UPDATE

Pulsed lasers and endocorporeal laser lithotripsy

Lasers pulses et lithotritie laser endocorporelle

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Summary  Endocorporeal laser lithotripsy (ELL) is currently the gold standard for the treatment of renal stones during retrograde intra-renal surgery (RIRS). The newly-authorised thulium fibre laser (Tm-Fibre) in now evaluated as a holmium:yttrium-aluminium-garnet (Ho:YAG) laser alternative, which is the most well-known laser source for ELL. This update aimed to present the fundamentals of pulsed lasers for EEL [technology, period, pulse characteristic (rate, duration, energy, shape), peak power, average power], and the available lithotripsy modes for both Tm-Fibre and Ho:YAG lasers.
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Introduction

Endocorporeal laser lithotripsy (ELL) is currently the gold standard for the treatment of renal stones during flexible ureteroscopy (f-URS) [1]. Firstly described in 1992 in the field of urology, the holmium:yttrium-aluminium-garnet (Ho:YAG) pulsed laser has gained popularity to become the gold standard of ELL, due to its safety profile and efficiency to ablate urinary stones [2]. The newly-authorised thulium fibre laser (Tm-Fibre) is now evaluated as an alternative to the Ho:YAG laser [3]. This update aimed to define the fundamentals of pulsed lasers for ELL and the comparative characteristics of both Ho:YAG and Tm-Fibre lasers.

Laser

LASER is the acronym of light amplification by stimulated emission of radiation. Lasers produce or amplify a luminous radiation for infrared, visible and ultraviolet wavelengths. A laser consists of three main elements (Fig. 1) [4]:

• an amplifying medium: solid-state (ex: crystal YAG, thulium-doped fibre), liquid- or gaseous-state (ex: Argon, CO₂). The medium takes advantage of the ability of the atoms, molecules, ions or electrons to deliver energy, according to the stimulated or spontaneous emission principles. This phenomenon results in the amplification of the luminous radiation;
• a pumping system: produces the luminous energy that is amplified thereafter. It could be optical (sun, flash lamp, continuous-arc or tungsten filament lamps, laser diodes, another laser source, etc.), electric or even chemical;
• the produced radiation wavelength (nm).

Fundamentals of a pulsed laser

The laser emission can be on a continuous or pulsed mode. Only the second one is suited for ELL (Fig. 2a). Pulsed lasers produce bursts of light spaced in time: between each emission, there is no light production.

In the field of endourology, the laser emission is transmitted through a laser fibre, connected to the laser generator and introduced into the working channel of the endoscope. This pulsed emission happens in a liquid medium that could be either saline solution, deionised water, urines or iodinated contrast agent. Consecutively to the radiative emission, a heat production appears at the fibre tip and creates a single or several vapour bubbles (induced vapour bubbles or bubble streams). The direct ablative effect of the induced vapour bubbles (contact between the vapour bubble and the stone) is called mechanical ablative effect. It coexits with another ablative mechanism: the radio-ablative effect (laser radiation transmitted through the vapour bubble to the stone). The created vapour bubbles between the fibre tip and the stone is frequently cited as the Moses effect (Fig. 3). Firstly described with Ho:YAG, it occurs also with Tm-Fibre, creating a real vapour channel between the laser fibre tip and the stone [2,5—7].

We detail below the fundamentals of pulsed lasers.

Period-pulse rate-pulse duration

Period is the time between the initiation of one laser pulse and the start of the next one. The pulse duration (pulse width, μs) is the effective time measured across the pulse during a period (Fig. 2b). Consequently, there is no period or pulse duration for continuous lasers.
Figure 2. (a): Continuous and pulsed laser emissions; (b): Pulsed laser emission: Period and pulse rate and pulse duration.

Figure 3. Induced vapour bubble after laser activation with Ho:YAG in saline solution.

Figure 4. Short or long pulse duration.

Figure 5. Pulse energy.

Pulse rate (Hz) represents the number or emitted laser pulses during a single second (Fig. 2b).

Pulse duration (PD) can be short (SP: 200–400 μs) or long (LP > 800 μs) (Fig. 4).

Pulse energy

The pulse energy (Joule) represents the intensity of a laser pulse during a period. The amount of energy delivered during a period is also often represented as the area under the curve (AUC) (Fig. 5).

Power

The laser power can be subdivided in three distinct entities:

- peak power (PP): maximum level of power during the pulse (Fig. 6a);
- instantaneous power: level of power at a given instant of the pulse;
- average power (AP): power usually announced by the laser generator.
The peak power differs from the average power because PP consists in the maximum level of power during the pulse, corresponding to the initial portion of the pulse for Ho:YAG (pike profile), followed by a rapid decrease on the rest of the period. At the opposite, PP and AP are similar with Tm-Fibre (uniform staged profile) (Fig. 6). PP and PD are associated.

**Laser pulse modulation**

Recently, the Moses effect has regained popularity due to the development of double laser pulses, represented by the Moses technology (Lumenis©) (Fig. 7). Fig. 8 summarised the laser pulse’s fundamentals.

**Ho:YAG and Tm-fiber lasers**

Firstly described for tissue ablation because of hemostatic properties, Ho:YAG laser was then applied to ELL [3,8]. As a solid-state laser composed by a crystal of yttrium, aluminium and garnet that has been chemically doped with Holmium ions, the amplifying cavity is pumped by a flash lamp. The produced light passes through the crystal, providing a 2120nm wavelength. After several reflections on the cavity’s mirrors, the laser beam is emitted as a laser pulse [3].

The Tm-fibre differs from Ho:YAG on its technological characteristics (Fig. 9). Its 1940nm wavelength endows a
higher absorption peak in water than Ho:YAG’s, consisting in a safety aspect. As its name implies, the thulium fibre laser consists of a very thin and long silica fibre (10–20 μm core diameter, 10–30 m long), which has been chemically doped with thulium ions (Fig. 10). The laser pumping is made by multiple laser diodes. The emitted Tm-Fibre laser beam is thinner than the one by the Ho:YAG laser (70 vs. 300 μm), as well as the minimum core-diameter laser fibre accepted (50 vs. 200 μm).

ELL with Ho:YAG lasers presents several limits, potentially surpassed by the Tm-Fibre (Table 1): Regarding the pulse rate, Ho:YAG laser allows low (1–5 Hz) or high (15–80 Hz) pulse rates, even only high power Ho:YAG generators (HP–Ho:YAG) can propose pulse rates over 20–30 Hz. HP–Ho:YAG are manufactured with multiples cavities (each one has a maximum power of 30 W). Consequently, their architecture needs a large water-cooling system to control the temperature rise, contributing significantly to their large size, fragility and noisy aspect. On the other hand, Tm-Fibre allows high pulse rates, up to 2000 Hz. If the range of pulse energies for Ho:YAG goes from low (0.2 to 0.5 J) to high (1 to 6 J) levels, Tm-Fibre allows very low values (down to 25 mJ). Tm-Fibre’s architecture does not expose to temperature rise, using a simple fan as cooling system.

Tm-Fibre generators are also smaller, more resistant to external shocks and lighter.

Concerning the pulse duration, Ho:YAG generators allow LP. In-vitro studies on LP impact on stone lithotripsy reported thinner but deeper craters, similar ablation volumes and fragment sizes, compared to SP with identical settings (Fig. 5) [9]. LP seems to be associated with less stone retropulsion and fibre degradation, likely due to a lower PP [10]. Tm-Fibre presents only LP, regardless of the pulse modulation setting [11]. The pulse modulation has been recently introduced with Ho:YAG, according to the development of Moses technology, consisting in a first SP followed by a main LP in the same impulsion cycle. In-vitro data on Moses technology support a lower stone retropulsion and better ablation rates, compared to the single pulsed modulation [5, 12]. However, up to date, we are lacking clinical data, especially comparative studies with Tm-Fibre, which has also a ”Moses mode”, to adopt this pulse modulation in our daily practice [11].

If the peak power’s modulation is a dominated notion by engineers, urologists are still not used to this term in clinical practice. No stone fragmentation is possible in case of insufficient PP, without enough mechanical ablative effect. Ventimiglia et al. reported a 2000 to 20,000 W PP
with Ho:YAG and rapid decrease of power during the laser pulse (Fig. 6b and Fig. 9) [11]. On the contrary, a high PP exposes to higher stone retropulsion and fibre degradation (burnback effect), and lower ablation rates, explained by the initial overshoot occurring on the oscilloscopic profile. The compromise between retropulsion and ablation rate traduces the complex bubbles dynamics (surface bubble tension, dimensions of induced vapour bubbles). The Tm-Fibre, with its uniform staged oscilloscopic profile and consequently lower PP (500 W max) but closer to the AP, seems to answer this problematic. However, when using very low pulse energies (25 to 75 mJ), the low PP (from 150 to 400 W) could consist in a stone fragmentation limit (Fig. 6a and Fig. 9a) [3,11]. To conclude, in-vitro studies report that Tm-Fibre has two-fold to four-fold higher ablation rates and produces smaller fragments than Ho:YAG [13,14].

### Laser lithotripsy modes

A total of eight setting combinations is possible. At the setting, the practitioner has to define the pulse duration, the pulse energy and pulse rate in this order, respecting the maximal power limit of the generator. Three laser lithotripsy modes are mostly used (Table 2) in:

- **dusting:** low pulse energy (<0.5 J)-high pulse rate (15–20 Hz), long pulse duration;
- **fragmentation:** high pulse energy (1.5–2 J) — low pulse rate (5 Hz), short pulse duration;
- **pop-corning:** high pulse energy (1–1.5 J) — high pulse rate (10–15 Hz), long pulse duration.

Pop-corning mode aims to reduce the fragments’ size produced during fragmentation or dusting. Recently, the pop-dusting mode has been introduced with a possible better ability to dust the produced fragments than pop-corning, using the same settings than dusting, considering the low level of evidence in the available literature [15]. Finally, the Tm-Fibre provides an additional lithotripsy mode: Fine dusting [very low pulse energy (0.025–0.15 J) — very high pulse rate (40–2000 Hz), long pulse duration] [3].

### Conclusion and perspectives

Endocorporeal laser lithotripsy is widely realised during f-URS. If setting the pulse energy and rate is now well known to optimise the stone treatment, the pulse modulation (PP,
pulse duration and pulse shape) remains limited in daily practice, but represents the future of ELL. The Tm-Fibre seems to overcome the Ho:YAG technological limits. More clinical data is requested.

Disclosure of interest
The authors declare that they have no competing interest.

References