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Sapphire Needle Capillaries for Laser Medicine

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Abstract—New devices for laser photochemical and thermal methods of treatment of tumors of the prostate, liver, thyroid gland, and brain are developed on the basis of sapphire needle capillaries. These needles allow one to increase the irradiation volume substantially, to obtain an optimal temperature distribution, to simplify the design, and to eliminate a system for cooling the device.

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The ability of laser radiation to excite effectively photochemical reactions and heat up tissues is used in modern methods for treatment of voluminous tumors of the liver, lungs, prostate, brain, and others.

Nowadays, the most promising trends in laser therapy are photodynamic therapy (PDT) and laser interstitial thermal therapy (LITT). PDT includes the delivery of homogeneous radiation to the tumor focus for exciting injected dye photosensitizers (PS), whose concentration is high in the tumor. PS under the light of a certain wavelength transforms the usual oxygen in the tumor into the active form of metastable (singlet) oxygen, which causes the death of tumor cells of the tissue by means of a combination of direct destruction of their components and damage to blood circulation in the irradiated area [1]. It is beyond question that the result of PDT is unique: the tissue structure and its skeleton is preserved; that is, at present, it is the therapy with the maximum possible organ-preserving effect.

Laser interstitial thermal therapy, which, in comparison with PDT, requires using radiation of higher power, is more promising for treatment of malignant tumors of the liver, lungs, and brain by means of volumetric heating above 60°C (thermal necrosis) or ablation (tissue vaporization) by laser radiation [2–4]. The development of calculated computer-aided planning of operations [5] and the ability of visualization by magnetic resonance thermometry [4, 6] of the changes occurring in tissues allow one to use these methods successfully for treatment of tumors of the head and neck, pancreas, prostate, and others.

The irradiation of subcutaneous and deep-lying tumors requires optical fibers able, under overall heating, to sustain a long contact with the internal environment and the photothermal decay products without changes in the beam quality and structure. Quartz fibers have a low allowed radiation power level during interstitial irradiation. This is a constraint on the development of progressive therapy methods in oncology with available devices. The light guide for interstitial irradiation contains a quartz optical fiber and a quartz or polymeric tip on the irradiating edge (diffuser), and is used with a catheter for introduction of friable irradiator into the tissue. Beginning with the mode of coagulation, which is characterized by a temperature increase up to 60°C, it is necessary to cool the quartz fiber, furthermore photoablation (tissue vaporization) by short powerful impulses is possible only with a noncontact cooled probe [7, 8].

Quartz irradiators have a strong probability of local overheating, causing areas of carbonization. With the exception of photoablation, during irradiation of the planned volume, the carbonization of tissues is absolutely undesirable, as the appearance of soot, absorbing radiation, reduces the area of effective irradiation, breaks the quality and structure of the laser beam, and leads to rapid overheating of and damage to the fiber itself. The associated units for the fiber introduction and cooling system increase the diameter of the light delivery system and, consequently, traumatism of the operation. Among other deficiencies of quartz fibers working directly with blood and tissues is the impossibility of sterilization and multiple use.

For the solution of these problems, we have designed a new class of contact irradiators on the basis of needle capillaries made of sapphire, which has high heat resistance, hardness, strength, heat conductivity, corrosion stability, and chemical inertness to human blood and tissues (including electrolytic passivity), and having transmission in a wide range of wavelengths. A sapphire capillary not only protects the quartz fiber from interaction with blood and tissues, but it also generates, in the area of the fiber point introduced into the tissue, the required light field, which remains stable during the whole process of irradiation.

Sapphire capillaries, closed on one side, were grown from melt by Stepanov's method. Here, we have to solve quite a difficult technical task of formation and maintenance of the structure of the capillary in the

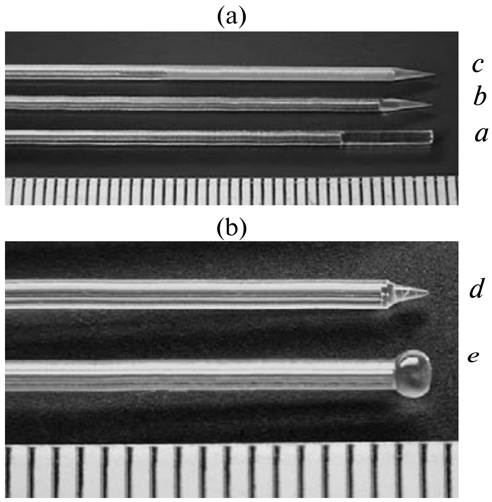

Fig. 1. Sapphire needle capillaries (external diameter of 1.2 mm, internal diameter of 0.5 mm): (*a*) closed capillary after growing; (*b*) capillary with a point formed by mechanical operation of the butt; (*c*) capillary with a point and diffuser (frosted external surface) formed by mechanical operation; (*d*, *e*) variants of the geometry of the tips of capillaries formed directly in the process of growing.

crystal, which was reduced not only to the optimization of the rates of growth and temperature regimes in the area of crystallization but also to the use of new approaches to the structure of shapers and to the control system of the crystallization front.

The internal diameter of the sapphire needle capillary (0.5–0.6 mm) was chosen on the basis of the requirements for capillary durability and with allowance for the diameter of standard quartz optical fiber of 400 μm (Fig. 1*a*). The external diameter (1.2 mm) and the length of sapphire needles (>200 mm) allow them to be used for interstitial irradiation of the tissues of the prostate in devices for transcutaneous radiation therapy (brachytherapy) of the prostate with ultrasonic guidance. The high hardness of sapphire allows a point to be formed with a very small radius of rounding (up to 25 nm), stable in multiple work cycles, including sterilization. The small external diameter of irradiators with needle sharpening, the absence of bulges, and the high purity of the sapphire surface making contact with tissue provide their easy introduction to the required depth and extraction without additional, increasing the irradiator section, devices. The last circumstance decreases considerably the probability of bleeding.

Sapphire capillaries were tested for interaction with blood using a laser with 2.5 W of power. The study showed that, at full immersion of the crystal attachment into the erythrocyte concentrate, its surface does not change in any way up to a radiation dose of 2.3 kJ in the presence of coagulation and evaporation of a liquid component [9].

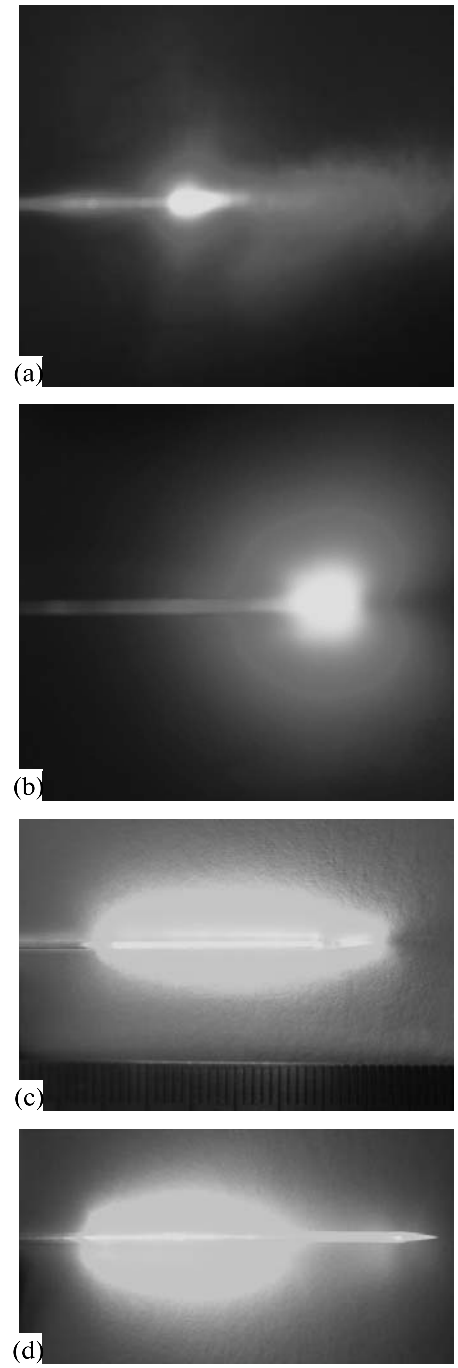

Fig. 2. The geometry of light field in blood volume upon irradiation: (a) through the splitted quartz fiber (field irregularity and stray radiation forward are observed); (b) through the same fiber placed into sapphire needle capillary; (c) fiber with diffuser 25 mm long in sapphire needle capillary with growth surface; (d) the fiber end pulled 15 mm from the capillary end.

In addition to a high chemical stability of sapphire protective capillaries, one can control the distribution of laser radiation in the tissue, depending on the geometry and the condition of the point surface. The capillary point, depending on the task, can be made of different shape both mechanically (Figs. 1*b*, 1*c*) and in the process of growing: ball or point (Figs. 1*d*, 1*e*). Particularly, in cone-shaped sharpening, the obtained sapphire supporting needle can redistribute the beam, going out from the end of the fiber in such a way that the radiation forward, undesirable in most cases, weakens significantly, and the remaining radiation is distributed evenly in the whole volume (Figs. 2a, 2b). The use of specially constructed completely diffusing scatterers (diffusive surface is formed both on the quartz fiber and on the external surface of sapphire capillary (see Fig. 1)) allows one to solve the problems of distribution of luminous fluxes and thermal fields inside the tissues of various human organs. For example, the ground capillary surface allows one to get a leveled cylindrical laser beam (Fig. 2c), which is used effectively for interstitial PDT and laser thermal therapy of voluminous tumors. For an additional increase in irradiation volume, we can use the shift of the fiber with a diffuser in an optically transparent capillary during laser therapy (Fig. 2d).

The use of a fiber or sapphire capillary with diffusive surface allows one to decrease the radiation power density per unit of irradiator surface. In addition, for the same dose from a point irradiator and diffuser, given the tissue, the heating of the sapphire capillary with diffuser is considerably less, and it is possible to conduct a therapy session within the scope of thermal restriction of the planned action.

The developed system also allows one to define threshold values of constant flows and local fluctuations of light and heat fields, causing irreversible changes in tissues. For the sapphire supporting needle with a fiber with a diffuser 25 mm in length, the parameters of irradiation providing the heating of human tissue to 39°C were determined; that is, there are no thermal changes in it. This regime is required in PDT, where in classical scheme the process of cancer cell damage is absolutely photochemical. We chose experimentally the power of a continuous laser (λ = 810 nm) at which, for the tissue with the introduced irradiator (the diffuser is completely immersed), photothermal balance at a maximum temperature in the tissue of 39°C occurs. The integral radiation power from the diffuser was measured, and the irradiator was introduced into another fragment of the liver. Then the dynamics of tissue heating was recorded. At a laser power of 1.2 W, the radiation power density at the diffuser was 350 mW/cm^2; within 5 min, the irradiation dose of 100 J/cm^2 was produced; within 25 min, it was 500 J/cm^2; in the process, a photothermal balance at a maximum temperature in the tissue of 39°C was established.

The problem of protection of quartz fibers is especially topical in laser thermal therapy, when high powers are used to provide hyperthermia (the temperature range is 41–43°C), coagulation, or ablation of interstitial tumors, which cannot be ablated surgically and do not yield to chemotherapy. First of all are liver cancer and liver metastases, the treatment of which is ineffective by photodynamic therapy owing to the complications of delivery and accumulation of photosensitizer in a liver tumor.

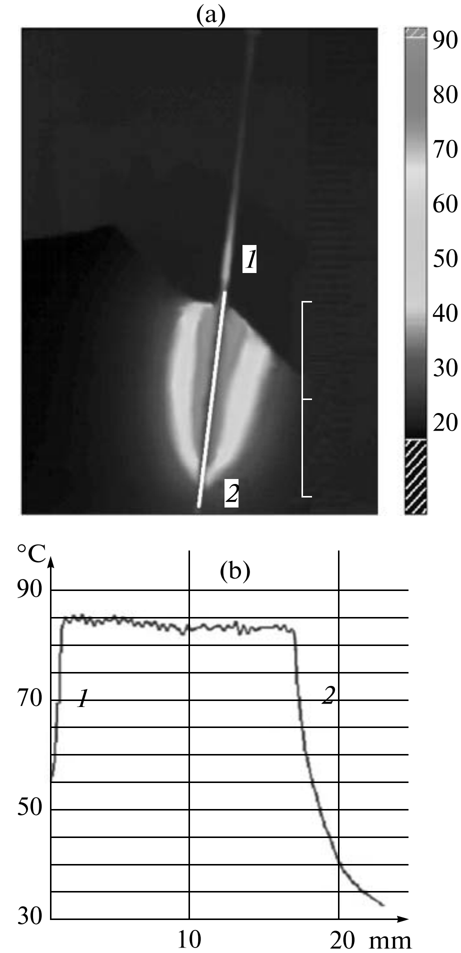

Fig. 3. Temperature distribution (infrared camera): (a) in liver sample upon laser irradiation (810 nm) through quartz fiber with diffuser (inserted to 20 mm) placed into sapphire supporting needle; (b) balanced temperature distribution along needle. Laser power is 5.7 W.

The high chemical inertness of sapphire capillaries allows one to work in a wide range of laser radiation powers with the ability to use various types of exposure by a single irradiator during the operation.

Experiments on observing the change in processes as a function of increasing temperature in tissue PDT were carried out: hyperthermia, coagulation, carbonization in one process, using a semiconductor laser with a wavelength of 810 nm and a fiber with sapphire supporting needle; a pig liver was taken as a model.

The needle was introduced parallel to the surface at the depth of about 3 mm. The laser power was increased from 0.5 to 8.3 W (carbonization) with a step

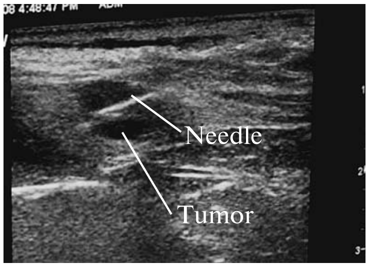

Fig. 4. Visualization of sapphire needle by ultrasound in tumor of a lymph node in process of laser interstitial photodynamic therapy.

of 300 mW. After each 15-s irradiation session, the temperature distribution on the section was determined by an infrared camera (Fig. 3). The parameters of passage of the sapphire supporting needle and the state of its surface did not change. The same results were observed in the experiments of irradiation of the liver at high powers, reaching 20 W of continuous radiation (810 nm) without using cooling systems.

The unique, for optical transparent dielectrics, thermal conductivity of sapphire excludes the possibility of local areas of overheating to considerably higher, in comparison with quartz, powers of radiation input, causing the growth of thrombi, nontransparent to radiation, around the irradiator. The use of interstitial irradiators on sapphire needle capillaries allows one to exclude the last element from the balance existing so far: calculated volume of the action—required radiation regimes—saving of optical fibers. This successfully helps to overcome the problems that slow down the development of promising and priority laser methods for treatment of cancer diseases of internal organs and soft tissue tumors.

The tests of irradiators on the basis of sapphire capillaries during laboratory experiments and clinical procedures under ultrasound control (Fig. 4) prove their use as irradiators in various methods of photochemical and photothermal action. Sapphire irradiators allow one to improve the methods of optical therapy and surgery of hypodermic tumors and internal organs and to bring about the ability to combine various regimes of laser action with the use of one irradiator in the process of one operation.

CONCLUSIONS

On the basis of grown sapphire capillaries, new devices for delivery of laser radiation have been developed. They can be used for photodynamic therapy, laser hyperthermia, voluminous laser coagulation, laser interstitial thermal therapy, and ablation of tumors of various organs, for example, prostate, liver, pancreas, brain.

The high hardness of sapphire provides a stable point on the irradiator end for independent introduction of the irradiator into the tissue without using directors that lead to the increase in irradiator cross section.

Sapphire contact irradiators preserve the stability of reproduction of geometry and laser beam quality. Thanks to high strength and exceptional chemical inertness of sapphire, they do not undergo any surface or structural aging in multiple operating cycles and in any kind of sterilization.

The use of sapphire irradiators will make it possible to improve the control over the dynamics of spatial photothermal distribution during the whole irradiation procedure, since the effective redistribution of released heat by the sapphire decreases the possibility of formation of overheating nuclei, leading to the appearance of thrombi, nontransparent to laser radiation.

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