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INVITED REVIEW

Intracorporeal lithotripsy

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Abstract

Since the introduction of ESWL, PNL and URS during the early 1980s the application rate of ESWL has declined while those of PNL and URS have increased. This is mainly due to the facts that instruments and techniques for Intracorporeal Lithotripsy (IL) have made a continuous progress. This review shows that today an array of options for IL within the entire urinary tract is available to treat stones in a perfect minimal invasive way. At the same time further improvements of IL are already visible.

Keywords Intracorporeal lithotripsy · Impact lithotripsy · Ultrasound lithotripsy · Ballistic lithotripsy · Electrohydraulic lithotripsy · Laser lithotripsy · Holmium:YAG laser

Abbreviations

CT	Computed tomography
EKL	Electrokinetic lithotripsy
EL	Extracorporeal lithotripsy
ESWL	Extracorporeal shock wave lithotripsy
Ho:YAG	Holmium:yttrium–aluminum–garnet
HU	Hounsfield unit
HUD	Hounsfield units density
Hz	Hertz (events/second)
IL	Intracorporeal Lithotripsy
J	Joule
LP	Long Pulse
NEPL	Nanosecond electropulse lithotripsy
RIRS	Retrograde intrarenal renal surgery
RSL	Reemitted stone light
SP	Short pulse
URS	Ureterorenoscopy
PNL	Percutaneous nephrolithotomy

Introduction

Extracorporeal lithotripsy (EL) and intracorporeal lithotripsy (IL) have one step in common: generation of a volume of stone fragments equivalent to the initial stone volume. The advantage and practical attraction of IL is that the surgeon can visually determine if the disintegration process is successful and complete or has to be continued. This is the “smash-part” of the procedure. The surgeon may than opt for the “smash and extract” or “smash and go” procedure. The latter, being similar to the ESWL® process, is used when there is no possibility to extract the fragments like in Micro PNL or as an option in URS. The patient has to pass all fragments to achieve a stone-free status.

Several techniques for IL are available. They vary in energy source, probe size and flexibility, comminution potential, expressed in time and fragmentation efficiency, stone retropulsion effects, side effects on tissue, versatility of use and costs. Mechanical lithotripters are only used for bladder stones, electrohydraulic lithotripsy is rarely applied today and different forms of impact lithotripsy and laser lithotripsy are most widely used for renal and ureteral stones. Principally ballistic and electrohydraulic lithotripsy crack stones and turn them into fragments, while ultrasound and especially laser lithotripsy offer both dusting and fragmenting effects even though the results vary with the stone hardness. Just like ESWL® also IL techniques produce larger fragments if the stones are hard and have high HU or HUD values in CT [1].

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Mechanical lithotripsy

Instrument makers still market mechanical, hand-operated lithotripters: a stone crushing forceps to deal with small stones fitting through a 25 Fr. cystoscope sheath or a 26/28 Fr. resectoscope sheath; for larger stones a 24 Fr. lithotrite with curved coaxial opening jaws, which has to be introduced blindly into the bladder, is available. The Mauermayer stone punch [2] comes with a 25 Fr sheath and a sheath insert with a channel to introduce 7 Fr. flexible instruments like electrohydraulic probes or laser fibers. Stones up to 2 cm in diameter can be crushed fast and fragments are extracted or flushed out easily; larger stones require preliminary disintegration with non-mechanical devices; use of mechanical lithotripsy in PNL was once suggested [3].

All devices applied in the bladder are used under visual control. Their use is still described in the current literature [4–6]. Their main advantages are robust technique, simple application and reusability.

Impact lithotripsy

Impact lithotripsy acts like mechanical lithotripsy by direct mechanical forces on the stone; energy is not supplied manually but through metallic probes which vibrate with single or multiple pulses mainly longitudinally. These movements are generated by intermittently applied different types of energy such as compressed air (pneumatic lithotripsy), electromagnetic impulses [electrokinetic lithotripsy (EKL) or piezoelectricity (ultrasound lithotripsy)]. The action is a “hammer and chisel” principle. The stone disintegration is caused by very small excursions of the probe.

The lithotripter probes do not cause essential trauma to tissue by their vibration and are dangerous only if they are pushed like any other non-vibrating metallic rod with undue force against tissue.

Ultrasound lithotripsy

Ultrasound lithotripters were primarily developed for the treatment of bladder stones [7, 8] and applied secondary for the use in PNL [9, 10]. Piezoceramic components convert electrical voltage into mechanical oscillations of $>20{,}000$ Hz transmitted to a probe. The heat generated through this process requires cooling of the generator and probe. This is provided by suctioning of the irrigation fluid through the hollow ultrasound probe which at the same time evacuates stone debris. The very small probe excursions turn soft stones preferably into dust and cause hard stones to also brake into small and large fragments. Stones can be disintegrated by continuously working on the stone surface and diminishing the stone in size instead of breaking it into bigger pieces. Malfunctions in 10–30% are not infrequent [11, 12]. Most are a temporary issue: When getting clogged by the stone debris the probe may lose its fragment-suction and cooling efficiency and must be cleared mechanically. While brittle stones are pulverized and sucked out quickly, hard stones may take longer. These stones may break into fragments or the probe may drill a hole, get stuck and lose efficiency due to reduced oscillation. Freeing the probe from the stone by pulling it against the sheath is required. Stone propulsion is negligible.

The Calcuson lithotripter® (Karl Storz), used by the author since 1976 [13], has two different probes: one with a movable tip and one without it (Fig. 1a, b). Jackhammer movements of the movable tip are initiated by the ultrasound probe thus combining both, ultrasound and ballistic effects in one probe. To benefit from this effect the stone has to be touched superficially with the movable tip. When pressure is applied, only the ultrasound effect comes into action. The other, tipless, exclusive ultrasound-action probe is also perfect for working up small fragments which are sucked to the tip and virtually disappear during the disintegration. Probes of 1.8, 3.0, and 3.5 mm with or without oscillating tip for PNL and Cystolithotripsy and of 1.5 mm Ø for URS are available.

Other combined combinations of ballistic and ultrasound lithotripters are the Lithoclast Master® or Swiss LithoClast Select™, the Swiss LithoClast Trilogy™ (EMS), the Cyberwand™ and the ShockPulse-SE™ (Olympus) (see below).

One of the latest ultrasound lithotripters evaluated was the UreTron® (Med-Sonics.com). In a study on 31 patients it outperformed the CyberWand® (Olympus), the

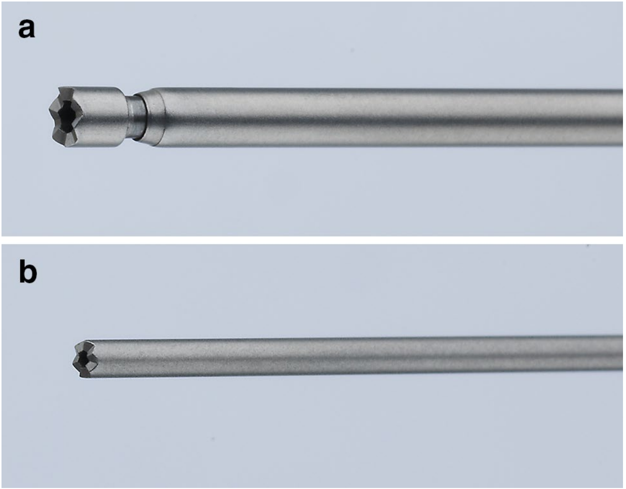

Fig. 1 **a** Tip of Calcuson® lithotripter ultrasound probe with movable portion. **b** Tip of Calcuson® lithotripter ultrasound probe without movable portion. (Courtesy of Karl Storz GmbH & Co. KG)

StoneBreaker© and the LithoClast Select® (Boston Scientific). FDA approval was received in 2012. Since one publication in 2015 [12] there are no news on the device. Currently, the home page where videos on PNL and URS can be watched gives a neglected impression. The disadvantage of ultrasound lithotripters is the reduced effectivity on very hard stones.

Ballistic lithotripsy

The term ballistic stems from the Greek word βάλλειν (bἀllein): thrust, hurl or throw.

Compressed air (pneumatic lithotripsy) or electromagnetic/-mechanic impulses [electrokinetic lithotripsy (EKL)] are used to accelerate an inner mobile metal body attached to the external probe, passed through the scope and touching the stone. Return movement of the metal body is provided by simultaneously compressed springs or elastic material within the hand piece. Probes of 6–2.5 Fr and 40–57 cm length are available.

The probes can be used in single or continuous pulse fashion. The frequency (0.5: Cook Stonebreaker®—3.4 Hz EMS Lithobreaker®), the extent (0.8–2.5 mm) and velocity (10–30 m/s) and thereby the intensity (kinetic energy) of the probe tip displacement can be selected and these parameters are positively related to the stone disintegration but in general also to stone propulsion which is a typical negative side effect of ballistic lithotripsy.

The majority of lithotripters in use are pneumatic machines and several companies offer such systems (http://www.medicalexpo.com/medical-manufacturer/lithotripter-1683.html). There is at least one company (http://www.walz-el.de/en/urology/products) still offering an electromechanical/electrokinetic lithotripter, the Lithotron®, which was probably refined after its initial introduction in 1996 when it was marketed as Combilith® [14, 15]. To ease the handling of the lithotripters no-cord/no-tube devices driven by CO_2 cartridges (pneumatic: StoneBreaker®, Cook Medical) or batteries (electromechanic: Lithobreaker®, EMS) were introduced. In vitro evaluation showed slight advantages for the pneumatic device [16], the cartridge of which has to be replaced after 80–100 shots.

To overcome the basic disadvantages of ballistic lithotripsy—stone retropulsion, large fragmenting instead of dusting, no continuous fragment removal—modifications have been added.

The pneumatic lithotripters originally come with bare probes to be passed through the scope sheath. The mechanical impact on the stone in combination with the irrigation can cause stone and fragments retropulsion, which is a frustrating complication especially during ureteroscopy with upward migration of stones into the kidney.

To prevent these complications suction devices were added [17]. The pneumatic probe was advanced within and together with a hollow suction probe LithoVac®, both mounted on the handpiece. Both, probes and suction pipe come in different sizes to be used in scopes for the ureter, kidney or bladder. But with the 1.6-mm suction probe used to drag the stone toward the 0.8-mm Lithoclast probe applied in a 9.5 Fr Ureteroscope no suction during lithotripsy was possible [17]. Delvecchio et al. [18] described the successful application in an 8.5 Fr ureteroscope with a 0.8 mm Lithoclast probe in a 4.8 Fr hollow Lithovac® probe, a size currently not offered. But only one of 21 patients had a proximal ureteric stone; the majority had distal ureteric stones where migration is not a frequent problem.

Combination of ultrasound and ballistic lithotripsy were realized in the Lithoclast Master® or Swiss LithoClast™ Select (EMS) and the CyberWand® (Olympus). The Lithoclast Master was introduced in 2001/2002 as Lithoclast Ultra: it combines pneumatic lithotripsy with ultrasound lithotripsy at > 20,000 Hz. Solid probes of 0.8–3 mm diameters for pneumatic lithotripsy can be introduced through the hollow ultrasound lithotripsy probes for simultaneous ore separate use. Continuous suction can be attached to either probe [19]. The CyberWand® [20] is a fixed dual probe lithotripter with an inner ultrasound probe working at 21,000 Hz with suction and an outer probe vibrating at 1000 Hz. The ultrasound/pneumatic mode or ultrasound can be selected separately. Both modes can be used with simultaneous suction. Outer probes of different length come in diameters of 3.3 and 3.8 mm and ultrasound probes in 0.8, 1.0, 1.6 and 2 mm diameter. A flexible probe, Pneumatic FlexProbe® 0.89 mm × 940 mm is also available, but there are nor publications on its use. The combined system cannot be regarded as a double or dual ultrasound probe as ultrasound is defined by frequencies above 20.000 Hz which is the upper limit of human hearing.

Performance of these devices is usually better than the single ballistic or ultrasound lithotripters [19].

The latest development in this area is the Olympus ShockPulse-SE® lithotripter. Similar to the CyberWand® it is a dual-action system with constantly emitted ultrasound energy at > 20.00 Hz and intermittent ballistic impulses at 300 Hz. Different to the two-probe CyberWand® it uses a single probe with a large suction channel for continuous stone fragment removal. All functions can be controlled from the hand piece. It has a very good efficiency and can even be used through a miniscope with such a perfect performance that the end of large PNL tracts even for big stones could come to an end (Janak Desai: personal communication).

Since the introduction of the machine in May 2015, there was one publication showing good performance in vitro and in six clinical cases [21]. A development in the pipeline was presented at the 2017 WCE: the Swiss LithoClast Trilogy®

(EMS Switzerland) employing an electromagnetic impactor and an ultrasonic lithotripter to deliver ultrasonic vibration and ballistic impact compression waves through the same hollow probe [22].

The mode of action of ballistic lithotripters limits their use to rigid probes. 0.89 mm Ø flexible probes are offered by EMS. They allow a deflection of only 30°–40°. There are no published reports on their effectivity.

Electrohydraulic lithotripsy

Electrohydraulic lithotripsy was the first non-mechanical technique and the first that could be applied through flexible scopes although not existing at that time. The fine electrodes could be passed through pediatric cystoscopes or the curved instrumentation channels of regular cystoscopes.

The principle of function is identical to electrohydraulic ESWL with a spark generated between two electrodes inducing a cavitation bubble and—at the collapse of the bubble—a shock wave. The two flexible metallic electrodes are imbedded in a plastic sleeve much like in a normal electric cable and come with a metallic tip to host the spark and reduce possible actions on the scope or tissue. Power output and spark frequency can be regulated. Direct application to tissue or telescope optics can cause more damage than any other technique.

A German company, Walz (http://www.walz-el.de/en/urology/products) offers probes of 2–7 Fr. diameter and 6–30 cm length. An American company (https://northgatetech.com/products/lithotripsy) offers probes of 1.9 and 9 Fr. and 54–375 cm length as they are also used for gastroenterological use to treat biliary stones.

An advanced spark gap technology was Nanosecond Electropulse Lithotripsy (NEPL). With direct contact to the stone, higher voltage and faster discharge than with conventional EHL the energy was passed directly into the stone and not in the surrounding liquid causing the stone to crack. Since publications of experimental [23–25] and clinical work by a Russian group in 2013 [26] there was only a report on in vitro studies showing a good performance compared to Laser lithotripsy [27]. The clinical experience has not been duplicated so far.

Laser lithotripsy

Laser types

Different lasers—Dye [28], frequency-doubled double-pulse neodymium:YAG (FREDDY) [29–31], Thulium [32–34], Tm:YAG [35], erbium:YAG [36]—have been and are still evaluated for their use in IL. Despite some advantages compared to the holmium:YAG laser, for various reasons they have not made it into a significant concurrency to the latter. Holmium:YAG laser combines at present a satisfying disintegration capacity, with minimal tissue trauma, a relatively modest stone retropulsion, thin fiber application in flexible instruments and, in high power versions, versatile use for different urological indications.

The major drawbacks of the other lasers which also have certain definitive advantages [34] are either large fragments, weak performance on hard stones, side effects or no availability of fibers that can be used reliably in practice [37].

Holmium:YAG laser

The holmium:YAG laser emits a light of 2140 nm wavelength which is highly absorbed in water and has, compared to other lasers, a relatively long, and in modern high power versions selectable pulse duration of 350–700–1500 µs [38–40].

Both—high absorption in water and long pulse duration—contribute to stone destruction: Initially the water surrounding the tip is heated and thereby transformed into a vapor bubble; this splitting of the water is the so called Moses effect which is known since the late-eighties [41]. The bubble absorbs less energy of the still emitted—long pulse—laser beam which travels through the bubble to hit the stone surface; there, by heating the stone a photothermal stone destruction happens. This well-known Moses effect has recently found a revival as a marketing tool in a new laser series with pulse modulation and special “Moses” fibers [42]. Stone destruction also happens with direct contact between laser tip and the stone surface as the energy is directly absorbed by the stone. Because of the small bubble size and the high absorption in water side effects to tissue even during direct contact are minimal. The pressure generated by the bubble mechanics is small, and thus causes stone retropulsion but no stone disintegration. Because of the high absorption in water the fiber tip is usually kept in direct or very close contact (1 mm) to the stone to be effective. This is why stone retropulsion even within the mm-range reduces effective stone comminution.

Low/high power laser

So called low power ≤ 20 W lasers are the working horses for IL. High power lasers are more expensive and usually require a more complex installation. A few publications report on high power lasers especially for treating large renal stones in PNL [43–47].

Large, 1000 µm fibers, 3.0 J and a frequency of 10 Hz were successfully applied to disintegrate large renal stones [44]. The concept to replace ultrasound IL in PNL by high power laser IL is efficient [48] but probably more costly.

High energy as used in the high power lasers can principally cause two problems: Fiber tip burning and stone retropulsion. In the setting within the renal collecting system—other than in the ureter—retropulsion should be an irrelevant problem. As large fibers of between 550 and 1000 µm are used the energy is dispersed in a large cross sectional fiber area diminishing the energy per fiber volume and the risk of tip burning. None of the authors mentions how many fibers were used in a single patient.

High power lasers allow applying higher energy and/or higher frequency and offer to select long and short pulse durations. At present there is no clear cut evidence that high power lasers offer substantial advantages for the routine use [40].

Laser fibers

The fibers consist of at least three components: a silica core whose diameter characterizes the fiber technically, a first coating (cladding) that keeps the light in the core fiber and a colored plastic coating (jacket) for better visualization. All three determine the diameter of the fiber. A special fiber connector has to fit technically to the laser light generator. Fibers and connector have to match with the generator [38]. The interaction between generator and fiber will dictate which power (W), energy (J) and frequency (Hz) can be used.

Different sizes indicated by the diameter of the core are available: 150–300 µm are used in flexible and rigid ureteroscopes, respectively, 300–500 µm in rigid URS and PNL and >500 µm in the treatment of kidney and bladder stones. The fibers are sometimes marketed with numbers referring to the size of the core fiber and sometimes with completely misguiding market names and numbers. Depending on the manufacturer the real size of the complete fiber—core + cladding + jacket—can vary significantly and can be up to the double of the core fiber [38], which may only be realized when it reduces flow or hampers deflection of flexible scopes. In a 2015 review the total diameter of fibers with type marking of 200 to <300 varied between 374 and 460 µm and those with 300 and more between 465 and 604 µm [49]. This group of authors has also shown that the quality of fibers differs among and even within manufactures. They have continuously published trials on laser fibers and the interested reader is referred to these publications [50–53].

Different fibers of same sizes have no significantly differing influence on the lithotripsy effects. If the same energy is coupled into fibers of different diameters the disintegrated stone volume is identical [54]. Also when choosing between different fibers in one size class flexibility is less important as it is comparable. Important aspects are stable energy transfer and durability; the former affects OR-time; reduced durability can ruin the scope when the active laser beam escapes a defective fiber within the scope. Small diameter fibers being used in flexible scopes are more susceptible to damage and have a limited reusability [52].

Fiber tips have an influence on the disintegration capacity. During laser application on the stone they were off (burn back) and loose transmission capacity [55]. Shape and surface of the tip become irregular and may ruin instrument channel and scope during reintroduction or to-and-fro movements.

The industry offers ball-tip fibers with the promise of atraumatic passage through the bent scope.

This is in effect true but pays off only during the first few seconds to minutes of use as the ball tip progressively burns back into the same irregular configuration like a normal fiber does [40, 56]. Single and multiple use fibers are offered. Economically choosing one or the other will depend on terms and conditions with fiber and scope manufactures and the total workflow within the hospital. With single use, costs for fibers may double but costs to reprocess fibers and to repair scopes may be halved [57]. But in some evaluations multiple use fibers performed better than single use ones and were more cost effective [51].

Cleavage of fibers is recommended to renew the quality of power transmission during IL.

How should the fiber be cleaved? Recommended standard was stripping the colored sleeve and then cutting core and cladding with special instruments. “Are We All Doing It Wrong? Influence of Stripping and Cleaving Methods of Laser Fibers on Laser Lithotripsy Performance” was the title of one publication [58] of the team around Traxer which has given good answers to many questions in laser lithotripsy [54]: Fibers can be cut with simple metal scissors and do not need to—in fact should not—be stripped from their colored sleeve. The authors showed less fiber tip degradation and a higher fragmentation capacity when the colored outer jacket was left intact instead of stripping it in the same way as the new fibers come from the manufacturer [58]. Ceramic scissors offered by the fiber manufacturers give better initial results but after only 3 min of IL there is no difference in power output [59]. In addition leaving the coloured sleeve partially covers the silica tip of the fiber and protects the instruments channel of the scope from damage during fiber passage even through bent scopes: “Cleaving the ends of standard fibers greatly facilitated their passage capabilities” [60]. It may be that a lot of scope damage described in the literature as fiber related was due to recommended but essentially wrong fiber handling.

Laser damages of scopes are preferably located in the distal 3–4 cm [61]. It has, therefore, been recommended to cleave the distal 4 cm of used fibers to remove damaged portions and prevent thermal scope damages due to fiber cracks [57].

When should the laser fiber be cleaved?

Combing the vast literature on Laser IL shows remarkably few hints on when to cleave. Unpublished data “suggested that cutting the fiber tip every 10 kJ may be beneficial.” which is “achieved every 15 min of laser lithotripsy approximately” [62]. No cleavage was recommended because of a stable long term energy output over 15 min, however, with only 5 kJ applied in an experimental setting [59]. Others described a mean energy delivering of 1.36–1.50–2.12 kJ per procedure with “270” µm and “365” µm fibers used in flexible scopes and semirigid scopes, respectively, without mentioning intermittent cleavage, which was only done to reprocess multiple-use fibers [52].

A figure from the publication of Kronenberg and Traxer [63] illustrates the general problem of translating experimental findings into clinical practice. A new fiber has perfect performance signalized by its physical properties. After only 60 s of lithotripsy they show fundamental changes and the fiber seems to be indiscernible from a cleaved and used fiber with identical, clinically sufficient performance (Fig. 2). This fits to the findings of Peplinski et al. [59] who showed that the initial power output of different new fibers is initially significantly different and high, than diminishes and within the first 3–4 min it becomes stable and comparable thereafter.

Laser disintegration techniques

Different disintegration techniques are described: “Dancing” or “dusting” to turn soft stones into tiny particles, “chipping” to chisel fragments as small as possible from a hard stone, “fragmenting” for hard or big stones and “popcorning” to turn small fragments into smaller fragments [64]. The laser settings have to be adapted to the stone because the effect generated will depend on the stone hardness. Stone hardness becomes apparent during lasering: the hard stone will only respond to high energy and low frequency and will turn into larger pieces; dusting is not possible or meaningful in this situation. Dusting is easy with soft stones with different laser settings.

Principally fragmenting requires high energy/low frequency and short pulse while dusting is done with low energy/high frequency and long pulse. Popcorning applies intermediate settings.

The “popcorn technique” [65] is undirected high frequency/low power (1 J/20 Hz) laser firing on small fragments in a small area of the collecting system like a calyx. It is usually applied by a dissatisfied surgeon seeing too many fragments too small to be extracted. The idea is that the fragments pass stochastically to the fiber tip to be fragmented further. It has been shown experimentally that the technique has a limited effect [66] mostly depending on the energy used and the time spend [67]. Probably the most satisfying effect is to see the fragments being stirred up by the laser bubbles and irrigation and finally leaving the site alongside the scope.

Clinically the conditions of IL—stone size—hardness—composition, laser beam direction, retropulsion, irrigation effects, visibility—are so variable that conclusions drawn from experimental studies cannot be transferred one-to-one in clinical action. But when planning a procedure it

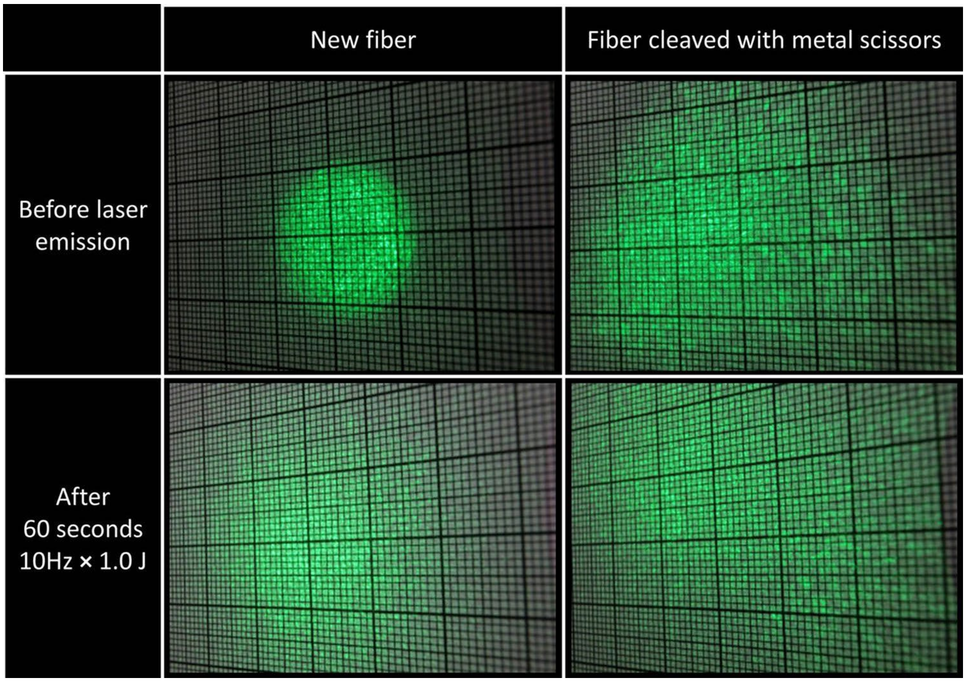

Fig. 2 “Laser light scattering patterns comparing a newly, untouched fiber with a fiber cleaved with metal scissors. After a short time of laser emission, both fibers scatter the laser light and are almost undistinguishable from one another.” (From: [63])

is reasonable to estimate effects and consequences. In this respect the calculations made by Kronenberg and Traxer offer a nice theoretical support: Turning stones with a volume of 1, 8, or 27 mL, into 5-mm fragments results in 8, 64 or 216 fragments respectively. Dusting of a 3-cm stone into 3 mm fragments produces 1000 fragments [54]. Practice, however, may show different.

Recommendations on laser setting with low power lasers or high power lasers do not follow a uniform scheme and vary between 1 J/pulse and 6 Hz to 3.5 J/pulse and 20 Hz.

Lithotripsy effects different from low power laser application are described with high power: When using 3 J/pulse at 10 Hz for stones > 3 cm Ø drilling into the stone center causes a sudden burst of the stone into several smaller pieces [43, 44]. Similar "vaporizing and bursting" lithotripsy effects are described with a 100 W laser [46]. An initial "high-power 70 W (3.5 J × 20 Hz)" contact with the stone causes dust being produced and then the stone bursts into small fragments easy to irrigate out leading to an overall shorter procedural time [46].

Very elaborate studies evaluating different settings of energy, frequency, and pulse duration [68] can be summarized in two rather simple conclusions:

Whenever retropulsion and fragment size do not matter and stones are large—large renal or bladder stones with a large access—high fragmenting laser energy may be used to achieve a fast disintegration into extractable fragments. When retropulsion carries the risk of difficult to access fragments and when tract size limits large fragment extraction—small tract PNL and URS—low dusting laser energy is recommended. Stone composition may override these principles. Calcium-oxalate-monohydrate stones are most resistant to Holmium:YAG lithotripsy and tend to break up in fragments while Struvite stones are least resistant and easy to dust [1, 69, 70]. In addition the physical properties of a particular stone will determine its susceptibility: a stone with loosely packed crystals and urine filled interspaces will react by explosive vaporization of the liquid components plus the thermal decomposition of the solid parts while the latter effect is the only one acting on a stone with densely packed crystals regardless of their chemical composition. Different physical properties of stones may explain, why data on the susceptibility of different stone types to Ho:YAG LI are not uniform [1, 69, 70].

Laser lithotripsy complications and collateral damage

In vitro trials showed the Ho:YAG laser to perforate the ureter with 1–2 shots [71]. But the penetration depth is between 0.5 and 1 mm, the defect is minimal even with high-power (3.0 J) [44] and at a distance of 2 mm there is no effect. Inadvertent prolonged perpendicular laser application to tissue can happen during through and through laser-perforation of a stone and should be avoided just as a safety distance of 2 mm to tissue should be kept as a rule.

Organ related complications during laser lithotripsy for ureteral or renal stones are usually not described as resulting from the lithotripsy process itself but from surgical mistakes [72]. Damages to instruments are more specific. The time to melt a nitinol wire is in the second range and that for guide wires in the minute range [73]. Also ultrasound lithotripters but not ballistic lithotripters had this effect on nitinol baskets [74].

The most costly collateral damages happen to the scope: A survey among the major ureteroscope manufacturers revealed that the most flexible scope damages were caused by punctures or burns with laser fibers in the distal 4 cm of the working channel [61]. The main causes are forceful advancement of the fiber through the bent scope or laser beam escapes through maximally bent damaged small caliber fibers. Fiber braking within the bent instrument is energy and fiber manufacturer dependent.

Damages to the scope tip can be prevented by a simple trick: Talso et al. [75] showed that neither the vapor bubble at the fiber tip nor stone disintegrates will reach the scope tip if a safety distance of 3 mm between fiber tip and scope tip is kept. This distance is assured when the fiber tip is visible in at least ¼ of the screen diameter regardless of the scope used.

Retropulsion

Due to the long pulse duration of the Ho:YAG laser and the shape of the vapor bubble the cavitation is too weak to cause a shockwave for stone fragmentation [41] but it contributes to stone retropulsion [76] just as the energy released during the thermal decomposition of the stone. In vitro experiments have measured retropulsion. The results differ significantly and confusing, depending on the experimental setting. If the artificial stone is continuously disintegrated and moves unhampered it may be pushed 25 cm ahead [77]. In a horizontal tube model the maximal displacement with a few shots, high energy of 1.5 J and low frequency of 10 Hz was 3.93 mm [35]. In a friction free perpendicular model [78] with the same laser settings the maximum stone displacement was 4.37 mm. Other studies showed up to 16 mm displacements [76].

This is much less compared to the displacement by ballistic IL. In the clinical situation this is sufficient to move the stone out of the active laser radius. The judicious use of irrigation and fixation of the stone with the instrument or fiber tip during IL is probably just as important to prevent stone displacement.

Prevention of stone and fragment propulsion can be achieved by different means. For PNL suction devices have been developed [79–81] and a comparative quasi-experimental study showed comparable effectivity in PNL [82].

Stone and fragment displacement is more relevant in URS. Several disposable devices are available. If stones and fragments assemble underneath the device, their fragmentation in the fixed position allows a more efficient lithotripsy [68] reducing OR-time. The rate of secondary procedures for stone removal is lowered and the primary stone free rate is higher. But prices of 290–390$ add to IL costs [83]. Unfortunately the cheapest technique, a lubricating jelly block dropped above the stone performed worst [84, 85]. Coiling a guide wire immediately above the stone is another cheap option [85], but it could be time consuming and results have not been duplicated so far.

Ursiny et al. [86] determined in a decision analysis model that using the commercial devices pays off if retropulsion happens in more than 6.3% of the cases. The assumptions made for the cost computation may not apply to the individual clinic but they give food for thoughts.

Tissue recognition, stone analysis

Smart Lasers have been hypothesized and realized [87]. The principle is to measure and analyze reemitted light from the target area. The purpose is twofold: to differentiate tissue from stone and to analyze the stone composition in vivo. Initially two fibers, for light emission and analysis were used in an in vitro setting with a dye laser [88]. Its pulse-length of 3 µs offered enough time to analyze within 500 ns the light reemitted from tissue or the stone to either subsequently release the complete high power impulse on the stone or, if targeting at tissue, to shut the laser beam down before any tissue damage could happen. The system was successfully applied clinically [89, 90]. While the dye laser technique measured fluorescence of the stone surface, first experiments with the Ho:YAG laser used “incandescence”, a thermally induced radiation in the range between 585 and ~ 1100 nm [87]. An actual study used stone fluorescence induced by the 532 nm green aiming beam of the Ho:YAG laser [91, 92].

In vivo stone analysis was evaluated by analyzing emissions of the vaporized stone material [88], and more recently by Raman spectroscopy [93, 94]. At present both, stone analysis and tissue/stone differentiation during Ho:YAG IL are still experimental. Once they have reached clinical reality the first true urological robotic scenario can be envisaged:

The case: a mid-ureteric Calcium-Oxalate stone of 6 mm Ø and a lower calyceal stone of 8 mm Ø. The configuration of the whole upper urinary tract determined by CT is fed into the robot.

The robot’s assistant introduces the ureteroscope in the ureter. The robot [95] takes over and completely controls the action: the ureteroscope is continuously advanced under automatic real-time feedback control of delivered laser energy. Reemitted stone light (RSL) signals the ureteral stone. Lithotripsy is started until no RSL is detected. The robot detects no residuals, proceeds to the upper urinary tract and visually checks each calyx of the renal collecting until RSL signals the calyceal stone. Irrigation assisted IL is restarted until no RSL- signal is picked up any more. The robot leaves the urinary tract. The assistant decides that no Double-J is needed.

Conclusion

In vitro tests on IL show extremely varying results depending on the experimental set-up [96, 97] and clinical trials do not necessary confirm each other [11] or the in vitro results [20]. In addition in-vitro tests may show statistically significant differences to drill holes in a small gypsum block but a difference of between 28 and 32 s [97] may be overridden by clinical reality. Reading some in vitro tests and studies comparing different lithotripters one gets the impression that in vitro testing is more complicated than clinical application and that the findings from in vitro tests are difficult to impossible to transfer into clinical praxis [21].

The IL method used in the individual case depends on the availability of instruments, the procedural time will depend on personal experience and temper, the residual stone rate on intraoperative irrigation technique, perseverance of searching for residuals, definition of fragment size and detection technique; the postprocedural emergency room visits may depend on patients sensitivity. What to do in the individual patient is a personal decision and the surgeon will ask for more or less power, higher or lower frequency and more fancy disposables depending on the impressions he has of the difficulties and of the progress he is making in the individual case. It cannot be expected that the literature offers a personal clue to what technique to apply. Elaborate experimental settings try to “to recreate the multifactorial interaction surgeon’s encounter during laser lithotripsy” but fail to do so and come to the conclusion that “clinical trials should be performed to confirm these results” [98].

Compliance with ethical standards

Conflict of interest Alken P is consultant for Karl Storz GmbH and Storz Medical.

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