a model with lumped parameters, while in reality resistance and pliability are distributed along blood vessels.

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Live Tissue Surrogate for Surgical Laser Testing

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Live tissue surrogate is proposed, consisting of a filler, egg albumen, donor blood, and glycerol. When exposed to an Nd-YAG laser operating at a wavelength of 1064 nm in pulsed or permanent modes, the surrogate changes color, which allows one to determine the borderline parameters of radiation causing thermal necrosis and to select the optimal conditions of laser surgery. The sensitivity of the live tissue surrogate to the working power range is close to that of live tissue containing blood.

Key Words: *surgical lasers; tissue surrogate; thermal necrosis*

Recently, lasers have found a wide application in surgery. However, lasers (CO_2, 532, 1032, or 1064 nm Nd-YAG, argon, etc.) cause thermal necrosis while operating in the destruction and coagulation modes. This necrosis provides "welding" of tissues [3], their sterility [11] and ablasty [8], and intraoperative hemostasis [13,10]. However, deep thermal denaturation caused by laser surgery may have unfavorable consequences, such as prolongation of the regeneration period due to decelerated resorption of large volumes of necrotic tissue [1,9]. Optimal conditions for clinical application of lasers can be selected after labor- and time-consuming operations on tissues of laboratory animals. Various surrogates of live tissues (TS) have been tried for preclinical experiments with lasers, such as egg albumen and yolk, gels, some plastics, etc. [5,14,15]. We propose a new surrogate which is better approximated to live tissues. This TS permits rapid, accurate, and well reproducible assessment of the effect of surgical lasers.

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MATERIALS AND METHODS

Nd-YAG lasers operating in the permanent (Raduga) and pulsed (laboratory installation) modes at a wavelength of 1064 nm were used. Tissue surrogate was exposed to long-distance and contact irradiation through a quartz light guide (diameter 400 nm); hepatic tissue of narcotized white rats served as a control. Egg albumen was the main component of TS. When irradiated beyond the denaturation threshold, the TS changes color and becomes insoluble and compact; these qualities are often used for laser tests [14]. The composition of TS is as follows: 20 ml egg albumen, 2.5 ml glycerol, 4.5 ml donor blood (blood with expired storage term), and 10 g filler (ion-exchange resin on cellulose). The ingredients should be thoroughly mixed to obtain evenly colored thick

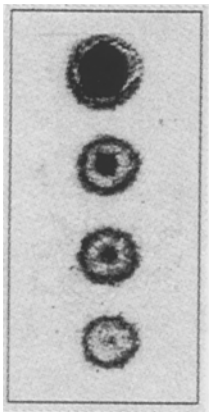

Fig. 1. The size of spots as a function of exposure time (8-20 sec) (from bottom to top). Here and in Fig. 2: laser working in the continuous mode at a power density of 80 W/cm^2, ×1.8.

Fig. 2. Blurred spots in tissue surrogate with nonoptimal ratio of components.

Fig. 3. Different spots after application of an electrocauter (1 sec) to the tissue surrogate at 37, 4, and -20°C (from top to bottom), ×1.8. Laser operating in a typical mode (power 5 W).

red paste. The paste is placed in a mold, and its surface is smoothed with a roll through tracing paper. For storage the paper is not removed, the mold is covered with a slide, and stored at temperatures below -18°C for at least one year. Before tests, the slide and paper are removed, and the TS heated to required temperature is exposed to a laser operating in the preset mode. All manipulations should be as rapid as possible to prevent drying of the paste; the TS should be stored with wet cotton tampons. After tests, the paste is covered with tracing paper and slide and stored in the refrigerator until photos or measurements are made. Preliminary results of TS trials without description of its composition were published previously [2,6].

RESULTS

Irradiation of TS in the permanent mode at a power density of 85 W/cm^2 and a distance of 10 mm from the tip of the light guide resulted in the appearance of greenish gray spots on the surface; these spots were distinguishable from the initial material both visually and on photographs (Fig. 1). As irradiation was prolonged, starting from the threshold time (1.1 sec), the spots increased in size, and their edges became darker. Further irradiation led to ablation: TS fumed and a coal-black spot appeared (8.5 sec), the ablation pit became deeper (11 and 16 sec), and, finally, a crater formed with carbon deposits not only inside it but also at its edges. Experiments with TS of various compositions showed that our composition is almost optimal with respect to color contrast between exposed and intact sites and other parameters (Figs. 1 and 2). The extent and intensity of laser-induced changes did not vary considerably in different blood samples and proteins (the accuracy of measurements was 25 μ). This TS was also used for testing the thermocoagulating properties of an electrocauter. A relationship between the size of thermal necrosis and the temperature of the sample was established (Fig. 3).

Measurements of the size and depth of the spots differing in color and of rat liver necroses (the NADH dehydrogenase reaction was employed as a marker of necrosis, Fig. 4) at the moment when the size of necrosis was the largest (24 h after irradiation) showed that under the same conditions of laser irradiation the spots on TS were slightly smaller than those on the liver (1.0 and 1.2, respectively) in the working power range (10 W and higher). At a lower power, TS is much inferior to live tissue, particularly during short exposure.

The TS can be employed for testing the lasers operating in pulsed mode with a light guide placed at a distance or contacting with the TS surface. Most informative results were obtained upon calibration of

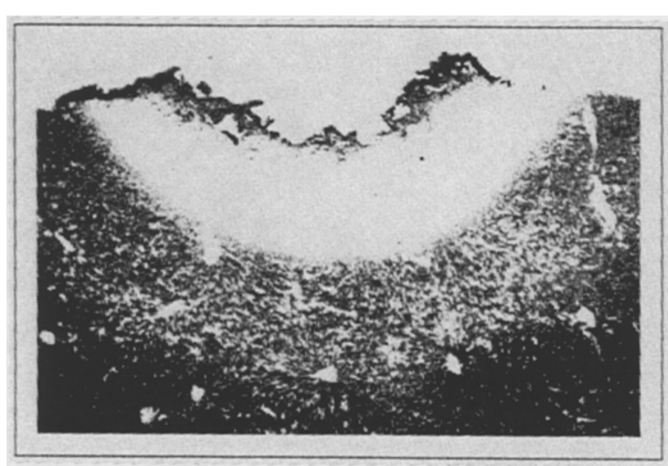

Fig. 4. Transverse cryostat section through a laser-induced wound on the liver. Staining for NADH dehydrogenase, ×30. Laser operating in a pulse mode (pulse duration 150 μsec, frequency of pulses 50 Hz, mean power 25 W).

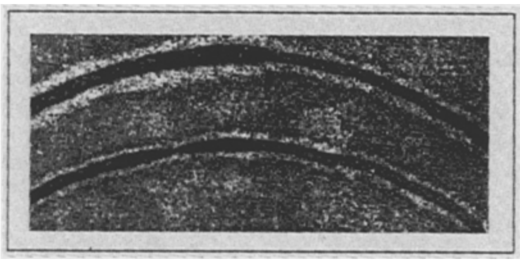

Fig. 5. Linear incisions at V=1 (left) and 4 mm/sec (right) on the tissue surrogate with (lower track) and without (upper track) the system of power autoregulation, ×2.6. Laser operating in a pulse mode: pulse duration 150 μsec, pulse frequency 50 Hz, mean power 12.5 W (left portions of incisions) and 25 W (right portions of incisions).

a laser power autoregulation system [4], when the rate of tissue dissection with a laser "scalpel" was varied (Fig. 5).

Thus, TS can be used for testing some medical lasers and preliminary evaluation of the thermal necrosis parameters at the site of exposure as well as for optimization of some surgical manipulations requiring the standard level of injury during incision and coagulation of tissue. The TS is easy to prepare and cheap, its ingredients are readily available, the test is fast, and the results obtained can be analyzed by standard statistical methods. Therefore, the TS is recommended for preclinical tests of lasers and their operation modes. The TS may be useful for the development and tests of light guides with asymmetric configuration of the tips that ensure intratissue coagulation of pathological formations of a complex shape, for example, benign tumors of the prostate [7,11]. In such cases TS can be used for "visualization" of thermal necrosis (Fig. 6) at all stages of designing the tips of desired configuration. Finally, the TS may be useful in routine tests performed in laser surgery departments for detecting (by the shape of spots) the defects of optic systems conducting energy from laser to object.

Fig. 6. Coagulated samples removed after irradiation through a light guide introduced into the tissue surrogate, ×2.8. Device operating in a continuous mode (power 10 W).

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