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Comparison of cutting and coagulation properties of 1.56 and 1.94 µm fiber lasers and a 0.98 µm semiconductor laser

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ABSTRACT

Aim of the study was to compare the cutting and coagulation properties of 1.56 and 1.94 µm fiber lasers with those of a 0.98 µm semiconductor laser.

Materials and methods. A comparative study of the biological effects of 1.56 and 1.94 µm lasers and a 0.98 µm semiconductor laser used in a constant, continuous mode was carried out. The cutting properties of the lasers were evaluated on the chicken muscle tissue samples by the width and depth of the ablation zone formed via a linear laser incision at a speed of 2 mm/s, while the coagulation properties were assessed by the width of the lateral coagulation zone. The zones were measured using a surgical microscope and a calibration slide. For statistical analysis, power values of 3, 5, 7, 9, and 11 W were chosen for each laser wavelength.

Results. Analysis of the findings confirmed that laser wavelength had a statistically significant effect on the linear dependence between incision parameters and laser power. It was found that the 1.56 µm fiber laser (water absorption) had a greater coagulation ability but a comparable cutting ability compared with the 0.98 µm laser (hemoglobin absorption). When used in the power mode of 7W or higher, the 1.94 µm laser provided superior cutting performance compared with the 0.98 µm semiconductor laser at the same exposure power. Elevating the power in any of the lasers primarily increased the width of the ablation zone, and to a lesser extent – the crater depth and the width of the lateral coagulation zone. Therefore, in comparison with the 0.98 µm semiconductor laser, higher radiation power in the 1.56 and 1.94 µm lasers mainly influences their cutting properties, expanding the width and depth of the ablation zone, and has a smaller effect on their coagulation ability.

Conclusion. The findings of the study showed that the 1.56 and 1.94 µm fiber lasers have better coagulation properties in comparison with the 0.98 µm semiconductor laser. was statistically proven that all incision characteristics (width of the lateral coagulation zone, depth and width of the ablation zone) for the 1.56, 1.94, and 0.98 µm lasers depend on the power of laser radiation. The 1.94 µm laser is superior to the 0.98 µm laser in its cutting properties.

Key words: laser, ablation, coagulation, wavelength, power.

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Сравнение режущих и коагуляционных свойств волоконных лазеров с длиной волны 1,56 и 1,94 мкм с полупроводниковым лазером 0,98 мкм

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РЕЗЮМЕ

Цель – провести сравнительную оценку режущих и коагуляционных свойств волоконных лазеров с длинами волн 1,56 и 1,94 мкм с полупроводниковым лазером 0,98 мкм.

Материалы и методы. Проведено сравнительное исследование биологических свойств волоконных лазеров с длиной волны 1,56 и 1,94 мкм с полупроводниковым лазером 0,98 мкм в постоянном непрерывном режиме. Режущие свойства лазеров оценивались на мышечной ткани курицы по ширине и глубине зоны абляции, формируемой в ходе линейного лазерного разреза со скоростью 2 мм/с, коагуляционные – по ширине боковой зоны коагуляции. Измерение зон проводили в условиях микроскопии с помощью калибровочного предметного стекла. Для статистического анализа выбрали значения мощности 3, 5, 7, 9 и 11 Вт для каждой длины волны лазерного излучения.

Результаты. Анализ полученных результатов измерений подтвердил статистически значимое влияние длины волны лазерного излучения на характер линейной зависимости параметров лазерного разреза от мощности воздействия. Установлено, что волоконный водопоглощаемый лазер с длиной волны 1,56 мкм обладает большей коагулирующей способностью, но сопоставимой способностью к резке тканей по сравнению с гемоглобинпоглощаемым лазером с длиной волны 0,98 мкм. Лазер с длиной волны 1,94 мкм на мощности 7 Вт и выше превосходит по своим режущим свойствам полупроводниковый лазер 0,98 мкм на той же мощности воздействия. Для всех лазеров прирост мощности излучения в большей степени увеличивает ширину зоны абляции, в меньшей степени – глубину кратера и ширину боковой зоны коагуляции. Таким образом, прирост мощности излучения для лазеров с длиной волны 1,56 и 1,94 мкм преимущественно влияет на режущие свойства, увеличивая ширину и глубину формируемой зоны абляции, в меньшей степени – на его коагуляционные способности в сравнении с полупроводниковым лазером с длиной волны 0,98 мкм.

Заключение. По результатам экспериментального исследования обнаружено, что лазеры с длиной волны 1,56 и 1,94 мкм обладают лучшими коагулирующими свойствами в сравнении с полупроводниковым лазером 0,98 мкм. Статистически доказано, что все параметры лазерного разреза (ширины боковой зоны коагуляции, глубины и ширины зоны абляции) для лазеров с длиной волны 1,56; 1,94 и 0,98 мкм зависят от мощности лазерного излучения. Лазер с длиной волны 1,94 мкм превосходит лазер 0,98 мкм по своим режущим свойствам.

Ключевые слова: лазер, абляция, коагуляция, длина волны, мощность.

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INTRODUCTION

In recent years, laser technologies have been rapidly developing with creation of semiconductor and fiber lasers with various wavelengths never used before (0.53, 0.81, 0.97, 1.06, 1.47, 1.56, 1.94 µm) and production of high-power lasers, which expands the scope of their application in different modes (continuous, pulsed, contact, and distance modes). Novel medical equipment expands the range of therapeutic interventions; however, biological effects of the majority of machines rarely receive any empirical evaluation. Therefore, the right operation mode is usually found by trial and error, which makes surgical intervention less predictable and increases the risk of complications. Since the wavelength defines the properties of a laser, a lack of data on the biological effect of different wavelengths prevents practitioners from selecting the right laser device and its operation modes.

In most experimental studies, ablative performance is assessed by measuring the ablation rate, which is the volume of ablated tissue per a unit of time (g/min), while coagulation properties are evaluated by determining the bleeding rate (g/min) and tissue necrosis depth (mm). This method involves the *in vivo* use of living tissue models (in many cases – blood-perfused porcine kidney), though evaluation results provide only circumstantial evidence on the extent of ablation and coagulation properties [1]. Current Russian and foreign studies on the effects of diode and fiber lasers with various wavelengths (0.81, 0.94, 0.97, 1.47, 1.56 µm) use vein models as samples for comparative experimental analysis, which makes it impossible to evaluate the cutting properties of lasers [2–8]. There are few papers on semiconductor lasers being used on the cartilaginous tissue models (0.97; 1.56 µm), but they do not discuss the ablative and coagulation characteristics either [9].

The main aspects of laser performance relevant for clinical practice include cutting properties measured by the width and depth of the ablation zone, as well as coagulation properties, or hemostatic effect of the laser, that manifest themselves through tissue blanching along the incision.

The development of new 1.56 and 1.94 µm fiber lasers makes it relevant to study their biological effects prior to using them in clinical practice. The 0.98 µm lasers have been extensively used for various surgical purposes [1], including ENT surgery [10–13], and, therefore, it is reasonable to use this experience for a comparative analysis of the biological effects of other lasers.

The aim of the study was to compare the cutting and coagulation properties of the 1.56 and 1.94 µm fiber lasers and the 0.98 µm semiconductor laser.

MATERIALS AND METHODS

To assess the biological effects of laser radiation, linear incisions were made on the chicken muscle tissue at a fixed rate. The laser fiber was rigidly fixed with tripods on a support stand at a 60° angle relative to the incision projection. The biological object was placed on a mobile recorder sheet moving uniformly at a speed of 2 mm/s [12]. The width of the ablation crater and the lateral coagulation zone was evaluated using a slide with the graduation of 10 µm and an operating microscope with ×15 magnification. To assess the crater depth, cross sections of the tissue were made relative to the linear incision line, and the parameter was measured using the above-described method. The width and depth of the incision served as indicators of the ablative performance, while the width of the lateral coagulation zone represented the hemostatic properties of the lasers.

The incisions were made with the 1940 and 980/1560 nm lasers (LSP, IRE-Polus, Moscow, Russian Federation) in a continuous contact mode. The procedure was performed with a freshly cleaved optical fiber end with a width of 400 µm after its charring by a short-term contact with a wooden surface (spatula). At power values from 3 to 11 W and interval of 2 W, 3 incisions for each wavelength were made, and the results for each incision were measured in 10 positions (30 measurements in total).

Statistical processing of the data was carried out using the IBM SPSS Statistics software package (version 22). The evaluation methodology included descriptive statistics methods, regression analysis, and multiple regression analysis with a madiating variable. The parameters of the laser incision (width of the lateral coagulation zone, depth and width of the ablation zone) were dependent variables. The regression analysis of each dependent variable was performed separately. The power and wavelength of radiation were regarded as independent variables. Since the experiment involved three lasers with wavelengths of 0.98, 1.56, and 1.94 µm, the qualitative mediating variable "wavelength" was coded with two dummy variables representing the 1.56 and 1.94 µm lasers.

RESULTS AND DISCUSSION

The graphs depicting the dependence of the width of the lateral coagulation zone and the depth and width of the ablation zone on the power and wavelength are shown below (Fig. 1–6).

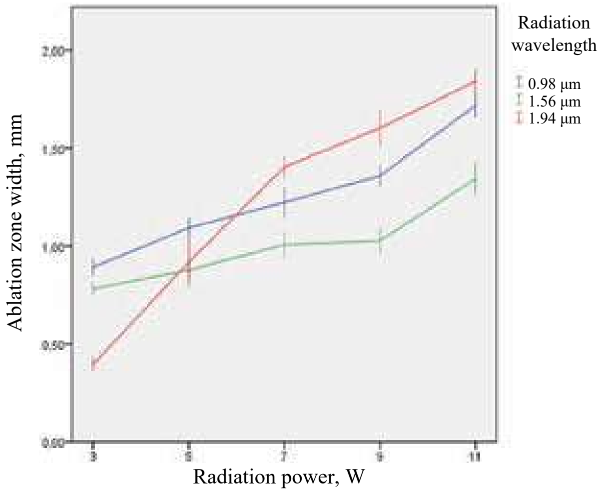

Fig. 1. Dependence of the ablation zone width on laser power (average values and 95 % confidence interval (CI)

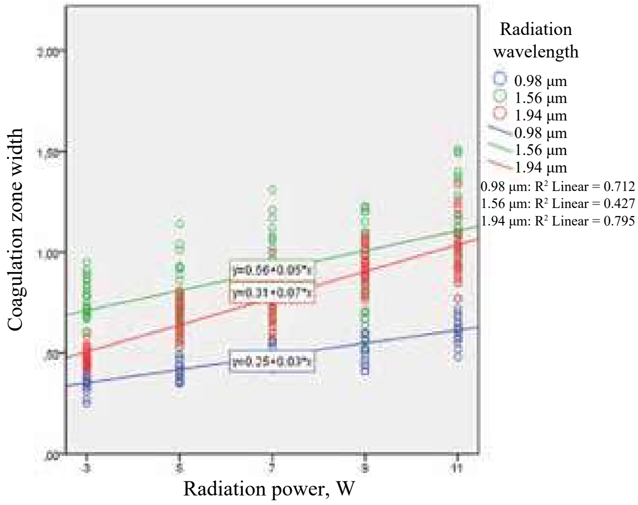

Fig. 4. Dependence of the coagulation zone width on laser power (linear regression)

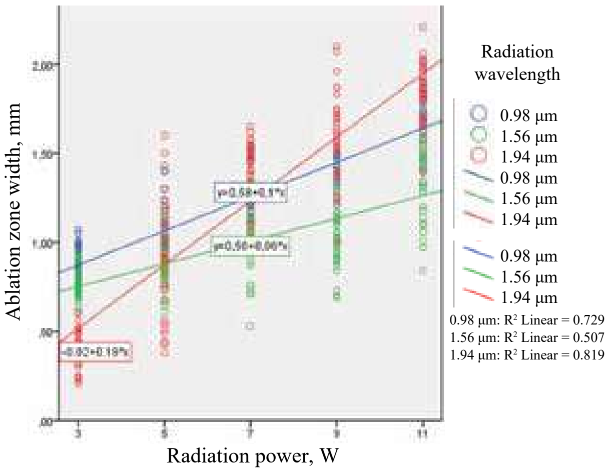

Fig. 2. Dependence of the ablation zone width on laser power (linear regression)

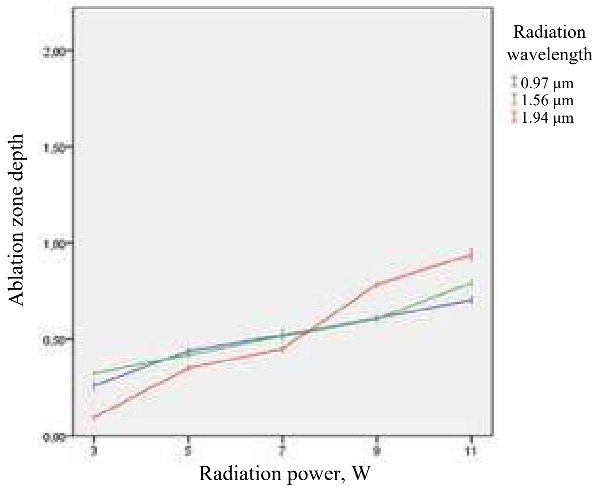

Fig. 5. Dependence of the ablation zone depth on laser power (average values and 95 % CI)

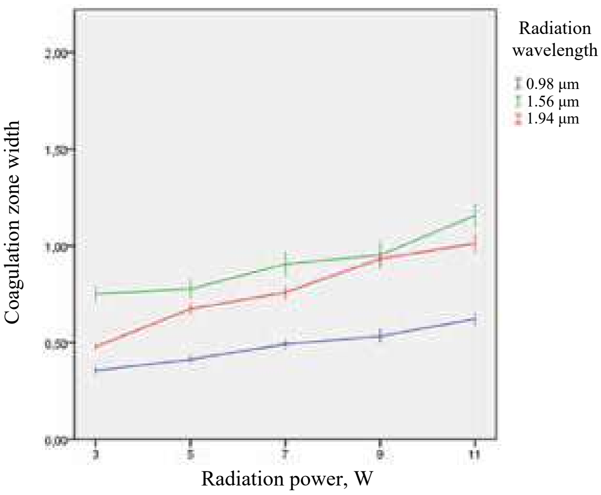

Fig. 3. Dependence of the coagulation zone width on laser power (average values and 95 % CI)

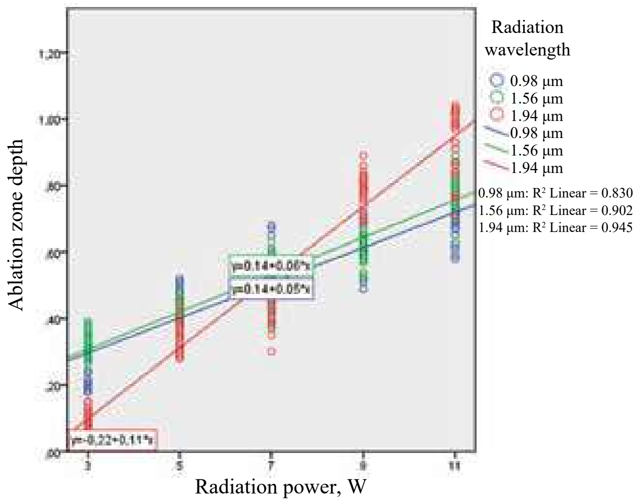

Fig. 6. Dependence of the ablation zone depth on laser power (linear regression)

The statistical analysis of the results was based on multiple regression:

$$Y = \beta_0 + \beta_1 \cdot P + \beta_2 \cdot D_{1,56} + \beta_3 \cdot D_{1,94} + \beta_4 P \cdot D_{1,56} + \\ + \beta_5 \cdot P \cdot D_{1,94} + \varepsilon,$$

where Y is a dependent variable (the coagulation width for the first model; the ablation depth, for the second model; and the ablation width for the third model); P is the laser power; $D_{1,56}$ is a dummy variable that equals 1 for the 1.56 μm laser and 0 in other cases; $D_{1,94}$ is a dummy variable that equals 1 for the 1.94 μm laser and 0 in other cases.

The 0.98 μm laser is a benchmark, and the regression equation for it is $Y = \beta_0 + \beta_1 \cdot P + \varepsilon$. The regression equation for the 1.56 μm laser is $Y = \beta_0 + \beta_2 + (\beta_1 + \beta_4) \cdot P \cdot D_{1.56} + \varepsilon$, while for the 1.94 μm laser, it is $Y = \beta_0 + \beta_3 + (\beta_1 + \beta_5) \cdot P \cdot D_{1.94} + \varepsilon$.

Thus, the significance of the β_2, β_4 coefficients indicates the statistical difference between 0.98 μm and 1.56 μm lasers, and the significance of the β_3, β_5 coefficients indicates the statistical difference between the 0.98 μm and 1.94 μm lasers.

Multiple regression analysis with a mediating variable showed a statistically significant relationship between all the parameters (the width of the coagulation zone, the depth and width of the ablation zone) and the laser power (Table 1, 2). In all but one case, it was established that the laser radiation wavelength (mediating variable) had a statistically significant effect on the linear dependence of laser incision characteristics on the laser power. Only when comparing the 0.98 and 1.56 μm lasers, no statistically significant difference in the effect of the laser power on the ablation depth was revealed.

Table 1

Overview of dependence of incision parameters on power and wavelength

Model	R	R^2	SE	F	df1	df2	*p*
Model 1 (coagulation zone width)	0.88	0.78	0.014	444.7	5	444	<0.001
Model 2 (ablation zone depth)	0.96	0.92	0.004	1107.3	5	444	<0.001
Model 3 (ablation zone width)	0.88	0.78	0.013	378.3	5	444	<0.001

The dependent variable for model *1* – coagulation width; for model *2* – ablation depth; for model *3* – ablation width; *p* – significance level; SE – standard error, df – degrees of freedom.

Table 2

Regression parameters for dependence of laser incision characteristics on radiation power and wavelength

Model	Parameter	Coefficient	SE	p	Lower confidence interval limit	Upper confidence interval limit
Model 1 (coagulation zone width)	Constant	$\beta_0 = 0.483$	0.006	<0.001	0.472	0.495
	Power	$\beta_1 = 0.033$	0.002	<0.001	0.029	0.037
	1.56 μm	$\beta_2 = 0.426$	0.015	<0.001	0.399	0.458
	1.94 μm	$\beta_3 = 0.289$	0.01	<0.001	0.269	0.309
	Power* 1.56 μm	$\beta_4 = 0.017$	0.005	<0.001	0.007	0.027
	Power* 1.94 μm	$\beta_5 = 0.034$	0.004	<0.001	0.027	0.041
Model 2 (ablation zone depth)	Constant	$\beta_0 = 0.508$	0.006	<0.001	0.496	0.519
	Power	$\beta_1 = 0.053$	0.002	<0.001	0.049	0.057
	1.56 μm	$\beta_2 = 0.024$	0.007	<0.001	0.01	0.039
	1.94 μm	$\beta_3 = 0.017$	0.008	0.040	0.001	0.033
	Power* 1.56 μm	$\beta_4 = 0.003$	0.002	0.183	-0.002	0.008
	Power* 1.94 μm	$\beta_5 = 0.054$	0.003	<0.001	0.048	0.059
Model 3 (ablation zone width)	Constant	$\beta_0 = 1.258$	0.014	<0.001	1.23	1.283
	Power	$\beta_1 = 0.096$	0.004	<0.001	0.087	0.105
	1.56 μm	$\beta_2 = -0.25$	0.02	<0.001	-0.289	-0.211
	1.94 μm	$\beta_3 = -0.024$	0.024	0.314	-0.073	0.027
	Power* 1.56 μm	$\beta_4 = -0.032$	0.007	<0.001	-0.045	-0.019
	Power* 1.94 μm	$\beta_5 = 0.083$	0.007	<0.001	0.068	0.097

Statistical analysis of the data obtained showed that the laser power significantly ($p < 0.05$) influenced the cutting and coagulation properties of all lasers. This was confirmed by the statistical significance of the β_1 coefficient in all the three models (width of the coagulation zone, depth and width of the ablation zone).

The 1.56 μm laser radiation (water absorption) did not differ much from the 0.98 μm radiation (hemoglobin absorption) in its cutting properties (the statistical differences in the ablation zone depths are non-significant, $p > 0.05$), though its coagulation properties were more prominent: compared with the 0.98 μm laser, the 1.56 μm laser created a wider coagulation zone at the same power mode (β_2 differs significantly from 0).

The cutting properties of the 1.94 μm laser followed a different correlation pattern with its power than the 0.98 μm or 1.56 μm lasers (due to a different angle of the regression line, which was confirmed by the fact that β_5 is statistically different from zero in model 2). Unlike the 0.98 μm and 1.56 μm lasers, the power of 3–5 W resulted in a smaller width and depth of the ablation zone, while the power of 9–11 W increased these incision parameters. The 1.94 μm laser was found to have greater coagulation properties than the 0.98 μm laser with hemoglobin absorption.

The research showed that greater laser power primarily increased the ablation zone width (the regression coefficients were 0.1, 0.06, and 0.18 mm/W for the 0.98, 1.56, and 1.94 μm lasers, respectively), to a lesser extent – the ablation crater depth (the regression coefficients were 0.05, 0.06, and 0.11 mm/W, respectively), and to the least extent – the width of the lateral coagulation zone (the regression coefficients were 0.03, 0.05, and 0.07 mm/W, respectively). Thus, the increase in laser power predominantly affected the cutting properties, making the ablation zone deeper and wider, but had a modest effect on the coagulation abilities. Therefore, using greater laser power during surgery will increase the cutting properties of the laser more than the hemostatic ones.

The visual analysis of the regression lines demonstrated that the 1.94 μm laser had less prominent coagulation properties than the 1.56 μm laser, since the former was absorbed by water more easily and had a greater target chromophore absorption rate, as well as a smaller penetration depth. However, the statistical analysis of differences between the 1.94 and 1.56 μm lasers was not performed, as it was not intended by the research design.

Contact laser exposure mainly involves radiation absorption by the area of carbonization and its transmission to the surrounding tissues. Since most of the near-infrared radiation is absorbed by carbon particles, no significant differences in the cutting properties of the tested wavelengths were recorded. All the lasers showed good cutting properties. The difference in the coagulation properties appears to depend on the amount of remaining radiation (unabsorbed by carbon) penetrating the tissue and can be explained by differences in the wavelength characteristics (different chromophores and tissue absorption coefficient).

CONCLUSION

The research and the resulting data analysis confirmed the statistically significant dependence of all laser incision characteristics (width of the lateral coagulation zone, depth and width of the ablation zone) on the radiation power for the 0.98, 1.56, and 1.94 μm lasers. The 1.56 and 1.94 μm lasers have better coagulation properties compared with the 0.98 μm semiconductor laser. The 1.94 μm laser is superior to the 0.98 μm laser in its cutting properties.

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Authors contribution

Ryabova M.A. – design. Ulupov M.Yu. – collection of data for analysis, analysis of the data. Shumilova N.A. – review of publications on the topic of the article. Tikhomirova E.K., Portnov G.V. – carrying out of the experimental part of the study. Malkova M.E. – statistical analysis of the results.

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