

A PRELIMINARY ANALYSIS OF POSSIBILITIES OF COMPENSATING FAULTS OF LASER AND ULTRASONIC TECHNOLOGIES IN SURGERY

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The active applications of ultrasounds and laser light in surgery are similar. Both technologies complement each other and allow us to obtain desired effects, eliminating the limitations of ultrasounds and lasers used separately. Therefore what happens very often during a medical procedure is the simultaneous use of these two methods from separate standard devices. Having proved the possibility of acoustic wave propagation through optical fibers, the combination of laser light and ultrasounds in one device seems more effective. A comparative analysis of both systems shows that combining the advantages of ultrasonic devices and lasers in one device allows us to compensate for the faults of each of the technologies and improve the effectiveness of surgical operations. The preliminary tests of the operation of the laser-ultrasonic cutter produced positive and encouraging results. The combined technology has made it possible to use ultrasounds for endoscope operations and to decrease the power of laser and consequently lessen the risk of burning the quartz tip and the optical fiber. A precise selection of the optical fiber seems to be crucial to obtaining an effective laser-ultrasonic surgical device. What is equally important is the appropriate way the light and ultrasonic energies interact.

Keywords: surgical laser, high intensity ultrasound, acoustic wave propagation, optical fiber.

1. Introduction

The active applications of ultrasounds and laser light in surgery are similar. The high intensity and low frequency ultrasounds and surgical lasers (high-energy) are used among others to:

- cut parenchymatous organs, rich in blood (liver, kidneys),
- remove tumors (brain, eyeball),
- remove atherosclerotic plates.

Additionally, thanks to the use of optical fibers, lasers are used in laparoscopic and endoscopic surgical operations.

Apart from advantages, each of the mentioned technologies has also some disadvantages limiting the area of application of each of them. Both technologies complement each other and very often during a medical procedure there is the simultaneous use of these two methods from separate standard devices.

The working ending of the ultrasonic surgical cutter is most often made of titanium. The transmission of ultrasounds via metal waveguides leads to the undesirable heating of the titanium tip and tissue at larger distances. Additionally, the fact that the titanium tip is not elastic makes the ultrasonic cutter useless in endoscopic surgery. After demonstrating the possibility for the propagation of sound wave via optical fibers [1], what seems more effective is the combination of laser and ultrasounds in one device.

2. Comparative analysis and results of initial tests

A comparative analysis of both systems shows that combining the advantages of ultrasounds and laser light in one device makes it possible to compensate for the faults of each of the technologies (Table 1) and improve the effectiveness of surgical operations.

The main disadvantages of ultrasonic technology are:

- unsatisfactory coagulation of vessels,
- lack of a flexible titanium tip,
- undesirable heating of the titanium tip and tissue.

One of the lasers most often applied in surgery is the Nd : YAG.laser. It can be applied in non-contact and in contact modes.

The disadvantages of laser technology are:

- considerable depth of tissue damage for contact method and more extensive tissue necrosis covered with carbonized layer – it lessens the efficiency of the laser and covers up the main vessels placed deeply,
- threat of burning the quartz tip during contact with tissue or blood,
- lack of selective cutting of different tissues,
- poor cutting properties in the non-contact mode, the contact mode has made it possible to improve the cutting properties while weakening of the coagulation properties of laser radiation,
- resection producing smoke,
- the dynamics of the crater depth in the time function shows that the most effective cutting is in the first second, then a rapid satiation of this curve and overheating of the fiber take place; it is caused by the difficulties in removing the tissue destruction products and the sedimentation of these products at the end of the fiber.

The profits of combining both technologies include the possibility for lessening the laser power, which will decrease the fiber's heating and consequently lessen the risk of burning the end of the quartz fiber.

The device would make it possible to reduce the total operation time and bleeding during and after the operation [2]. Reduced bleeding is caused first of all by the selectivity of cutting different tissues using ultrasound. The more collagen and/or elastin there are in the tissue the greater the strength and the lesser the tissue removal ability of the

device. In result it is easy to expose and preserve larger vessels and nerves, making it possible to remove undesired tissues (tumors) precisely [3].

Table 1. Comparison of laser and ultrasonic technologies in surgery.

| Parameter | Laser | | Ultrasound | Joined (prognosis) |
|------------------------|------------------------------------|----------------|-----------------------|--|
| | Non-contact | Contact | | |
| Operation time | 31.5 min | — | 36.8 min | 16.5 min |
| Necrosis | 3–5 mm | 0.3–0.8 mm | 0–1.4 mm | 0.1–0.2 |
| Depth of tissue damage | 3–5 [mm] | 0.5–1 [mm] | < contact | < non-contact |
| Cutting | poor | good | good | good |
| Coagulation | good | good enough | poor | good |
| Smoke production | yes | practically no | reduced quantity | sucked out |
| Selectivity | no | no | yes | yes |
| Hemostasis | yes | yes | no | yes |
| Sterility | yes | yes | no | yes |
| Bleeding | 79 [ml] | < non-contact | 60 [ml] | 47.5 [ml] |
| Power | optimal 50–60 W | 20–25 W | 90% of the max. power | Laser: 25 W non-contact, Ultrasound: 60% of the max. power |
| Energy | 25 W – 17 ± 1.2 kJ, 100 W – 3500 J | 1053 ± 206 J | — | 4711 J |

3. Simultaneous laser – ultrasound transmission

In order to make the combination of both technologies effective, a selection of appropriate material the fiber is made of is required. A precise selection of the optical fiber seems to be crucial to obtaining an effective laser-ultrasonic surgical device. Relations concerning the propagation of the acoustic wave in the optical fiber can be calculated by analogy from some well-known optical formulas.

Optical (n) and acoustic (N) refractive indexes:

$$n = \frac{c_0}{c}, \quad N = \frac{V_0}{V}, \quad (1)$$

c_0 – speed of light in vacuum, c – speed of light in medium, V_0 – sound waves' velocity in air, V – sound waves' velocity in medium.

Weak guidance conditions can be used for the description of the propagation of the acoustic wave in optical fibers.

Weak guidance condition in optics:

$$\Delta_o = \frac{n_1 - n_2}{n_1} \ll 1, \quad (2)$$

n_1, n_2 – refractive index in core and cladding respectively, Δ_o – normalized core-cladding refractive index difference.

Weak guidance conditions for an acoustic wave [4]:

1) mass density condition:

$$\Delta_\rho = \frac{|\rho_1 - \rho_2|}{\rho_1} \ll 1, \quad (3)$$

ρ_1, ρ_2 – core and cladding density respectively, Δ_ρ – normalized core-cladding mass density difference;

2) sound wave velocity condition:

$$\Delta_v = \frac{|v_1 - v_2|}{v_1} \ll 1, \quad (4)$$

Δv – normalized core-cladding sound wave velocity difference.

The mass density condition and the sound wave velocity condition can be combined into one condition called the acoustical weak guidance condition:

$$\Delta_a = \Delta_\rho \Delta_v. \quad (5)$$

When $\Delta_\rho \ll 1$ and $\Delta v_T \ll 1$, apart from guided transverse-type mode there is another set of modes that are leaky and longitudinal (axial-radial) types.

The attenuation due to the leakage of power is governed by the transverse wave velocity and density differences in the core and in the cladding. Because $\Delta_\rho \ll \Delta v_T$, the main parameter is Δv_T .

The longitudinal character of leaky modes is influenced strongly by the longitudinal velocity difference:

$$\Delta_{vL} = \frac{|v_{L1} - v_{L2}|}{v_{L1}} \ll 1, \quad (6)$$

Since $V_{L1} \approx V_{L2}$, the transverse component of the mode is much smaller than the longitudinal component, and such a mode is predominantly longitudinal.

The appropriate transducer of longitudinal waves can eliminate the transverse mode.

The conditions for propagation of the longitudinal acoustic wave are: $V_{L1} < V_{L2}$, $V_{T1} < V_{T2}$, $V_{L1} > V_{T2}$.

What results from the above mentioned conditions is that a good fiber for both transmissions should simultaneously have the smallest values of: the normalized core-cladding refractive index difference Δ_o and the normalized core-cladding sound wave velocity difference Δv (for longitudinal and transversal wave). Such a combination of parameters cannot be obtained.

Fibers appropriate for both types of transmission are a compromise between a good quality for the acoustic application and a good quality for the optical application. The core of the fiber made of 92.5% of SiO_2 and 7.5% of TiO_2 . The cladding made of 100% of SiO_2 enables the simultaneous transmission of the light wave and the ultrasound wave.

The very weak match-up of impedance between the transducer and the air and between the air and the optical glass fiber is one defect in the use of optical fibers for the transmission of the acoustic wave. For this reason optical glass fibers should be fixed directly to acoustic transducers. An efficient mounting method to connect the fiber to the transducer is doing it by using some high performance glue (epoxy resins) at the end of the amplitude transformer (Fig. 1). Applying the indirect coupling system is also possible (although it is bound up with some energy losses). Such a solution is forecast for the future.

4. Results of initial tests

A sandwich ultrasonic transducer was designed and manufactured for initial tests, with a velocity transformer working at the frequency of 52 kHz with an optical fiber placed and firmly fixed at the transformer's end. The sound velocity in the core is 5806 m/s, ($\lambda = 111.6$ mm). The applied diameters of optical fibers in the surgery are 400–1000 μm , so $\lambda \gg 100$ diameter of the core (the axial component will be predominant). Additionally, silica glass has a very small value of the Poisson's ratio (smaller radial oscillation amplitudes) [5]. The length of the optical fiber should be $\lambda/2$ (or a multiple of $\lambda/2$) in order to obtain the maximum of the vibration amplitude.

The possibilities for simultaneous delivery of laser radiation and ultrasounds of low frequency and high intensity are as follows:

- introducing ultrasound oscillations in the optical fiber by the stiff fixing of the fiber to the vibrating element (Fig. 1),

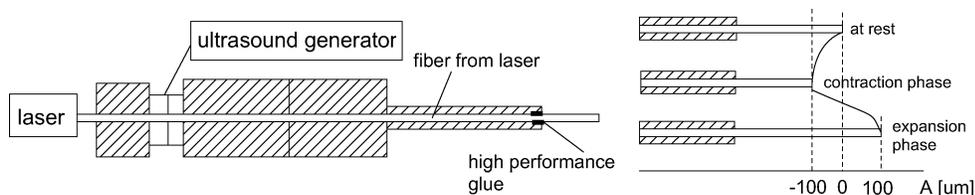


Fig. 1. Stiff fixing of fiber to ultrasound transducer, A – elongation (demonstrative figure only).

- non-contact influence of the ultrasonic wave on the laser beam (Fig. 2),

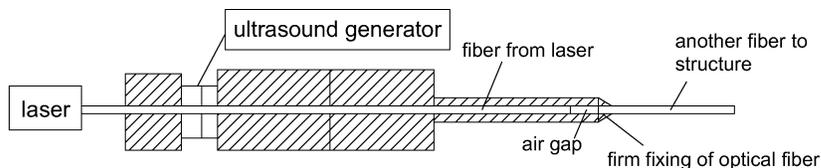


Fig. 2. Influence of ultrasonic wave on laser beam through air-gap.

An air gap makes it possible to decouple the optical transmission from the acoustic oscillation, and thus a modulation of the optical radiation by ultrasonic oscillations can be realized. This solution was presented in literature [5, 6].

The acoustic wave causes the change of the refractive index of light and thereby it is possible to modulate the laser radiation.

The Mach–Zehnder optical interferometer was used to observe the phase change of the laser radiation. The light beam is divided into two parts, and then again joined in one. An ultrasonic transducer with an optical fiber inside it is placed on one of the roads. The oscillations cause an expansion of the optical fiber and thus a change of its length, causing the phase displacement of the signal.

5. Conclusions

There is a possibility of combining the benefits of ultrasonic and laser cutters, at the same time limiting the defects of using these surgical devices separately. In order to make the combination of both technologies effective, it is necessary to select appropriate material the fiber is made of and an appropriate way of how the light and ultrasounds co-operate. The development of versatile devices in medicine is desired in order to reduce the number of equipment in hospitals. The development of multifunctional devices combining some effects of lasers and ultrasounds complementing each other could contribute to elimination of some defects of the two methods used separately. The experiments performed show the possibility of the simultaneous transmission of light and ultrasonic wave. The result is a possibility of obtaining the effect of fragmentation (cuts) of structures with the use of both technologies simultaneously and with reduced summary power delivered to the cutter.

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