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On the Difference in Action of the Laser Light with Wavelength Near 2mm on Biotissue in Gas and Water Media

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Abstract

It is shown that unlike action in the air environment, section of the biotissue in the water environment (physiological solution) is performed by the steam-gas stream which is formed as a result of superintensive boiling in thin (about 0.1 mm) a liquid layer in which absorbed laser radiation. Coagulation of the biotissue, adjacent to a section, happens due to heat which is produced via vapor condensation.

Keywords: laser radiation in urology, a laser enucleation of the BPH, laser removal of the bladder cancer.

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The laser radiation with wavelength near 2 μm is considered as the most perspective from the point of view of the urological applications as it can be effective for different surgeries on soft tissues, and for a lithotripsy [1]. It is not surprising that devices of this range are issued many vendors, each of which draws on advantage their production. The purpose of this article is to carry out the comparative analysis of the properties of different lasers from this range radiation, opportunities of the laser devices developed on their basis in urology and also perspectives of their enhancement.

1. Lasers, generate radiation with the wavelength near 2 μm.

Fist of all we are to note that the accepted division into "thullium" (Tm) and "holmium" (Ho) lasers doesn't give the exhaustive characteristic of the laser media, used in devices. The matter is that characteristics of lasers and a possibility of the devices developed on their basis are influenced by not only an ion of the activator of the laser media, but also a matrix in which it is introduced. Now there are used in medical devices of 2 μm range lasers with:

1. Ho:YAG;
2. Tm:YAG;
3. Tm-doped fiber.

Characteristics of several relatives in output parameters of the devices (including the Russian device ”Urolas”, the approval No. RZN 2017/5446) generating a laser radiation with wavelength near 2 µm with the maximum power output of this radiation of 120 W are presented in table 1. and being of interest for urological applications.

It should be noted, that in the device ”Urolaz” according to [2] the possibility to add in the output fiber of additional radiation with wavelength of 1.55 µm is realized. At the same time capacities and temporal operation modes of this radiations are regulated independently. Photos of these devices are presented at fig.1.

Table 1

Device	Pulse 120H	RevoLix 120	Vela-XL	Urolas
Active media	Ho:YAG	Tm:YAG	Tm-doped fiber	
λ, µm	2.1	2.01	1.94	1.94+ 1.55
Output power, W	120 (average)	120	120	120+15
Mode	Pulse 0,2-6Дж, 5-80 Гц	Pulse 50ms-1s, CW	Pulse 1 ms - CW	Pulse 0,2ms-1s, CW
λ pointer, µm	0.53	0.53 or 0.635	0.53	0.53
Weight, кг	245	150	150	<40
Sizes, cm	47x116x105	42x95x89	30x95x105	55x46x29
Power consumption	200-240V, <46A	200-240V, <15A	200-240V, <16A	220V±10%, <10A
Production	«Lumenis», Israel	«Lisa laser», Germany	«Starmedtec», Germany	NTO “IRE-Polus”, Russia

Use of fiber with the minimal diameter of a fiber core is desirable for reduction of invasiveness of surgical operations. The high quality of the fiber lasers radiation allows to enter easily radiations into an optical fiber with a core diameter of 100 µm and less. At the same time, for obtaining output radiation in the light waveguide with a diameter about 200 µm in devices on crystals it is necessary to use so-called tapered (tapered – conical, made narrower) fibers whith diameter of a core on the input end more, than diameter on the output (distal) end of a fiber. And even in this case it is not possible to reach diameter of 200 microns so the fibers NV-200 and RBLF-200 used with offices of the Lumenis have diameter of a core of 274 µm on an output end.

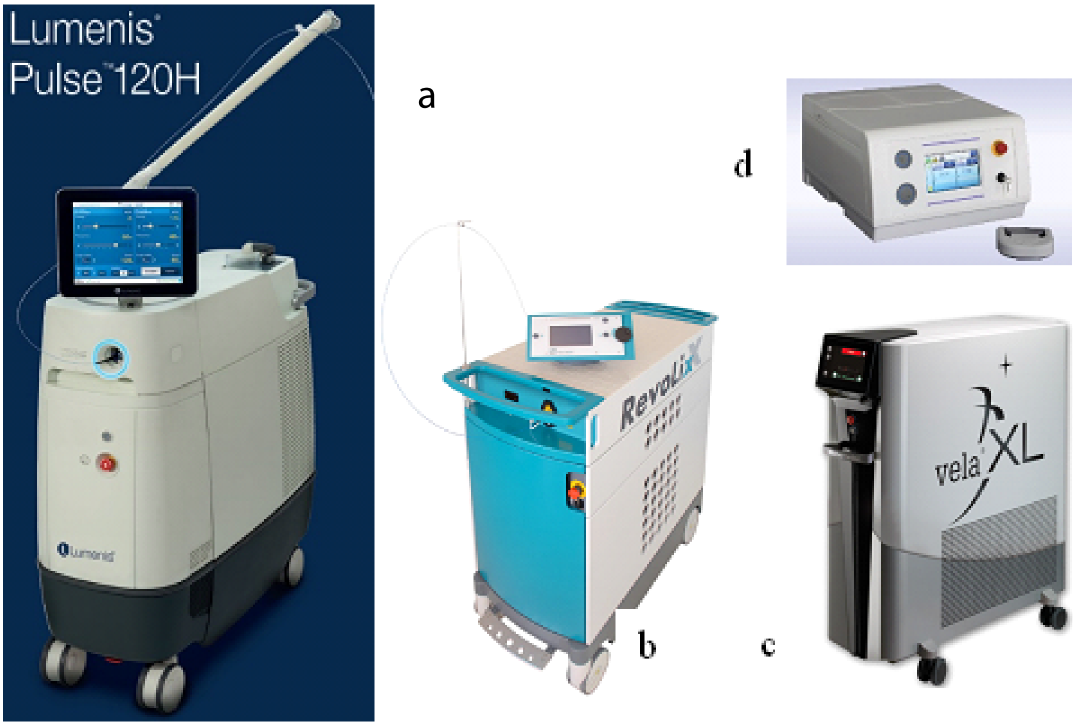

Figure 1: Medical laser devices for 2 μm range: a – «Pulse120H»; b – «Revolix 120»; c – «Vela-XL»; d – «Urolas».

The high efficiency of diode pumping allows to improve weight and dimensional characteristics of devices in comparison with the devices using lasers with a lamp pumping and to reduce their energy consumption. Further improvement of these characteristics is implemented upon transition from liquid cooling to air cooling that is applied in the device ”Urolas”.

Ho:YAG lasers with lamp pumping do not allow to ensure the CW duty functioning and work only in an pulse periodic duty, so duration of pulses and the frequency of their following can change in the limited ranges. Tm:YAG lasers and lasers with the Tm-doped fibers with diode pumping can work both in the CW, and in an pulse periodic duty in which duration of pulses and pauses is set turn-on time and pump switching off. Additional opportunities appear in case of modulation of pumping diode power supply, thanks to which it is possible to control the form of radiation pulses. In fig. 2 and fig. 3 typical oscillograms of a radiation pulses of the device ”VersaPulse Power Suite P100” (the predecessor of ”Pulse120H” with emissive power of 100 W) and the ”Urolas” are presented for an example in case of generation of square pulses, which duration for ”Urolas” can be changed from 0.05 ms to the CW.

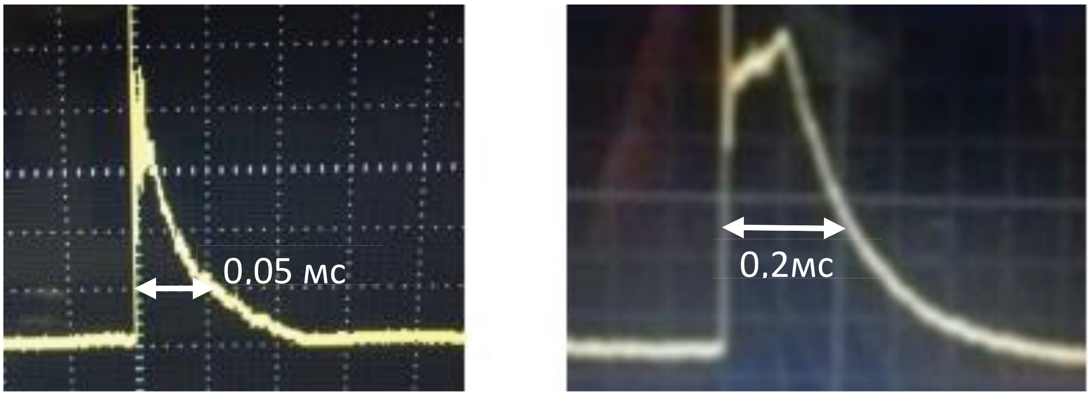

Figure 2: Pulse form for «VersaPulse Power Suite P100». Range of the pulse duration 0.05-0,3 ms.

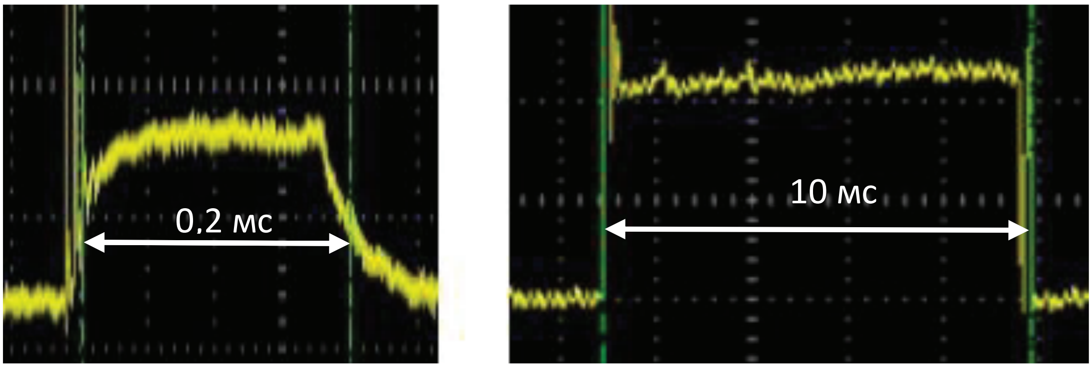

Figure 3: Pulse form for "Urolase".

2. Absorption of the laser radiation

Results of laser radiation action on biological objects is defined by process of its absorption in biotissue on the subsequent transformation of the absorbed energy into heat, so amount of the energy brought by radiation in a point of action and the size of that part of this energy which has been absorbed. At passing of radiation through biotissue there is its absorption by chromophores (the biotissue components absorbing radiation) and its scattering on inhomogeneities. Both of these processes lead to attenuation of radiation. At passing of radiation through transparent media (water, physiological solution) scattering is absent, and weakening is defined by absorption in the media. The attenuation determines thickness of a layer in which radiation will be absorbed and transformed in heat.

Absorption coefficients in chromophores define a ratio between amounts of the energy absorbed in them. The main chromophores for the radiation of the considered tissue of infrared range are water and hemoglobin. In fig. 4 for the wavelengths 1.4-2.1

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μm dependences of absorption coefficient μ in water [3] are presented. Near the same dependence (fig.5) is for RBCs in saline solution with a Hct 33.2% - blood phantom [4].

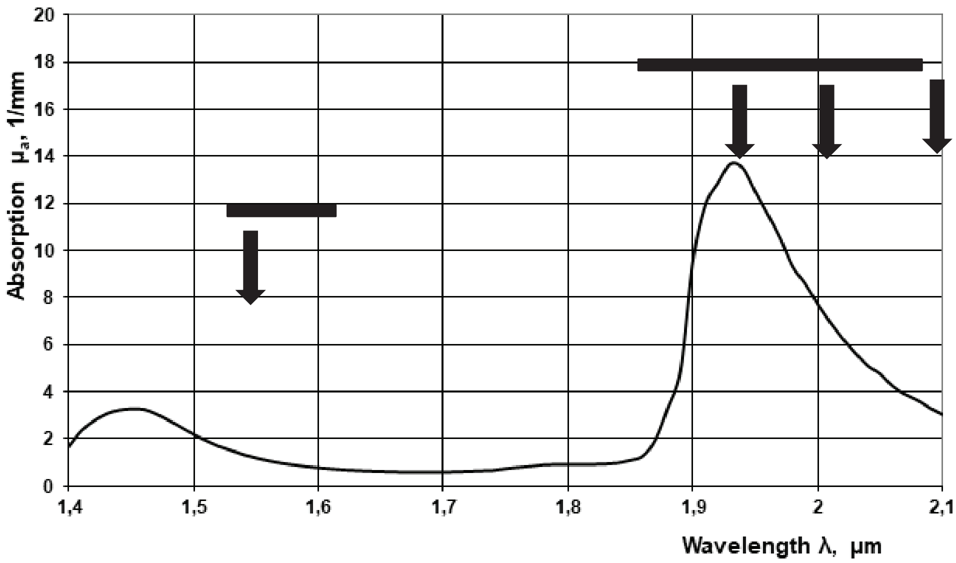

Figure 4: Absorption μ_a in water (arrows indicate wavelengths 1.55; 1.94; 2.01 and 2.1 μm).

The main difference between lasers on crystals and fiber lasers is that the lasers using the crystalline media, in particular Ho:YAG and Tm:YAG generate radiation with a small width of a spectrum on a certain wavelength (are shown by arrows in fig. 4), while fiber lasers are capable to generate radiation in broad bands of a wavelengths, and it is possible to select working wavelength within these bands.

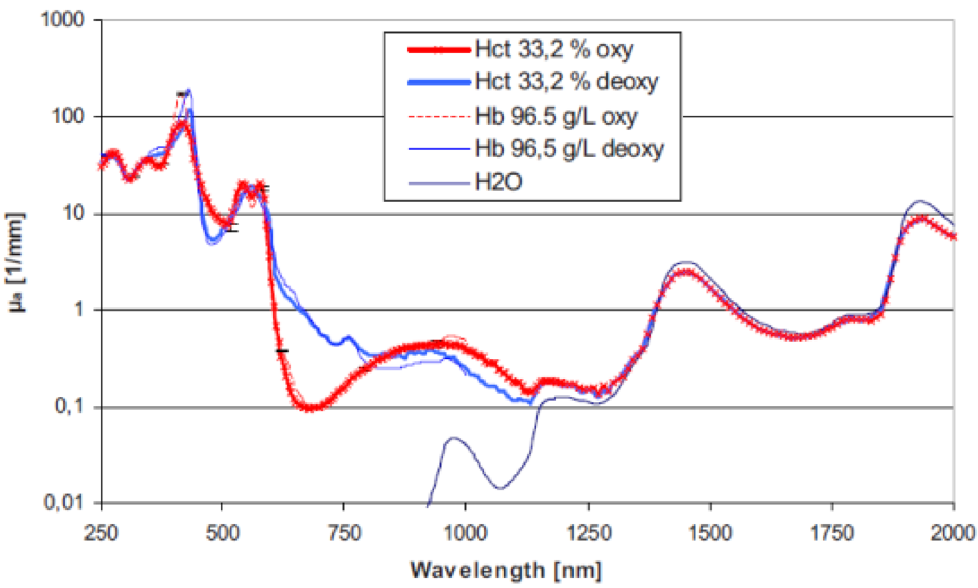

Figure 5: μ of RBCs in saline solution with a Hct 33.2% dependent on wavelength with an oxygen saturation of 100% and 0% compared with a hemoglobin solution with a corresponding hemoglobin concentration of 96.5 g/dL.

Wide lines in fig. 4 present areas in which implementation of generation in lasers on Tm- and the Er-doped fibers – according to 1.53-1.62 µm for Er and 1.86-2.09 µm for Tm is possible [5]. In particular, for medical applications for lasers on the Tm-activated fiber usually select wavelength of working radiation near 1.95 microns, (it is specified fig. 4 by an arrow) corresponding on the one hand to maximum efficiency of generation and, on the other hand, the maximum values μ_a and μ_{eff} in water and whole blood.

Besides the arrow in a figure marked wavelength 1.55 µm of the radiation of the laser with the Er-doped fiber, wich is added in output fiber of ”Urolas” to the main radiation of 1.94 µm.

Value of the effective attenuation of radiation μ_{eff} defines laser radiation penetration depth in biotissue, so the area in which laser radiation is absorbed and transformed in heat.

Follows from the given dependences that in the considered range absorption coefficients and effective attenuation of a laser radiation in water and whole blood at the wavelength of 1.94 µm, used in the devices ”Vela-XL” and ”Urolas”, approximately are twice higher, than at the wavelength 2.01 µm (”RevoLix”), is 4 times higher, than at the wavelength of 2.1 µm (”VersaPulse Power Suite P100” and ”Pulse120H”) and is about 10 times above, than at the wavelength of 1.55 µm.

3. Impact on soft tissue

Use of laser radiation for cutting and an ablation (vaporization) of biotissues sets a task of ensuring high speed of a tissue removal with the minimal undesirable thermal damage of tissue near area of influence and a reliable hemostasis. The solution of the first two tasks requires high absorption of radiation as in this case energy of radiation is absorbed in small volume and there is a fast local heating of tissue to temperatures causing its ablation. And, naturally, at reduction of field of absorption of energy, thickness of a zone of the tissues, adjacent to the place of influence, which are exposed to undesirable heating decreases. From these points of view the efficiency of action grows among laser light wavelengths 2.1; 2.01 and 1.94 µm.

At the same time, for a reliable hemostasis it is necessary to provide the sufficient depth of a tissue heating, adjacent to area, in which tissue are heated till coagulation temperature. As in case of application of radiation with wavelength 1.94 µm it can appear insufficiently for such heating, the possibility of adding to the main radiation of the additional radiation with wavelength of 1.55 µm more deeply penetrating into water and blood is provided in the device "Urolas". So it is possible to increase thickness the coagulated tissue layer receiving more reliable hemostasis. The level of coagulation can be varied in some limits as the power of this radiation can be adjusted independently of the power of the main radiation.

One of up to date problems of urology is the BPH treatment. The traditional open surgery is followed by a large number of complications in comparison with modern low-invasive technologies. Low-invasive electrosurgical and laser methods are generally applied in clinical practice now. Two approaches for treatment with use of laser radiation, are presented at fig. 6.

Laser vaporization (fig. 6a) at which by means of the fiber tools removing laser radiation at an angle to an axis of fiber (fig. 6b) the layer-by-layer ablation of pathological tissue is performed. Radiation of the Tm fiber lasers for vaporization of BPH which has shown prospects of use of this radiation has carried out N.M.Fried et.al. (see, for example, [6]). Within preclinical tests of the device "Urolas" the researches directed to optimization the action on soft tissues [7] was performed.

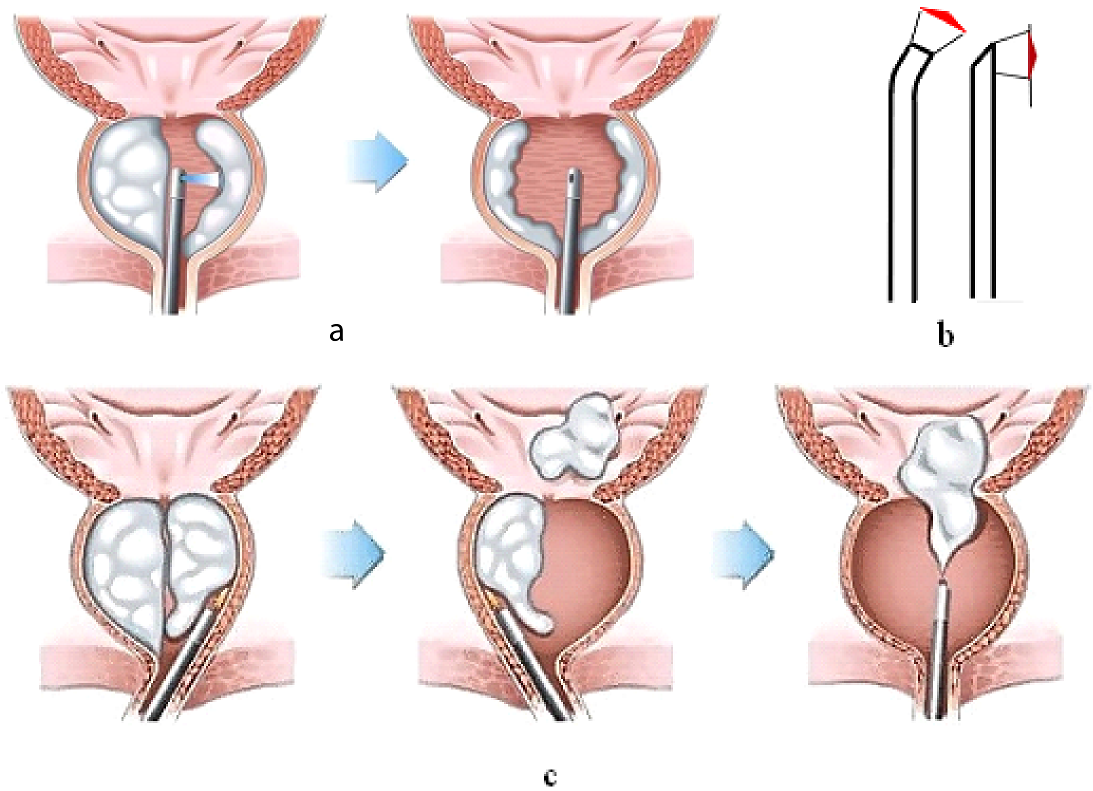

Figure 6: Transurethral BPH treatment via laser vaporization (a) and enucleation (c), and fiber instruments, used for vaporization – «twister» and «side-fiber» (b).

Now more preferable is low-invasive method of BPH treatment - transurethral laser enucleation (fig. 6c). In this case the laser radiation separate pathological tissue from the capsule and coagulate the bleeding vessels. This border is well differentiated through endoscope. The separated tissue is pushed out in a bladder from where removed by means of a mortsellyator.

Enucleation has the following advantages in comparison with vaporization:

- time and energy of laser radiation for vaporation of all pathological tissue isn't required that reduces operation duration;
- action accuracy, especially on border of pathological tissue with healthy increases, thanks to this there is possible a full removal of pathological tissue without increase in risk of intraoperative complications in the form of damage of the capsule of a prostate or a wall of a bladder;
- there is a possibility to have removed tissue for a histologic investigation;
- operation is carried out by means of the simplest and cheap fiber tool with a flat distal end allowing besides repeated sterilization and repeated application.

Similar approach is applied also to removal of nonmuscle-invasive bladder cancer [8].

We will consider the nature of the laser radiation action on biotissues in the gas environment and the environment of physiological solution. In the gas environment (fig. 7) local warming up of a tissue to the temperature above 250 °C in the place of absorption of radiation there is a biotissue carbonization because of which the coefficient of absorption increases and the area in which energy of the absorbed radiation is emitted decreases. Temperature of this area increases up to about 1000 °C. It, in turn leads to acceleration of an ablation of biotissue. At contact of the end of the fiber there is also his warming up to so high temperatures. As a result action of the heated end of the fiber is added to action of radiation [9]. At cutting of biotissue smoke, which needs to be evacuated away, is formed.

BPH enucleation and surgeries in a bladder is performed in physiological solution environment, so, practically in the water environment. In this case processes are more complex. In lack of contact with bioetissue laser radiation is absorbed in a thin layer of liquid near an output end of the fiber. The absorbed energy becomes the reason of release of the gases dissolved in liquid and superintensive boiling [10, 11]. As a result of this boiling the intensive two-phase (liquid-gas) stream (further just "stream") formed by small (about 50 microns in the diameter) steam-gas bubbles and the warmed liquid. Existence of this stream has threshold character: for the laser radiation of 1.94 μm and diameter of a fiber core of 0,4 mm it appears at the power of radiation more than about

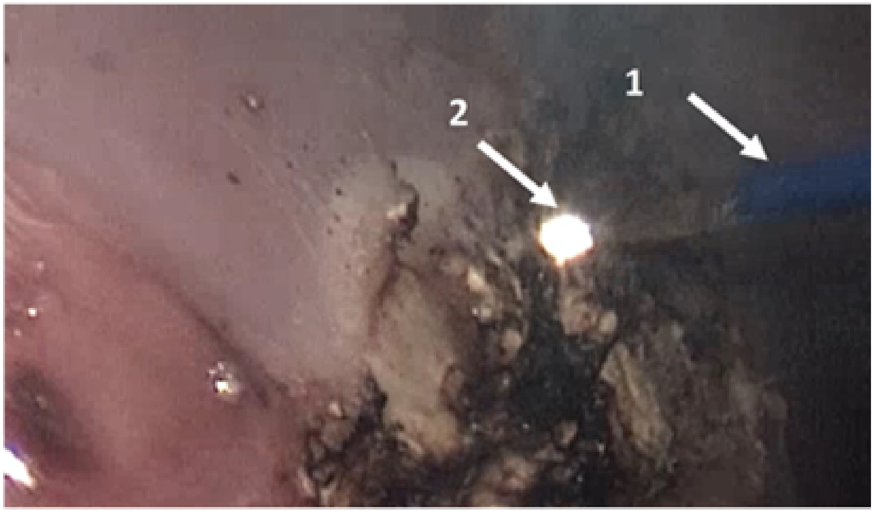

Figure 7: Endoscopic kidney laser cutting in gas media. 1 – fiber, 2.- contact of fiber end with tissue.

3 W. Speed of this stream quickly increases with a power of radiation from 85±15 mm/s at P =3 W up to 450±65 mm/s at P =10 W [11]. Due to high kinetic energy of a stream it cuts biotissues.

In fig.8a-d there were presented photos of biotissue cutting by a stream in operation of a laser BPH enucleation, which is performed with a radiation of 1.94 μm in the pulse - periodic mode with a average power of radiation of 60 W, Pulse duration 12 ms and energy of impulses of 1.4 J. In some moments steam-gas microbubbles merges, (fig. 8.b) and forms the macrobubble of 3-5 mm in size (fig. 8c).

Length of a stream cutting part is about 3-5 mm. At condensation of steam biotissues is heated, carrying out coagulation of layers, adjacent to a section walls. As temperature of a stream is significantly less than temperature of carbonization (about 250 °C), carbonization at section is practically absent.

If there is a contact of fiber end with biotissue, the fiber end is warmed for a short time (1 in fig. 7d) and begins to shine, at the same time because of pyrolysis of biotissue there is a carbonization, a considerable part of the carbonized tissue burns down because of the increasing absorption of radiation. At the same time, during the whole time the stream (2 in fig. 7) exists and cuts tissue.

Technology of carrying out operation of an enukleation of BPH with АИГ:Ho (”Lumenis Pulse-120”) and the Tm fiber laser are close. At the same time it is worth to remember about advantage of the ”Urolas” with the laser on Tm–doped fiber regarding the weight, dimensions and convenience of work. Besides, comparison was carried out for

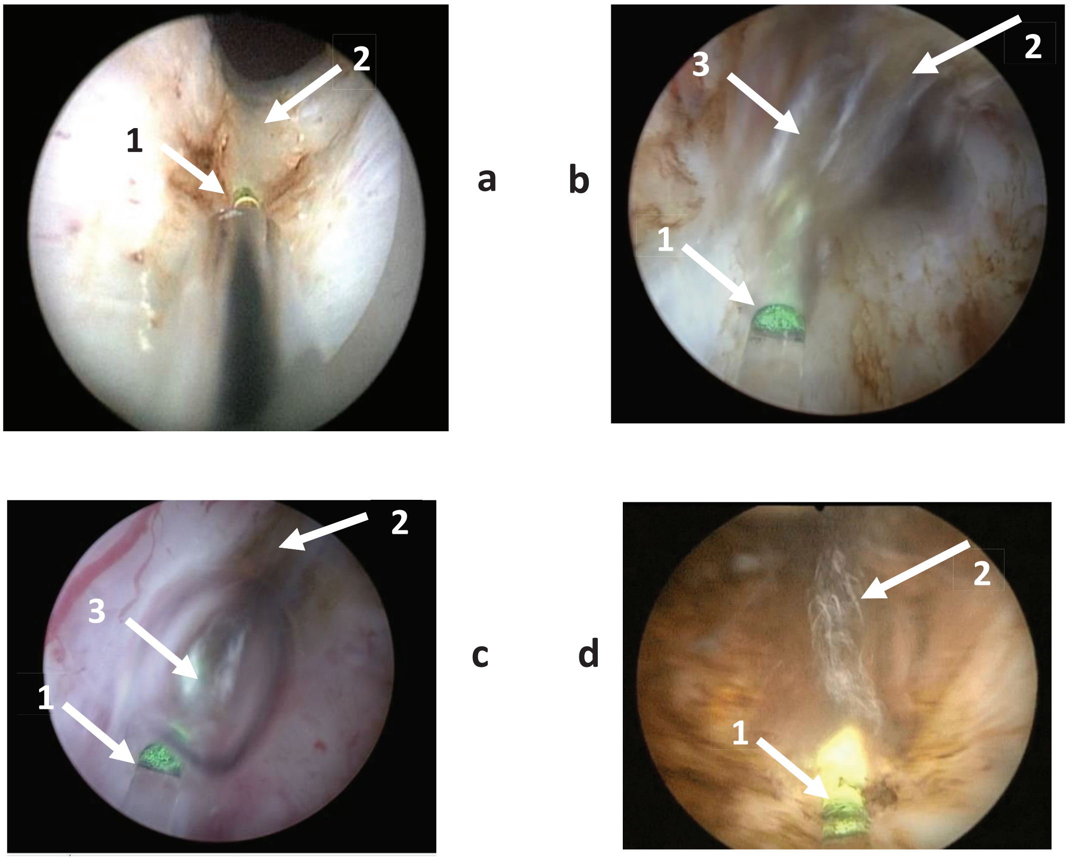

Figure 8: Laser action on tissue на: a, в, c – no contact of the fiber end with tissue, d- with contact of fiber with tissue (1- fiber end, 2- stream, 3 - macrobubble).

close operating modes whereas Tm fiber lasers give ample opportunities for optimization of action due to variation of parameters. And the device "Urolas", can expand a possibilities of use due to the addition radiation of 1.55 μm.

4. Conclusions

1. Laser devices with radiation wavelength near 2 microns are the effective tool for implementation low-invasive transurethral methods for treatment of BPH and nonmuscle-invasive bladder cancer.

2. Unlike action in the air environment, cutting of biotissues in the water environment (physiological solution) performed by the two-phase (liquid-gas) stream formed by the warmed liquid and small (about 50 microns in the diameter) steam-gas bubbles. This bubbles are formed as a result of superintensive boiling in thin (about 0,1mm) liquid layer in which laser radiation is absorbed.

3. Devices with fiber lasers allow to change working parameters in wider range in comparison with lasers on crystals that allows to continue work on optimization of operating modes from the point of view of efficiency of application.
4. Devices with lasers with Tm-doped fiber possess the best operational characteristics (weight, dimensions, energy consumption and reliability), practically don't demand engineering service at operation.

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