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Solder based on nanoparticles with metallic properties for laser reconstruction of blood vessels

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Abstract. Laser blood vessel reconstruction is a modern, non-invasive method of blood vessel closure. Until now, most previous work has used protein and dye-based solders (laser absorbers) to form welds. However, the addition of nanoparticles to the solder, which have outstanding bactericidal properties and the ability to accelerate wound epithelialisation, has the potential to improve the efficiency of optical wound healing. The aim of the study was to experimentally investigate the physicochemical properties of dispersed solders including antibacterial nanoparticles of metals Ni, Al, Fe_3O_4 and carbon nanotubes with metallic properties, biopolymer – albumin, and dye localizing laser radiation in the area of wound dissection – indocyanine green, the formation of a biological tissue compound and the study of their mechanical properties. The selected nanoparticles have a high absorption coefficient of laser radiation, which provides high efficiency of laser energy utilization and allows recovery with minimal losses. The effectiveness of solders with different metal nanoparticles was experimentally tested in cattle vessels. Tissue reconstruction was performed by diode laser with a wavelength of 810 nm. The suture was formed within 1 minute. The laser exposure temperature was 55 °C for each particular specimen. The results showed that the highest tensile strength was in the specimen with carbon nanotubes. The achieved strength with carbon nanotubes was 950 kPa.

Keywords: vessel reconstruction, nanoparticles, laser soldering

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Припой на основе наночастиц с металлическими свойствами для лазерного восстановления кровеносных сосудов

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Аннотация. Исследование направлено на изучение физико-химических свойств диспергированных припоев с антибактериальными наночастицами различных металлов и углеродных нанотрубок, а также на оценку их механических свойств.

Проведенные эксперименты на сосудистых моделях показали, что биополимерный припой, содержащий углеродные нанотрубки, обеспечивает наивысшую прочность на разрыв.

Ключевые слова: восстановление сосудов, наночастицы, лазерная пайка

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Introduction

Laser reconstruction of biological tissues is a modern method of wound healing, which is a non-invasive alternative to traditional methods. Laser tissue reconstruction is based on the reversible change in the molecular structure of tissues under the thermal influence of laser radiation. To prevent thermal necrosis of tissues, solder is applied to the area of dissection, which is an aqueous dispersion of protein – albumin and dye – indocyanine green [1]. The addition of nanoparticles to the solder, which have outstanding bactericidal properties and the ability to accelerate wound epithelialization, can potentially increase the efficiency of the optical method of wound healing [2, 3].

The aim of the study was to experimentally investigate the physicochemical properties of dispersed solders incorporating antibacterial metal nanoparticles Ni, Al, Fe_3O_4, and carbon nanotubes (CNT) formed the connection of biological tissues and to study their mechanical properties. Aluminum nanoparticles as the most budget-friendly and easily obtainable were chosen in two sizes: 50 nm and 100 nm.

Materials and Methods

Solder manufacturing. All solders were an aqueous dispersion of bovine serum albumin at a concentration of 25 wt.%, indocyanine green 0.1 wt.%, and the corresponding nanoparticles at concentrations ranging from 0.001 wt.% to 0.1 wt.%. A total of 28 different solders were prepared, varying in the type and concentration of nanoparticles. All solders were produced using the same technology. Metal nanoparticle powder was added to distilled water until the desired concentration was achieved. The resulting mixture was processed with a submersible ultrasonic homogenizer until the medium became homogeneous. Then, with continuous stirring, indocyanine green and bovine serum albumin were added to the dispersed medium. The resulting solder was treated in an ultrasonic bath until the protein was completely dissolved.

Laser soldering system. The laser system included an emission unit, laser guidance system, and temperature feedback. The system was capable of emitting radiation with two wavelengths: $\lambda = 810$ nm and $\lambda = 970$ nm. A laser with wavelength $\lambda = 810$ nm was used for laser soldering. To transmit laser radiation, the laser system was equipped with a 600 μm diameter optical fiber. The utilization of temperature feedback facilitated precise regulation of heating within the dissection zone, thereby mitigating thermal injury to adjacent tissues. Monitoring of the temperature within the laser-soldering region was achieved through an infrared sensor interfaced with a microcontroller. A proportional-integral-derivative (PID) controller was employed to modulate the laser radiation power in order to uphold the designated temperature. Visual representation of temperature variations was graphically depicted utilizing specialized software compatible with standard personal computers. The temperature control system exhibited a nominal error margin of 0.5 °C, a level of precision deemed suitable for the delicate process of biological tissue soldering.

Solder research methods. The following were selected as the main characteristics of solders affecting the strength of the laser connection of vessels: optical characteristics (absorption and transmittance), solder viscosity, studies of agglomerate sizes using the method of dynamic light scattering, and solder density.

Formation of laser welds. The effectiveness of solders with different nanoparticles was experimentally tested on bovine vessels. The welds were formed within 1 minute. The laser exposure temperature was 55 °C for each specific specimen [4, 5]. The heating temperature of the irradiated area was monitored by an MLX90614 infrared temperature sensor, which was installed directly above the collimator on the body of the surgical pen. When the desired surface temperature was reached, the temperature feedback system reduced the power of the radiation to maintain a stable temperature in the soldering area. After soldering, the tensile strength of the welds was determined using a testing machine.

Results and Discussion

Spectral characteristics of the solder. The study of the spectral characteristics of the solder makes it possible to determine the degree of localization of laser radiation in the solder application zone. In order to trace the absorption ability of the nanoparticles themselves, the first group of solders excluded the addition of dye – indocyanine green. The measurement results show strong absorption in the UV region provided by the spectral properties of the proteins. The addition of nanoparticles in all cases provides an increase in absorption over the entire range in the visible and infrared spectra, but there are no pronounced absorption peaks. The addition of carbon nanotubes (CNT) at a concentration of 0.05 wt.% results in complete absorption of radiation over the entire range under study (Fig. 1, *a*).

The results of the study demonstrate that the addition of indocyanine green to all types of solders leads to the formation of a pronounced absorption peak at a wavelength of 800 nm, which corresponds to the wavelength of the selected laser radiation (Fig. 1, *b*).

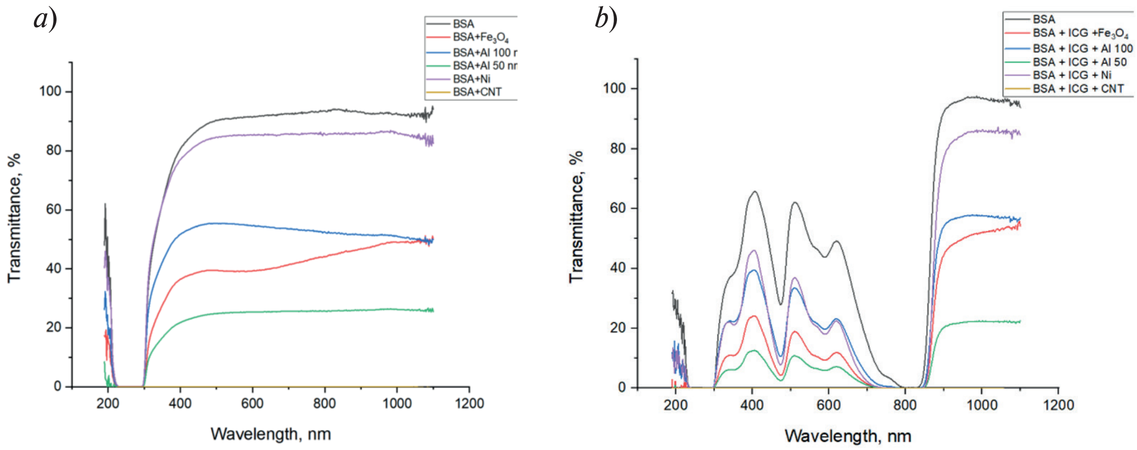

Fig. 1. Transmittance of solders: without ICG (*a*), with ICG (*b*)

Physical and chemical characteristics of solder. The density and viscosity of solder determines the consistency of solders their stability and ability to pre-glue the wound edges. The results of the studies are presented in Table. Carbon nanotubes provide the highest viscosity because they have higher surface energy and the ability to form a structure in the solder, which leads to an increase in viscosity.

The radii of the nanoparticles were determined by dynamic light scattering method. They are presented in Table. In general, for metal solders, it was observed that when dispersed in albumin, a protein shell is formed on the surface of the nanoparticles, increasing the particle size by 30% of the initial particle size. The size of nickel particles increased twice as much as the initial particle size. The structure of nickel nanoparticles itself is more prone to aggregation and formation of larger particles than other metals

Mechanical testing of welds. The effectiveness of solders with different metal nanoparticles was experimentally tested on ex vivo vessels and skin. Tissue reconstruction was performed with

Table

Study of physical and chemical characteristics of solder

Characteristics	Nanoparticles				
	Fe_3O_4	Al 100	Al 50	Ni	CNT
Viscosity, mPa*s	3.08	3.28	3.31	3.91	5.96
Density, g/cm	1.057	1.076	1.083	1.083	1.086
Particle size, nm	170 ± 60	145 ± 40	71 ± 15	159 ± 25	–

a diode laser with a wavelength of 810 nm. The suture was formed within 1 minute. The laser exposure temperature was 55 °C for each specific sample. The mechanical test results are shown in Figure 2. Solder based on carbon allows to localize the radiation as much as possible in the area of the joint formation and increases the strength of the formed welds by 10 times in comparison with solder without nanoparticles. In the case of aluminum nanoparticles, the size of the nanoparticles is critical on the strength of the welds. The strength of solders with the addition of 100 nm aluminum nanoparticles showed strength values equivalent to that of carbon nanotubes, while stable fabric bonding could not be achieved with 50 nm aluminum nanoparticles.

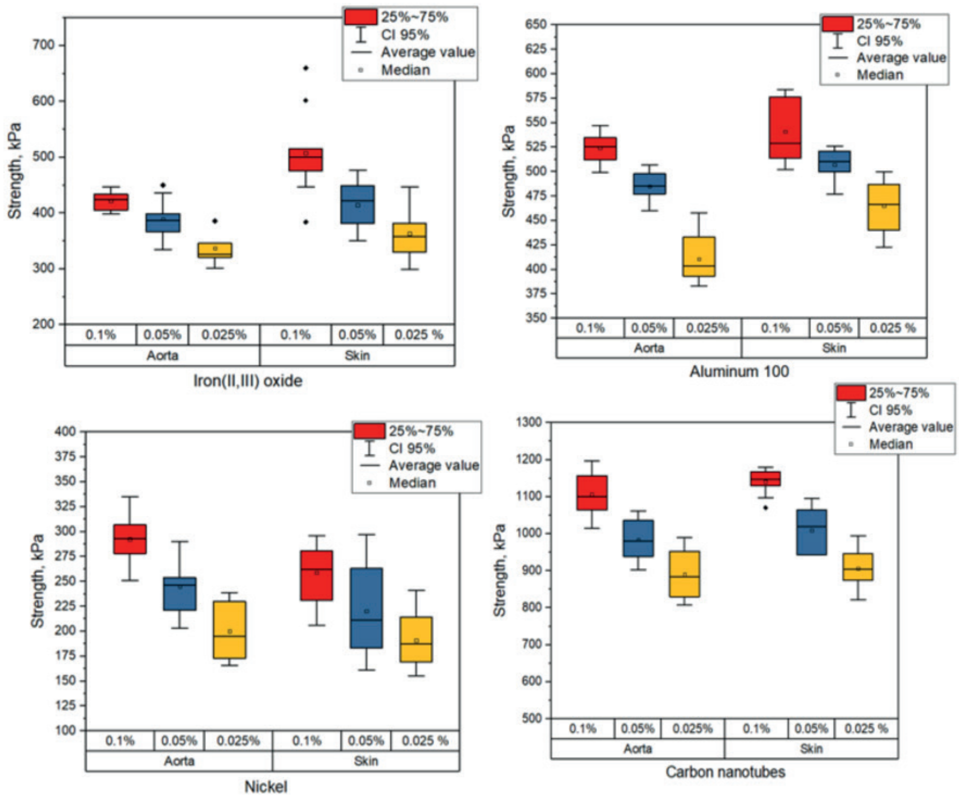

Fig. 2. Investigation of the strength of reconstructed welds

Conclusion

A new approach based on the high efficiency of laser energy and the excellent bactericidal properties of nanoparticles may lead to accelerated epithelialization of wounds and improved healing. The results of experiments on bovine aorta suggest that the use of solders with metal nanoparticles and carbon nanoparticles with metallic properties may be promising for the development of laser tissue reconstruction methods.

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