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Laser-induced shock wave lithotripsy

Influence of laser pulse energy and irrigation solutions on stone disintegration

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Summary. With a high intensity Q-switched Nd-YAG laser shock waves can be generated in a liquid close to the calculus. Up to 80 mJ single pulse energy with 8 nsec pulse duration can be transmitted through flexible quartz fibers. Energy conversion and enhancement can be accomplished at the fiber tip with optical focussing of the light at the quartz tip, with irrigation solutions and with high pulse energies. Iron-III-dextran solutions (1 mg Fe^{3+}/l) and magnesium chloride (50 mmol/l) increased the pressure in the laser induced breakdown up to ten times (8,000–10,000 bar). Smaller stone particles and higher efficacy in stone fragmentation could be achieved.

Key words: Laser lithotripsy – Nd-YAG laser – Irrigation solution – Iron-III-dextran

Extracorporeal shock wave lithotripsy (ESWL) has changed the management of urinary calculi to a non-invasive procedure.

Nevertheless ureteral stones, especially those impacted in the ureter, very hard stones (e.g. calcium-oxalate-monohydrate or uric acid stones) or stones in the mid ureter are still a problem. Ureteral calculi comprise of up to 50% of all stones now and can cause considerable discomfort for the patient.

Ureteroscopic manipulation with rigid instruments can only employ rigid ultrasonic probes, baskets or forceps.

Laser induced shock waves with an extremely steep shock wave front and a high pressure amplitude can be generated by localized optomechanic energy conversion from a Q-switched, nanosecond pulsed Nd-YAG laser. At the interface between the surface of the calculus and the surrounding liquid, an electrical breakdown-laser induced breakdown (LIB) can be created, by increasing the power density of the laser beam. In the focus part of the fluid vaporizes and a tiny, plasma-filled bubble is generated. By expansion and attenuation of this localized plasma, a shock wave front is emitted and propagated in the medium. Expansion and cooling of the plasma results in an oscillating plasma bubble, which causes cavitation in the liquid. With a Nd-YAG laser of 1,064 nm wave length, 8 ns pulse duration and a single pulse energy of 30–80 mJ, shock waves can be generated with peak pressures of 1,000 bar in less than 4 ns. The energy within the medium is of a few Watts, so that in practice no thermal effects at all are involved [3, 5].

Coupling of the Q-switched laser energy into 600-, 400- or 200 μm quartz fibres was performed by a specially designed tube into the plane end of the fibre. Focussing of the laser pulses at the fiber tip in the form of a laser cone was achieved by a formed fiber end. Optimal stone disintegration is performed within the laser induced breakdown (LIB), seen at the fiber tip as a light cone. Fragmentation also can be heard as a series of slight clicking sounds.

Energy conversion at the fiber tip can be accomplished in four different ways:

1. focussing of the laser light,
2. irrigation solutions,
3. high pulse energies, and
4. LIB in the stone.

Composition and colour of the calculus determine disintegration characteristics if the stone itself is used as energy converter by the laser-induced breakdown (LIB). Thus the method is extremely "stone dependend" (dye-laser) while laser-induced shock wave generation with the nanosecond pulsed Nd-YAG laser works by shock wave creation in a liquid surrounding the stone.

Focussing of the laser beam at the fiber tip can be achieved by three methods:

1. a nonfoccusing, light concentrating system (light cone),
2. energy converting metal absorber (absorption of laser energy by free electrons at the metallic surface), and
3. optical focussing by "fire polishing" of the fiber tip.

Application of a light cone or a metal absorber increases the diameter of the laser fiber at the tip, resulting in a device difficult to handle in small caliber endoscopes or in the ureter. Only polishing of a lens at the end of the

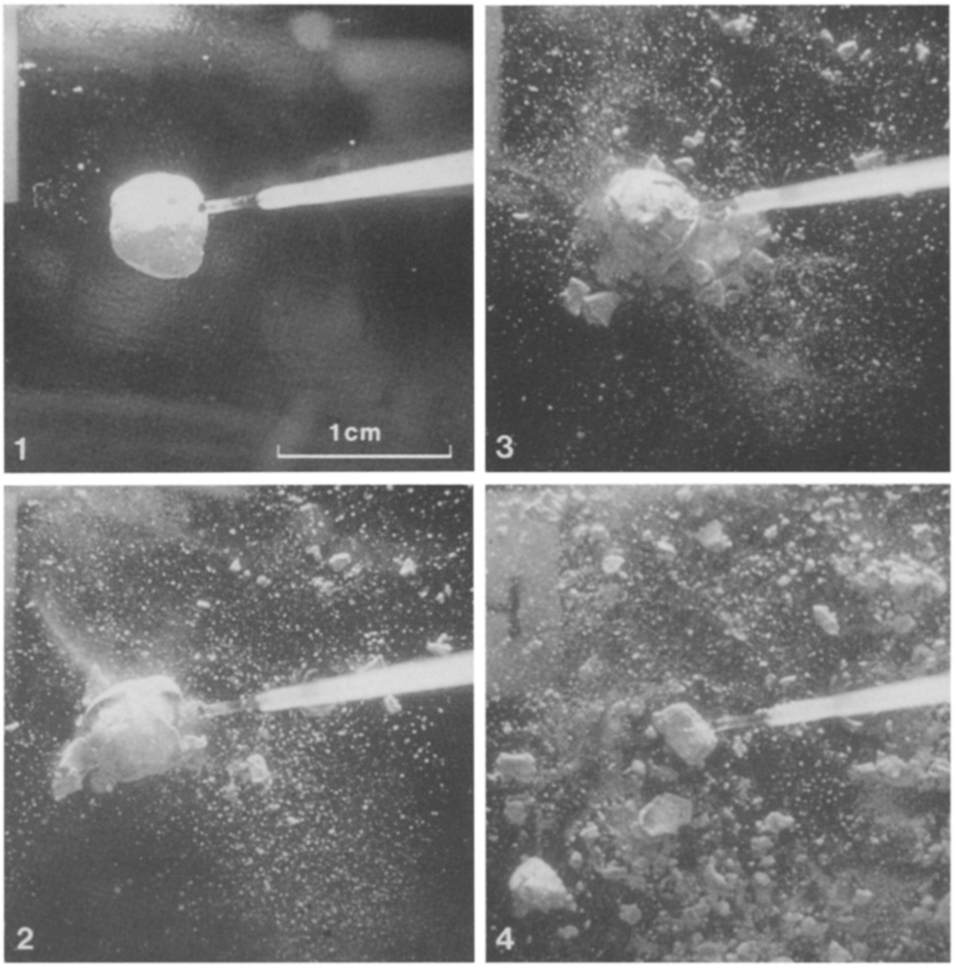

Fig. 1. Calcium-oxalate-mono-and-dihydrate stone in iron-III-dextran solution with 600 µm quartz fiber

Fig. 2. LISL after 1 s laser application with 50 mJ energy and 50 Hz repetition rate

Fig. 3. LISL after 2 s laser application (100 pulses)

Fig. 4. LISL after 15 s laser application (750 pulses)

quartz fiber itself results in a small enough focussing tip and can be moulded in all types and sizes of laser fibers.

Biological effects on the urothelium are limited to a tiny mechanical rupture of the tissue with focussed irradiation (100 µm width, 40 µm depth) without creating thermal effects or a hole through the ureteral wall. This mechanical effect of the shock wave is still confined to the urothelial mucosa [1, 2]. Intracorporeal laser-induced shock wave lithotripsy (LISL) with a high-intensity Nd-YAG laser using small flexible laser fibers has proved to be an effective and safe procedure for treatment of ureteral calculi. Large, obstructing stones can be completely fragmented into very tiny particles. The fragments are flushed out through the endoscope during laser treatment, so that the patient is free of stones immediately following the operation [3].

The aim of this study was to evaluate the influence of varying irrigation solutions during LISL, their impact on shock wave pressure generation in the liquid around the stone and their clinical application.

Material and methods

In an experimental setting, the stone and the laser fiber are brought under water and the stone is disintegrated under visual and acoustic control. After a few seconds, the liquid is blurred by stone powder thus absorbing the laser energy. Efficacy of stone disintegration and of vision are impaired. With irrigation of fresh solution to the stone, the liquid around the calculus is clear and LISL can be optimized. Different stone types show different hardness and resistence to LISL. Easily fragmentable stones such as apatite or struvite calculi are disintegrated into stone powder, thus opacifying the irrigation fluid to a greater extent than harder stones such as amorphous calcium-oxalate-monohydrate or uric acid stones (Figs. 1–4).

Variation of single pulse energy and pulse repetition rate results in a different size of stone particles. More than 100 different solutions – applicable for i.v. or local infusion in humans – have been tested for their ability to increase the LIB and consecutively increase efficacy of stone fragmentation. e.g. aqueous antibiotic solutions, ion solutions-sodium, potassium, calcium.... -metalic solutions and macromolecular solutions.

In vitro stone size – and in relation to fragmentation time – the efficacy were determined by two methods:

a. the stone was weighed and then packed into a net with defined mesh width. Laser irradiation created tiny stone particles, which fell through the net. The residual stone was weighed,

b. the stone was disintegrated in a certain time. Stone particles were either laid on a net or rafter and stone size was measured or stone particles were filtered through nets with different mesh width.

These procedures allowed correlation of the efficacy of stone disintegration (time/size) in relation to the composition of the stone. In an experimental setting, all stones, regardless of their composition were fragmented and laser parameters were optimized in this system.

During patient treatment however we realized that the experimental data for laser stone disintegration were not optimal for LISL in the ureter. In order to improve parameters for LISL in vivo, a new

Table 1. Efficacy of LISL in patient treatment

	35 mJ		45 mJ		50 mJ	
	30 Hz	50 Hz	30 Hz	50 Hz	30 Hz	50 Hz
0.9% sod. chl	+	+	+	+	++	++
1.4% sod. chl	+	+	+	++	++	+++
Mg2 + chl	++	++	++	+++	++++	++++
Fe3 + dextran	+++	+++	+++	++++	+++++	+++++

Nd-YAG laser λ = 1,064 nm; pulse duration = 8 ns; 600 μm quartz fiber; calcium-oxalate-mono- and -dihydrate calculus

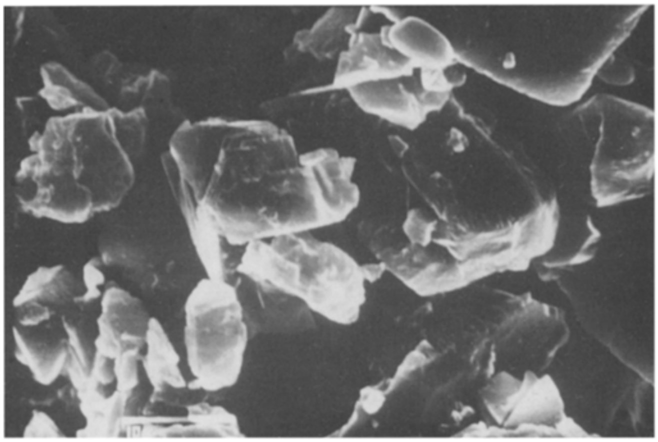

Fig. 5. Electron micrograph following LISL in the ureter (ca-ox-monohydrate stone, 50 Hz, 50 mJ single pulse energy, Fe^{3+}-dextran sol.) magnification × 1,550

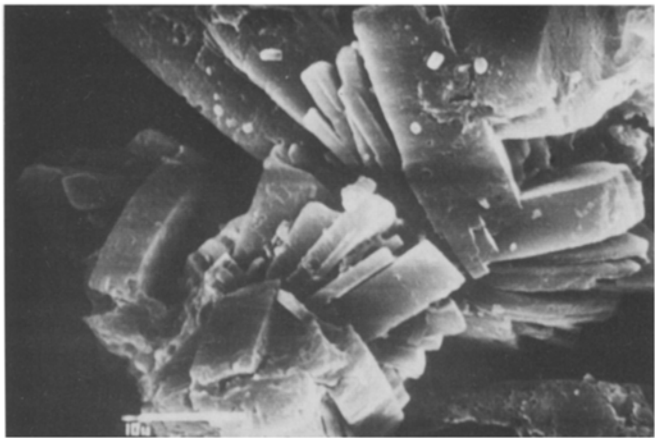

Fig. 6. Electron micrograph following LISL in the ureter of the same stone as in Fig. 5. 30 Hz, 35 mJ single pulse energy, Mg^{2+} Cl sol.), magnification × 1,550. Note bigger particle size

method to evaluate the efficacy of different treatment options at the same time was used.

During LISL, using a rigid ureteroscope and a 600 μm quartz fiber, single pulse energy and repetition rate of the laser was changed as well as the irrigation fluid. Stone particles created during the treatment were flushed out through the endoscope and collected separately. Stone particles were weighed and classified according to their size. Electron microscopy was performed to evaluate particle size and form. Stone analysis was done with X-ray diffractometry. Laser stone fragmentation was thus performed always on the same stone, allowing direct correlation between stone composition, laser- and irrigation solution parameters. Three different calcium-oxalate-monohydrate and three calcium-oxalate-dihydrate stones were irradiated with 35-, 45- and 50 mJ single pulse energy in the ureter. Pulse repetition rate was changed from 30 to 50 Hz and four different irrigation solutions were evaluated (0.9% and 1.4% sodium chloride, 50 mmol/l magnesium chloride and 1 mg/l iron-III-dextran solution).

Results

Irradiation of the same stone showed, that efficacy of laser stone disintegration was increased with higher single pulse energy and higher repetition rate. Moreover stone particles created with higher energy were smaller. Concentrated saline also improved LISL by generating a more powerful LIB in front of the stone, thus reducing particles size.

From the great variety of physiological irrigation solutions that are currently available, only two preparations showed an astonishing effect: magnesium chloride (Mg^{2+}-Cl) and iron-III-dextran complex (Fe^{3+}-dextran) (Table 1).

With these solutions, LISL was improved about tenfold, resulting in an increased LIB and a much higher desintegration rate compared to all other solutions. Especially Fe^{3+}-dextran proved to be most effective in a minimal concentration of 1 mg Fe^{3+}/l. Higher Fe^{3+} concentrations resulted in higher efficacy, however also in an increased probability of a LIB at the fibre tip with consecutive fibre damage. 1 mg/l Fe^{3+} solution did not cause fiber damage more often than sodium chloride solutions (0.9% – or 1.4%), while lower Fe^{3+} concentrations in the solution impaired the LIB. In iron-III-solutions smaller stone particles (or stone powder) were created compared to magnesium solutions, where slightly bigger fragments were induced (Figs. 5 and 6).

Discussion

Optimal parameters for intracorporeal laser induced shock wave lithotripsy have been found to be 8 ns pulse duration, 5o Hz repetition rate and 50 mJ single pulse energy (600 µm fiber). Constant irrigation and drainage of the stone powder is mandatory to keep vision and efficacy of the laser treatment optimal.

Increased concentrations of sodium chloride (1.4% comp. to 0.9%) resulted in an increased efficacy of LISL while two solutions-magnesium chloride and iron-dextran-complex-improved LISL tremendously. Especially 1 mg/l Fe^{3+} proved to be optimum.

The effect of metallic solutions on the laser induced breakdown in liquids is not fully understood so far, however a self-focussing effect of the laser beam in a metallic solution is assumed. The already focussed laser beam with high peak pressures (1,000–10,000 bar) can thus be intesified even more, creating a smaller focus and smaller stone fragments. Probably this development could also have some impact on shock wave creation with ESWL, as these shock waves might also be influenced by the solution surrounding the calculus.

When using a smaller laser fiber with 320 µm core diameter lithotripsy solutions are not necessary, as the focus is already smaller and fragmentation nearly equals the results with a 600 µm fiber in combination with metallic irriagation solutions.

References

1. Hofmann R, Hartung R, Geißdörfer K, Ascherl R, Erhardt W, Schmidt-Kloiber H, Reichel E (1987) Morphologische Untersuchungen des Urothels nach Einwirkung intensiver Nanosekunden Laserpulse. Urol Int 42:434
2. Hofmann R, Hartung R, Geißdörfer K, Ascherl R, Erhardt W, Schmidt-Kloiber H, Reichel E (1988) Laser induced shock wave lithotripsy-biologic effects of nanosecond pulses. J Urol 139:1077
3. Hofmann R, Hartung R, Schmidt-Kloiber H, Reichel E (1989) First clinical experience with a Q-switched Nd-YAG laser for urinary calculi. J Urol 141:275
4. Schmidt-Kloiber H, Reichel E (1984) Die Abhängigkeit der Druckamplitude einer Stoßwelle von der Feldstärke beim laser induzierten Durchbruch in Flüssigkeiten. Acustica 54:284
5. Schmidt-Kloiber H, Reichel E, Schöffmann H (1985) Laser induced shock wave lithotripsy (LISL). Biomed Tech 30:173

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