulated emission of gain media, allowing transfer of selective, controlled and focused energy to the targeted tissue. The application of laser to prostate surgery developed hand-in-hand with refinements to the equipment. Earlier lasers were low powered modalities with no significant tissue selectivity, aimed at thermal coagulation and resulted in significant side effects and recurrence. Since then, prostate lasers have developed towards a more high-powered and selective modality that allowed complete ablation of the tissue with fewer complications. Fiber technology has also developed to allow efficient and safe transfer of a continuously increasing energy output. It is important for the surgeon to understand these fundamental principles of laser and prostate surgery, not only to select the proper tools, but also to properly implement the technique as well.

Key Words: Prostatic hyperplasia, Laser therapy, Solid-state lasers

Introduction

Laser surgery represents a method for delivering precise controlled high levels of energy to relatively specific targets. Since the introduction of laser for practical use, the field of urology actively accepted its clinical applications. In the prostate, laser was widely adopted as a method to aid in reducing bleeding, effectively removing tissue without significant injury to the surrounding tissue for patients with benign prostatic hyperplasia (BPH).

The theoretical outline of the laser was first established by Einstein in his seminal paper “Zur Quanten-
theorie der Strahlung” in which he described the basis of stimulated emission of electromagnetic radiation. It was not long after that several applications were presented, beginning with the MASER (Microwave amplification by stimulated emission of radiation) at Bell laboratories by Townes. Later the application of this principle to the visible spectrum was suggested independently by several researchers. In 1959, Gould proposed the acronym LASER (Light Amplification by Stimulated Emission of Radiation). However, it was in 1960 when Maiman completed the first functional laser, using ruby crystals as the gain medium.

While the ruby crystal lasers were introduced to clinical applications early in the history of medical lasers, development of prostate lasers was not actively pursued until the 1990s. Early attempts included the initial clinical approach to prostate laser surgery began with Costello’s use of the Nd:YAG laser. However, initial applications were fraught with difficulties, mainly from technical shortcomings. Recent development of prostate laser surgery has allowed us access to sev-
eral different types of lasers and their appropriate methods of application. With such variety of choices, it is important for the surgeon to not only to be familiar with the basic principles behind its application, and to understand the difference between the various lasers and its peripherals, but more importantly to properly familiarize oneself with the proper method of surgical application based on such knowledge.

1. Principles of Laser

Laser is a device which emits monochromatic, collimated, coherent light by stimulated emission from a gain medium. The gain medium of the laser is stimulated by an external energy source, which is typically an arc light or, in some cases, another semiconductor laser. When stimulated, electrons in the gain medium are excited to a higher energy state. If sufficient energy is applied, the electrons become more populated in a higher energy state than the resting state, achieving population inversion. Light passing through the activated gain medium stimulates the release of electrons from the high energy state back to resting state, releasing electromagnetic radiation corresponding to the difference in quantum energy levels. Light is amplified as the output from the gain medium is greater than the light absorbed. Furthermore, light is repeatedly passed through the gain medium by parallel reflectors, forming an optic resonator (Fig. 1).

The frequency of electromagnetic radiation output is determined by the excitation state achieved by the gain medium, as well as further dopates that modify the energy response. Typically yttrium aluminum garnet (YAG) crystals are used as a solid gain medium for prostate lasers. Rare earth elements, such as neodymium, holmium and thulium are used as dopates to modify the energy level. The frequency of the laser is determined by the difference in quantum orbital states of excitation and resting, and is thus constant and monochromatic.

Wavelength characteristics also affect how the laser interacts with the target tissue. Wavelength determines how much energy is diffracted in the irrigant, how much energy is absorbed by the target tissue, and how much energy penetrates to what depth of the tissue, as well. More importantly, wavelength determines which types of tissue may better absorb the light energy, and influences the proportion of energy converted to heat. In some tissues, substances react to specific wavelengths, better absorbing laser energy. These substances, called chromophores, may include biological substances such as melanin, hemoglobin, bilirubin, porphyrin, carotene, and even common substances like water. In the prostate, hemoglobin and water are the major chromophores.

Another important variable in the application of laser is laser power. Power influences the amount of energy transfer to the tissue, resulting in varying tissue effects between coagulation, vaporization and even mechanical tearing. The amount of energy transfer, dictated by power, results in different levels of temper-
ature achieved within the tissue (Table 1, Fig. 2).

The power generated from the laser is also expressed in the mode of emission, either as a continuous wave or a pulsed wave based on power output by time scale. To generate a continuous wave it is required for population inversion of the gain medium to be continually replenished by a steady pump source. Some laser gain media cannot achieve a high output continuous wave sufficient for vaporization, as it would require pumping the laser at a very high continuous power level that would destroy the gain medium by producing excessive heat. Alternative methods are used to modulate pulsed frequencies to either achieve higher peak output, using Q-switching, or maintaining semi-continuous output by pulse pumping. While continuous wave lasers can achieve a constant controlled clinical interaction with the tissue, pulsed wave laser can deliver forceful bursts of laser, which is now primarily used for fragmenting stone.

The interaction of laser with tissue results in a series of fundamental optical phenomena that integrates to form a characteristic profile of each laser. Reflection occurs as the laser beam strikes the tissue surface due to difference in refractive indices of the irrigation fluid and prostate tissue. For the Nd:YAG laser, approximately 50% is reflected due to the sudden change in refractive index. Laser energy also scatters on contact with the irregular tissue surface. Scattering may occur either in a forward or backward direction. Only non-reflected and non-absorbed forward scattering photons are transmitted to either be absorbed or transmitted by the tissue. Wavelength is the primary variable in all of these interactions, as it governs the index of refraction, as well as absorption and scattering coefficients.

In a practical sense, laser tissue interactions can be summarized by two characteristic parameters, absorption coefficient (AC) and the extinction length (EL). A higher AC denotes greater absorption of energy by the tissue, while a lower AC indicates significant transmission of energy to underlying structures. Extinction length is defined as the depth of tissue at which energy transmission is reduced by 90%. It is generally considered the depth to which laser energy directly affects the tissue. Furthermore, a short extinction length indicates high energy density, leading to a propensity for tissue ablation, while a longer extinction length indicates lower energy density and a propensity for tissue coagulation (Fig. 3).

### Table 1. Different tissue effects appear by level of energy transfer

<table>
<thead>
<tr>
<th>Temperature Range</th>
<th>Effect</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt; 40°C</td>
<td>Photobiomodulation</td>
</tr>
<tr>
<td>42 ~ 45°C</td>
<td>Hyperthermia</td>
</tr>
<tr>
<td>45 ~ 50°C</td>
<td>Desiccation</td>
</tr>
<tr>
<td>50 ~ 100°C</td>
<td>Coagulation, irreversible</td>
</tr>
<tr>
<td>&gt; 60°C</td>
<td>Protein denaturation</td>
</tr>
<tr>
<td>&gt; 100°C</td>
<td>Carbonization, vaporization</td>
</tr>
</tbody>
</table>

**Fig. 2.** Tissue effect can also vary with the depth of penetration, due to different levels of temperature achieved within the affected zone.

**Fig. 3.** Laser wavelength and mode of emission can affect the depth of penetration, leading to a varied profile of energy density (HPS: high performance system, CW: continuous wave).
Difficulties had to be overcome. The most important technical aspect was finding the right laser to achieve effective ablation with few side effects. The initial development began with the widely used Nd:YAG laser, and progressed towards achieving more powerful output, more effective power usage, and safer treatment outcomes (Table 2, 3).

1) Nd:YAG laser: Treatment of prostate using lasers was first introduced in 1986. However, it was with the introduction of side-firing Nd:YAG laser in the early 90s that achieved a more widespread use. The 1,064 nm was used to perform visual laser ablation of the prostate (VLAP). The Nd:YAG laser, though currently fallen out of favor, represents the first foray into laser surgery for prostatic enlargement. The 1,064 nm wavelength of this laser penetrates tissue up to 10 mm. Early VLAP involved a 40 W laser directed at right angles to the prostatic tissue. Compared to TURP, the VLAP was safe to perform on patients taking anticoagulants, and carried no risk of developing TUR syndrome. However, due to the low energy absorption, tissue temperatures seldom rose above 65°C, resulting in broad tissue coagulation. Sloughing off of necrotic tissue followed treatment up to 6 months, accompanied by dysuria, and patients often required prolonged catheterization.

A different approach used the Nd:YAG fiber in contact with the tissue, as energy delivery is increased with decreasing breadth between the fiber and tissue, contact of the fiber could achieve vaporization. However, with the limited power output, tissue ablation was too slow, and the procedure was limited to smaller lesions (<40 ml).

Finally, interstitial laser coagulation (ILC) allowed for treatment of larger volumes by repeatedly inserting the fiber within the tissue, creating coagulation necrosis without sloughing, and even preserving the urothelium. Despite these innovations, ILC showed

Table 2. Prostate laser developed from the early low power Nd:YAG to the contemporary modalities through increased power and optimized wavelengths

<table>
<thead>
<tr>
<th>Year</th>
<th>Method</th>
<th>Laser</th>
</tr>
</thead>
<tbody>
<tr>
<td>1917</td>
<td>Theory of stimulated emission of electromagnetic radiation</td>
<td>Ruby</td>
</tr>
<tr>
<td>1960</td>
<td>First functional Laser</td>
<td>Nd:YAG</td>
</tr>
<tr>
<td>1993</td>
<td>VLAP</td>
<td>Nd:YAG + Ho:YAG</td>
</tr>
<tr>
<td>1994</td>
<td>CELAP</td>
<td>Nd:YAG, Diode (70 W)</td>
</tr>
<tr>
<td>1995</td>
<td>ILC</td>
<td>Ho:YAG</td>
</tr>
<tr>
<td>1995, 1996, 1997</td>
<td>HoLAP, HoLRP, HoLEP</td>
<td>Tm:YAG, KTP (60 ~ 80 W)</td>
</tr>
<tr>
<td>1998</td>
<td>PVP</td>
<td>Diode (120 ~ 200 W, 980 nm)</td>
</tr>
<tr>
<td>2005</td>
<td>Thulium laser resection of prostate</td>
<td>HPS: KTP or LBO (120 W)</td>
</tr>
<tr>
<td>2007</td>
<td>Laser vaporization of the prostate</td>
<td>HPS: KTP or LBO (120 W)</td>
</tr>
</tbody>
</table>


Table 3. Different lasers are characterized primarily by wavelengths. However, interactions with different chromophores, and modes of generation also affect tissue interactions and depth of tissue effect.

<table>
<thead>
<tr>
<th>Wavelength (nm)</th>
<th>Chromophore</th>
<th>Extinction length (mm)</th>
<th>Wave mode</th>
<th>Tissue interaction</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nd:YAG</td>
<td>1,064</td>
<td>-</td>
<td>10</td>
<td>Pulse or CW</td>
</tr>
<tr>
<td>Ho:YAG</td>
<td>2,100</td>
<td>Water</td>
<td>0.4</td>
<td>Pulse</td>
</tr>
<tr>
<td>KTP</td>
<td>532</td>
<td>Water</td>
<td>0.8</td>
<td>Quasi-pulse</td>
</tr>
<tr>
<td>Tm:YAG</td>
<td>2,000</td>
<td>Hemoglobin</td>
<td>0.25</td>
<td>CW</td>
</tr>
<tr>
<td>Diode</td>
<td>940/980/1,470</td>
<td>Water and hemoglobin</td>
<td>Variable</td>
<td>Pulse or CW</td>
</tr>
</tbody>
</table>

CW: continuous wave.
poor results with urinary infection rates as high as 35%, and retreatment at 1 year as high as 15%.

The fundamental limitation of the Nd:YAG laser and its 1,064 nm wavelength was its lack of corresponding tissue chromophores, which could enhance absorption despite its limited output and thus effectively achieve vaporization.

2) 532 nm photovaporization: The GreenLight laser photoselective vaporization (American Medical Systems, Minnetonka, MN) was introduced by Malek in 1998.16 The KTP is often hailed as a milestone in achieving a safe and effective prostate laser treatment through reliable tissue vaporization. The wavelength of KTP is achieved by "frequency doubling" the Nd:YAG laser. Frequency doubling involves a primary pump laser that is passed through a secondary nonlinear crystal which creates a secondary harmonic wave that is doubled in frequency. The energy conversion rate is generally high, with most frequency doubled energy at least 50% of the primary input, and in some laser achieve above 80%.17 Hence, with the Nd:YAG laser transformed by KTP crystals, the frequency is modified from 1,064 nm to 532 nm. While the power of the output itself is decreased in comparison to the Nd:YAG laser, the KTP laser compensates by interacting with hemoglobin as a chromophore (Fig. 4).18

The 532 nm KTP laser is fully transmitted through the irrigant and highly absorbed in the tissue by oxyhemoglobin in the vessels. This allows energy to be highly transferred to tissue with high oxyhemoglobin content, such as prostatic tissue. With selective absorption of wavelength, high tissue energy density is achieved, and tissue temperatures can be successfully elevated above boiling temperature, inducing immediate vaporization. As most of the energy is dissipated with vaporization, and tissue depleted of chromophore form a barrier of inefficient energy transfer, the extinction length is significantly reduced to 0.8 mm.19 Because of the efficacy of tissue vaporization, side-firing laser ablation with KTP is referred to as 'photovaporization of the prostate' (PVP).20

The initial KTP laser to gain popularity was the 80 W lasers delivered by side-firing fibers through a 23 F continuous flow cystoscope with normal saline irrigant.21 The initial models conveyed the laser beam on pulsed wave, which compensated for the low power output of the original Nd:YAG lasers that were further burdened by energy loss from frequency doubling, by Q switching.4 The shortcomings of the initial models were evident when the working distance increased and laser beams were diffracted, resulting in coagulation rather than vaporization.16 Surgeons were advised to maintain a 0.5 mm working distance, termed "near contact", for effective vaporization.

Improvements in power output has seen progression

Fig. 4. Chromophores allow selective absorption of specific wavelengths, vastly improving the tissue effect of certain lasers. Early Nd:YAG lasers are generally nonspecific to either water or hemoglobin. Modern green light lasers are highly absorbed by hemoglobin, while modern infrared lasers are highly absorbed by water.5

Fig. 5. Increased power allows the beam to be more collimated. The tissue laser interaction not only benefits from more power, but also from a more focused high intensity transfer of energy (HPS: high performance system, PV: photo vaporization).44
from the prototype 60 W continuous wave to the 80 W Q switching pulsed wave to the 80 W continuous wave, and currently the 120 W high performance system (HPS). Modern HPS uses lithium triborate (LBO) crystals, instead of KTP, for frequency doubling. The arc light as pump energy has been replaced with diode lasers allowing higher output without over heating the gain medium. The improved output allowed a working distance of 3~4 mm, while diode laser pump allowed for adjustable power outputs for either coagulation or vaporization (Fig. 5).

Increase power output has also allowed for larger prostates to be treated. The prototype 60 W laser was limited to treat prostates up to 60 g in a reasonable time period. Improved vaporization speed with 80 W lasers allowed vaporization of 80 g prostates in 1 hour.22 For larger prostates above 100 g, Sandhu et al reported mean operation times of 123 minutes, and re-operation rates of 5% at 1 year. Recently, long term follow up reports, average 30.6 months, showed sustained voiding parameter improvements and no relationship with prostate volume.24 Retrograde ejaculation (33%) is the most common complication in most long term reports, however transfusion is rarely necessary and reoperation rates are 0~7% at 5 years.25-27 The newer 120 W HPS lasers have yet to report long term results. Recent reports of 120 W laser, however, suggested that the high power also resulted in decreased hemostatic ability.28 In such cases, modulation to lower power settings may be useful.

3) Ho:YAG laser: The use of holmium as the main dopate for YAG crystals was an early development, initially used for treating urinary calculi. Holmium lasers also require addition of thulium and chromium to stabilize laser generation, as holmium alone results in severe overheating of the crystal. The benefit of Ho:YAG as a gain medium was its 2,140 nm infrared wavelength that was absorbed by water. Since the tissue is composed mainly of water, the majority of the holmium energy is absorbed superficially. The absorption depth in prostatic tissue is 0.4 mm, resulting in tissues being heated above boiling temperature, leading to immediate vaporization without deep coagulation.29 Tissue studies with holmium laser have shown that zones of thermal injury associated with laser ablation range from 0.5~1.0 mm, resulting in adequate hemostasis during ablation even for underlying vessels larger than 1.0 mm in diameter.30

Holmium lasers typically operate by pulsed wave. In contrast to continuous wave lasers where heat is generated continuously in the target tissue, pulsed waves allow for thermal relaxation time. Tissues receive less thermal injury and more ablative effect with pulsed waves, and the holmium laser, operating on 0.25 ms pulses have been shown to result in minimal thermal damage.

While, intuitively, holmium absorption by water may seem that the laser may be ineffective when crossing irrigant fluid, van Leeuwen et al suggested that laser was capable of penetrating irrigant fluid barriers by travelling across the vapor bubbles formed by initial absorption in the irrigant. Nevertheless, excessive vapor bubble formation also results in obstructed field of view for the surgeon, making direct contact methods the usual preferred choice of application.

The surgical methods of holmium laser application have also undergone several iterations. The first suggested method was a hybrid technique using holmium lasers as incision tools, while applying Nd:YAG VLAP techniques for overall debulking by coagulation necrosis (CELAP; Combined Endoscopic Laser Ablation of the Prostate).11 The CELAP technique, however suffered from deep thermal effects of Nd:YAG, resulting in recatheterization rate of 20~25% of patients. Nd:YAG was then abandoned and holmium laser was used along by non-contact method, called HoLAP (Holmium laser ablation of the prostate).10 As noted above, non-contact holmium laser ablation, while possible, was less effective and tedious than direct contact method. HoLRP (holmium laser resection of the prostate) simulated TURP by excising prostatic chips by direct contact resection.32 Despite the fact that holmium incision ablates nearly 75% of the prostatic tissue,29 HoLRP was able to yield tissue available for histologic examination. A refinement of this method is the present day HoLEP (holmium laser enucleation of the prostate), whereby the holmium laser simulates
open prostatectomy by removing the adenoma at the level of the surgical capsule. The enucleated tissue is then removed by morcellator, allowing greater yield of tissue and shorter operation time.

The major drawback of this procedure is the difficult learning curve, compared to KTP photovaporation. Also, while it shows great tissue absorption, the wavelength does not closely match water absorption peak in tissue, which is located at 1,940 nm. Furthermore, holmium is limited to pulsed wave due to its inefficient energy consumption. The major advantage of holmium laser is its extensive versatility, as it can also be used in various other urological procedures such as laser lithotripsy and urethral stricture resection.

4) Newer modalities: Thulium and Diode lasers: GreenLight (KTP or LBO) PVP and HoLEP currently boasts excellent results, possibly supplanting TURP entirely. As of 2008, prostate laser surgery consists of approximately 36.1% of prostate surgeries for bladder outlet obstruction. Newer modalities have been introduced attempting to improve upon current shortcomings.

By adopting thulium as the dopate for YAG crystals, the thulium laser achieves adjustable wavelengths between 1,750 nm and 2,220 nm, allowing exact match of 1,940 nm for optimum water absorption. The decrease in wavelength, and optimization to water absorption, greatly reduces thermal damage. Thulium laser is also diode pumped, in contrast to arc lamp pumped holmium laser, allowing for alternating output modes of either continuous or pulses waves. Finally, by stabilizing overheating typical of YAG crystals by thulium doping and diode pumping, thulium laser are energy efficient, allowing for tabletop devices supplied by common domestic electric outlets to be used as an energy supply. Only few reports have been made, though they have been presented at least equivalent outcomes compared to previous lasers.

Finally, semiconductor diode (SCD) lasers have also been suggested as the next best alternative to KTP and holmium based lasers. As previously noted, 120 W KTP lasers achieve improved ablation abilities while sacrificing hemostasis, with frequencies optimal for hemoglobin absorbance. Conversely, holmium lasers achieve excellent hemostasis; however efficiency drops when not in direct contact. The 980 nm wavelength produced by SCD lasers is attractive as they present high absorption for both hemoglobin and water, thus theoretically providing both optimal hemostatic and ablative properties. SCD laser, like thulium lasers, also use a secondary diode laser as the energy pump, allowing high efficiency/low energy consumption while providing variable wavelengths. How these advantages will translate to clinical outcomes have yet to be seen.

3. Laser fibers

One of the principle advantages of using laser in endourology is its innate ability to transfer high levels of energy to difficult-to-reach locations. The primary mediator is the laser fiber that can convey high energy with minimum loss through a small diameter optical conductor, allowing reduction in instrument size.

Laser fibers consist of a core optical fiber surrounded by two to three layers of optical insulators that act to contain laser within the core fiber by enhancing the refractive index between the core and outer layers. Most high energy medical applications utilize fibers within a pure synthetic fused-silica core. Impure or doped cores can cause attenuation of the laser beam, leading to fiber failure. However, the core silica often varies in saturation with hydroxyl (OH) groups. In general, infrared lasers use low OH silica, while visible to ultraviolet lasers use high OH silica.

Manufacturing defects in the production of laser fibers can result in optical irregularities. Defects can lead to leakage, resulting in charring, or even explosion. Other defects can result in decreased performance, including poor polishing, scratching and dust irregularities. Fiber tip failure may also occur with adherence of carbonized tissue. This increases heat applied to the fiber and may result in thermal failure. Mechanical fiber failure can occur with excessive bending. Laser fibers typically withstand bending to 100 times the primary diameter. With core fiber diameters typically in rage of 500 μm, this translates to approximately a curve radius of 5 cm.
Recent advances in fiber technology have seen modifications to improve durability and flexibility and decrease irregularities. With increased focus on laser power output, modifications have also aimed to stabilize fiber temperature during prolonged use. MoXy fibers, for the GreenLight HPS not only increased the fiber diameter to allow increase energy flux through the fiber, but also adopted fiber irrigation to taper thermal escape from the fiber (Fig. 6).41

**Conclusion**

With the advent of laser theory at the beginning of the 20th century, laser has shown drastic improvement and rapid clinical application. The present day prostate lasers continuously evolved from the early Nd:YAG laser through improved output, optimization of absorbance wavelengths, variable output modes and wavelengths, and even improved fiber technology to assist in conveying output. However, constant revision of surgical technique has also closely followed each step of technological improvement. Hence it is imperative for the surgeon to understand the underlying principles of prostate laser to provide optimal treatment and to adapt to the rapidly developing technological frontier.

**REFERENCES**

3) Yariv A. Energy and power considerations in injection and optically pumped lasers. P IEEE 1963;51:1723-31
5) Niemz MH. Laser-tissue interactions: fundamentals and applications. 3 ed. Germany: Springer Verlag; 2004:15-8
16) Malek RS, Barrett DM, Kuntzman RS. High-power


20) Te AE. The development of laser prostatectomy. BJU Int 2004;93:262-5


41) Peng SY, Kang HW, Pirzadeh H, Stinson D. MoXy...
fiber with active cooling cap for bovine prostate vaporization with high power 200W 532 nm laser. Proc SPIE 2011;7883ID

