中国激光

子脉冲序列模式 Er∶YAG 激光消融牙本质的实验观察

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摘要 研制了一台子脉冲序列模式 Er∶YAG 激光器，获得了每秒 80 个和 100 个子脉冲高能量激光输出，开展了不同脉冲宽度的子脉冲对离体牙本质的激光消融实验。实验中使用的是子脉冲序列模式激光器，其重复频率为 20 Hz，脉冲包络能量为 45 mJ，子脉冲宽度分别为 20，30，40，50 μs，在无冷却水雾条件下分别对比了子脉冲宽度对牙本质消融量、牙髓腔温升和坑洞组织形貌的影响。结果表明：在相同的激光脉冲能量下，较窄的子脉冲宽度不仅能够增加消融量，降低牙髓腔温升，从而延长操作时间，而且可以获得更好的消融坑洞组织形貌，牙小管的开放程度较高，有利于黏接修复治疗。

关键词 激光光学；Er∶YAG 激光；子脉冲序列模式；组织消融；牙本质

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1 引 言

2.94 μm Er∶YAG 激光在生物医疗、军事等领域具有广泛应用。该激光波长位于水和羟基磷灰石的强吸收峰附近[1]，对于生物软组织的消融以及对于骨头[2]、牙齿等硬组织[3]的切割都有着无可比拟的优势。目前，铒激光在临床应用中多采用静态（自由振荡）和动态（调 Q）两种模式[2]。灯泵静态铒激光的脉宽较大，通常可达 1000 μs，较大的激光热效应难以实现高重复频率的运行，而且消融过程中的热效应比较严重，容易导致坑洞碳化，同时过多的热量扩散也会导致周围组织细胞发生损伤[4-5]；而动态铒激光由于调 Q 增益的限制，很难在高重复频率下获得足够大的脉冲能量。目前，临床上应用的静态和动态铒激光治疗仪的重复频率通常都不高（大部分在 50 Hz 以下），消融效率低，在牙科治疗过程中具有一定的局限性。

采用子脉冲序列模式激光可以解决上述问题。对长激光放电脉冲包络进行调制，将较长的光脉冲变成几个短的子脉冲，就可以保证激光输出既具有长脉冲的光电转化效率，又具有短脉冲的消融精度，同时还能获得高频率的脉冲序列，从而可以解决静态和动态铒激光消融热效应严重和工作效率低下的问题[6-8]。2012 年，Mironov 等[6]进行了子脉冲序列模式铒激光和传统牙科高速手机钻的对比临床试验，结果发现，50 μs 的子脉冲序列模式铒激光消融产生的噪声小，消融坑洞边缘更加清晰；2015 年，Baraba 等[7]通过研究铒激光的消融速率和消融量发现，与 300 μs 的单脉冲模式相比，50 μs 的子脉冲序列模式铒激光在坑洞的消融速率和光滑度上均具有很大优势；2016 年，Akin 等[8]对激光消融牙釉质后的黏接强度进行研究后发现，与 100 μs 的单脉冲模式相比，采用 50 μs 的子脉冲序列模式激光进行消融处理能够更大幅度地提高黏接强度，从而有利于牙科的后续治疗。

已有实验研究中使用的子脉冲激光宽度均为

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50 μs,明显大于牙齿的热弛豫时间(24.4 μs)。为了避免消融过程中造成的热损伤,理想的子脉冲激光宽度应当小于牙齿的热弛豫时间。为此,本文研究了子脉冲序列模式铒激光宽度对消融效果的影响。本研究团队研制了一台子脉冲序列模式 Er∶YAG 激光器,获得了每秒 80 个和 100 个子脉冲序列的高能量激光输出;然后基于该激光器开展了不同脉冲宽度的子脉冲对离体牙本质的激光消融实验。实验结果表明,更窄的子脉冲序列模式铒激光能够提高消融效率和改善消融坑洞的组织形貌。

2 实验装置

2.1 子脉冲序列模式铒激光器的研制

如图 1 所示,通过对激光放电脉冲进行调制,可将单个长脉冲变成含 4 个短子脉冲的脉冲包络,从而能改善消融坑洞组织的形貌。对于相同的总脉冲能量,脉冲宽度的缩短能实现更高的峰值功率;同时,合适的序列子脉冲间隔能减少消融过程中产生的由等离子体吸收造成的激光能量损失,提高激光的消融效率[9-10]。

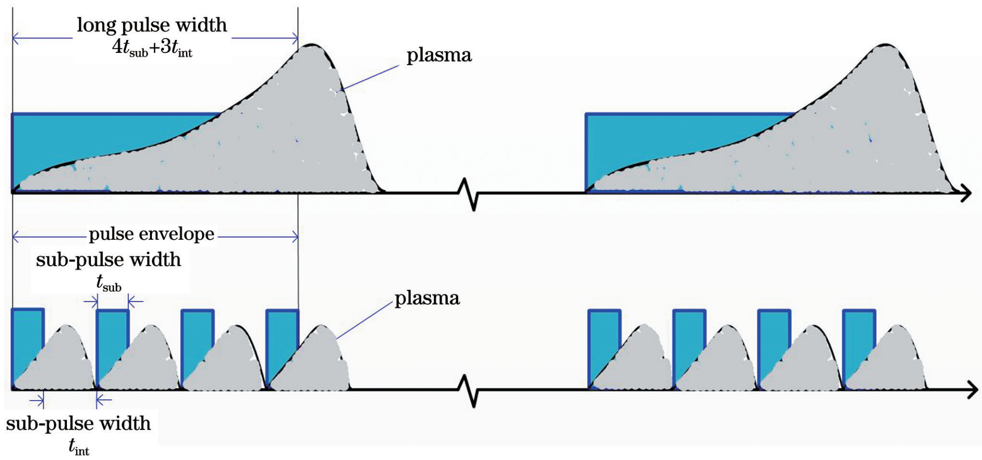

图 1 子脉冲序列模式原理图

Fig. 1 Schematic of sub-pulse sequence mode

激光加工牙窝洞或切割牙硬组织时,激光辐照区的牙本质因吸收激光能量而瞬间被加热,在激光脉冲冲击下,高温熔融物或气化物向四周喷射,形成坑洞或切口。同时,辐照区的热量传递也会导致其周边组织温度逐渐升高,温度场呈现出由照射点高温区向牙齿内部及表面周围快速下降的分布特征[11-12]。激光消融区温度的空间分布主要依赖于牙本质的热导率 λ、比热容 c 和密度 ρ 等参数。热量传导过程与脉冲激光加热的热扩散过程相似,热扩散时间可用热弛豫时间公式来描述。生物组织热弛豫时间 τ 的表达式为[13]

$$\tau=(4\alpha^2\kappa)^{-1}, \tag{1}$$

式中:α 表示组织对激光的吸收系数;κ 表示组织的热扩散系数,它与热导率 λ、比热容 c 和密度 ρ 的关系是 $\kappa=\lambda/(\rho c)$。牙本质的相关热学参数见表 1[14-16],由此可以得出牙本质的热扩散系数 $\kappa=2.56\times10^{-7}\ \mathrm{m^2/s}$,热弛豫时间 $\tau=24.4\ \mu s$。当子脉冲宽度小于热弛豫时间时,激光热量在辐照区域传导的过程可近似为绝热过程,辐照区域局部温升更快,有利于提高激光的消融效率;同时,子脉冲宽度小于热弛豫时间的窄脉冲激光的热量还来不及扩散,从而降低了对周边组织热损伤的可能性。

表 1 牙本质的热学参数

Table 1 Thermal parameters of dentin

Thermal conductivity λ/(W·m^{-1}·K^{-1})	Specific heat c/(J·g^{-1}·K^{-1})	Density ρ/(g·cm^{-3})	Absorption coefficient α/ m^{-1}
0.63	1.17	2.1	0.2×10^6

根据上述分析和临床需求,本研究团队研制了一台子脉冲序列模式铒激光器。通过外部信号触发控制激光电源的放电开关,实现对主放电脉冲的调制,从而获得子脉冲序列模式激光输出。激光器采用的 Er∶YAG 晶体棒的尺寸为 Φ4 mm×104 mm,Er^{3+} 的掺杂浓度为 50%(原子数分数),棒两端镀有 2.94 μm 增透膜。激光谐振腔采用平平腔结构,几何腔长为 194 mm。后腔镜为全反镜,在 2.94 μm

处的反射率＞99%；前腔镜为输出镜，在 2.94 μm 处的反射率为 70%。

在激光实验过程中，将主放电工作频率设为 20 Hz，将脉冲包络调制成 4 个子脉冲序列，分别进行 20，30，40，50 μs 子脉冲宽度的实验，子脉冲间隔时间为 85 μs。实验实现了每秒 80 个子脉冲的高能量激光输出，在子脉冲宽度为 50，40，30，20 μs 时，获得脉冲包络的最大能量分别为 671.1，741.1，814.1，798.8 mJ，相应的最大斜效率为 1.8%左右。激光脉冲输出随泵浦能量的变化如图 2 所示。由图 2 可以看出：随着泵浦能量提高，输出能量逐渐增加，但由于激光晶体热效应的影响，激光输出能量达到峰值后会出现下降；在将脉冲包络调制为 5 个子脉冲的条件下，获得了每秒 100 个子脉冲的激光输出，在子脉冲宽度为 20 μs 时获得的脉冲包络的最大能量为 536.5 mJ，最大斜效率为 1.7%；与调制成 4 个子脉冲时相比，调制成 5 个子脉冲条件下，激光的振荡阈值增大，但激光输出脉冲能量和转换效率有所降低。

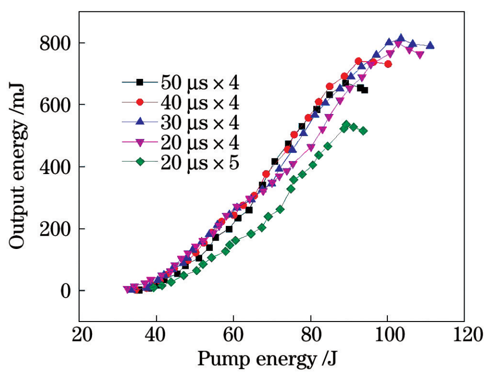

图 2　输出能量随泵浦能量的变化

Fig. 2　Output energy as a function of pump energy

2.2　牙本质激光消融实验装置

本次实验将近期拔除的完整无龋人恒磨牙作为实验样品。将实验样品放入生理盐水中保存，两周后用洁制器去除牙齿上残余的软组织，然后使用传统的牙科医疗设备——涡轮手机（金刚砂车针）去除牙齿表面的牙釉质和牙根部。牙本质样品的表面直径为(10±1) mm，用砂纸逐级对其进行打磨抛光，以确保样品的表面平滑度。

牙本质激光消融实验装置如图 3 所示。Er:YAG 激光器输出的光束首先经过45°全反镜反射，然后经过聚焦透镜（焦距 f=50 mm）聚焦。聚焦后的光斑直径为 0.54 mm，远小于牙本质样品的尺寸。聚焦后的激光垂直照射于样品表面。实验样品放置于二维电位移平台上，并确保样品表面在聚焦镜的焦点处。实验过程中未使用水雾冷却。

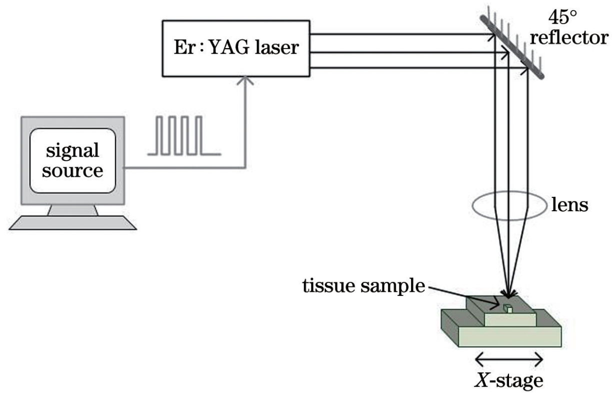

图 3　牙本质消融实验装置示意图

Fig. 3　Schematic of dentin ablation experimental set-up

3　结果与讨论

3.1　牙本质消融量

在铒激光消融牙本质过程中，辐照区吸收激光能量后迅速升温，产生熔融、气化等现象，从而实现组织的去除，形成消融坑洞。Baraba 等[7]在不同脉冲宽度条件下采用铒激光对牙本质进行了消融，结果发现，随着脉冲宽度缩短，牙本质消融量增多，坑洞的消融速率提高。这是因为，当激光脉冲能量相同时，脉冲宽度越窄，峰值功率密度就会越大，激光脉冲能量就更集中于组织的消融，组织温升更快，从而获得了更高的消融效率。

在本文研究高重复频率子脉冲宽度对离体牙本质消融特性影响的实验中，选择激光器工作在脉冲包络含有 4 个子脉冲序列的模式，激光器的重复频率为 20 Hz，脉冲包络能量为 45 mJ，子脉冲宽度分别设置为 20，30，40，50 μs，消融量随时间变化的曲线如图 4 所示。可见：随着子脉冲宽度减小，相同时间内的消融量逐渐增加；当子脉冲宽度为 20 μs 时，经过 60 s 的光照后，消融量为 90 mg；在子脉冲宽度

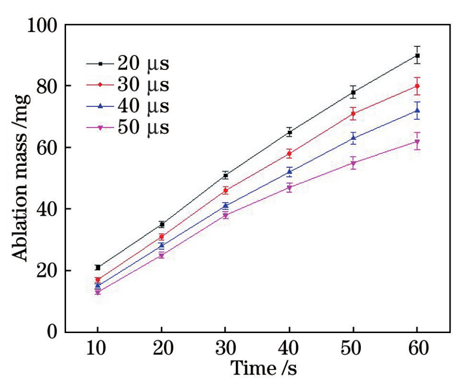

图 4　消融量随时间的变化

Fig. 4　Variation of ablation mass with time

为 50 μs 时，经过 60 s 光照后，消融量为 62 mg。这表明，使用子脉冲宽度较窄的子脉冲序列模式激光辐照牙齿，消融量更大，激光消融效率更高。

3.2 牙髓腔温度实验

在激光消融牙齿的临床治疗过程中，除了追求较高的消融效率之外，牙髓腔的温升也至关重要。牙髓腔的温度变化会直接影响腔内的健康牙髓组织，Zach 等[17]的研究表明：在人体口腔温度（37 ℃）的基础上，若牙髓腔温度升高 5.6 ℃，组织坏死率可达到 15%；若温度升高 11.1 ℃，坏死率就会上升至 60%；当温度升高 16.7 ℃时，牙髓腔组织几乎全部坏死。为了保证激光消融牙本质过程中的安全性，牙髓腔内的温升必须小于 5 ℃，即消融过程中应保证牙髓腔内的温度低于 42 ℃。

在高重复频率子脉冲序列模式铒激光消融牙本质的温度实验中，本文使用高速手机去除牙齿样本上表面的牙釉质和牙根部，从牙颈部开髓孔处插入热电偶探头，用热导率为 11 W/(m·K)的导热硅脂填充牙髓腔与热电偶探头的空隙，测量牙髓腔的温度随时间的变化，得到的结果如图 5 所示。

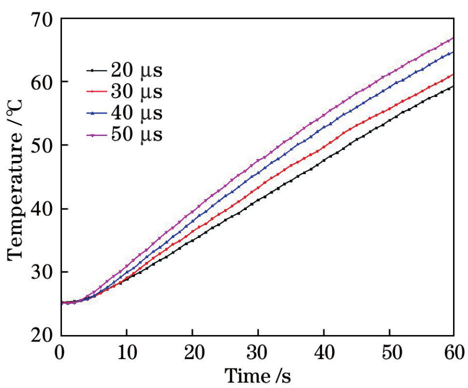

图 5 牙髓腔的温升曲线

Fig. 5 Temperature rise curve of pulp chamber

在重复频率为 20 Hz 的条件下，使用脉冲包络能量为 45 mJ 的 80 个子脉冲序列模式激光消融牙本质，随着子脉冲宽度减小，牙髓腔内的温升速率下降。当子脉冲宽度为 50 μs 时，温度达到 42 ℃仅需 25 s；而当子脉冲宽度为 20 μs 时，温度达到 42 ℃则需要 33 s。较窄的子脉冲宽度激光能减缓温度升高的速率，延长临床应用中的操作过程。但随着消融时间延长，4 组子脉冲宽度下的温度均会超过牙髓腔坏死温度（53.7 ℃）。这表明，在临床实际应用中，子脉冲序列模式铒激光消融过程仍需要进行水雾冷却，以避免温度过高导致牙髓腔健康组织坏死。

3.3 消融坑洞的组织形貌和结构

为了进一步研究不同子脉冲宽度的子脉冲序列模式铒激光消融的坑洞的组织形貌和微观结构，在与上述实验相同的条件下对牙本质样品进行 4 s 的激光辐照，重复频率为 20 Hz，脉冲包络能量为 45 mJ，消融能量密度为 11.5 J/cm^2。将消融后的牙本质样品进行喷金处理后，使用场发射扫描电子显微镜在加速电压为 10 kV 和束斑尺寸为 4 的条件下放大 2000 倍进行观察，获得了不同子脉冲宽度的子脉冲序列模式铒激光消融样品的组织形貌，如图 6 所示。图 6(a)、(b)的子脉冲宽度分别为 20 μs 和 30 μs，皆接近热弛豫时间，其消融坑洞表面未见碳化和熔融现象，底部牙小管完全开放；而当子脉冲宽度为 40 μs 和 50 μs 时，如图 6(c)、(d)所示，由于子脉冲宽度超过热弛豫时间，消融过程中的热量累积造成了热损伤，在电镜观察中虽然未见明显的熔融和碳化碎屑，但底部牙小管有部分封闭，说明发生了局部熔融现象。牙小管的开放程度越高，就越有利于树脂和黏结剂渗入牙本质形成机械锁合作用，从而实现更高的结合强度[18-19]。这表明，使用子脉冲宽度低于牙组织热弛豫时间的铒激光消融牙本质更有利于患者的下一步治疗。

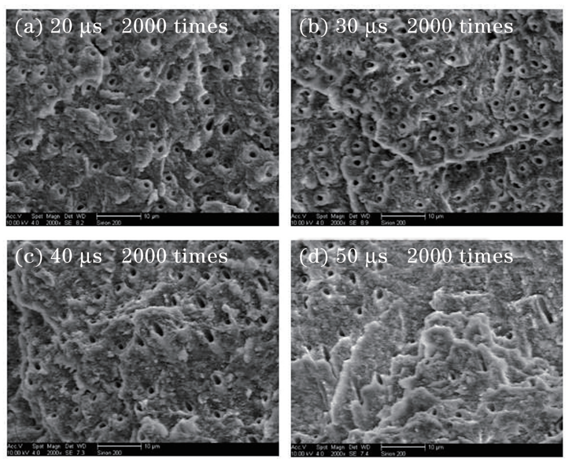

图 6 Er:YAG 激光消融牙本质的电镜照片。(a)激光子脉冲宽度为 20 μs；(b)激光子脉冲宽度为 30 μs；(c)激光子脉冲宽度为 40 μs；(d)激光子脉冲宽度为 50 μs

Fig. 6 SEM images of dentin ablated by Er:YAG laser. The sub-pulse widths: (a) 20 μs; (b) 30 μs; (c) 40 μs; (d) 50 μs

4 结 论

本文研制了一款子脉冲宽度分为 20，30，40，50 μs 的子脉冲序列模式铒激光器，它可以实现每秒 100 个子脉冲序列激光输出。在无冷却水雾条件

下，本文通过实验研究了子脉冲宽度对牙本质消融量、牙髓腔温升和消融组织形貌的影响。结果表明：在脉冲能量相同的条件下，随着子脉冲宽度减小，消融量增加，相同时间内牙髓腔的温升速率下降；子脉冲宽度越窄，消融坑洞的组织形貌越好，牙本质底部牙小管的开放程度越高，越有利于下一步的黏接修复。本实验结果有助于对子脉冲序列模式铒激光的牙本质消融特性进行深入了解，对高重复频率脉冲铒激光口腔治疗技术的应用和发展也具有一定的推动作用。

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Observation of Dentin Ablation Using an Er∶YAG Laser in a Sub-Pulse Sequence Mode

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Abstract

Objective Er∶YAG laser crystals can produce laser at a wavelength of 2.94 μm, which is close to the infrared absorption peaks of water and hydroxyapatite. Laser at a wavelength of 2.94 μm possess numerous advantages in the ablation of biological tissues and the cutting of hard tissues such as bones and teeth. In clinical applications, erbium lasers are mainly used in two modes: free-running and Q-switched. However, free-running erbium lasers have a pulse width of a few hundred microseconds. Long pulses used to affect tissues cause heat diffusion into the surrounding healthy tissues resulting in damage or necrosis. Due to the low gain of 2.94 μm erbium laser crystals, it is difficult to obtain Q-switched erbium lasers with high pulse energy at high repetition frequency. The low ablation efficiency caused by low pulse repetition frequency limits their efficacy in dental treatment. To solve the problems mentioned above, we have developed a sub-pulse sequence mode laser at a high repetition frequency. In this mode, a standard long pulse is divided into several short sub-pulses with the same sub-pulse interval. This enables the sub-pulse sequence mode to deliver short, high finesse pulses with a photoelectric conversion efficiency of long duration pulses without sacrificing the ablation precision of short duration pulses.

Methods We set four groups of sub-pulse widths as 20, 30, 40, and 50 μs, and the sub-pulse interval time as 85 μs. The repetition frequency of the laser was 20 Hz. An Er∶YAG crystal rod with 4 mm diameter and 104 mm length was used as a laser-active medium. Doping concentration of the Er∶YAG crystal was 50% (atomic fraction) for Er^{3+}. Two facets of the Er∶YAG rod were antireflection-coated at 2.94 μm. A resonator was formed using two plane mirrors separated by 194 mm. The reflectivity of the high reflective (HR) mirror exceeded 99% and reflectivity of the output coupling mirror was 70%. An insulated gate bipolar transistor module that can control pulse width and laser frequency through the external pulse signal was used in the laser power supply. In addition, the effects of sub-pulse width on erbium laser ablation in sub-pulse sequence mode were investigated. We used the Er∶YAG laser in sub-pulse sequence mode as the light source. The laser beam was reflected toward the dental sample using a 45° reflector. After being focused by a lens focal length (focal length $f=$ 50 mm), the beam vertically irradiated the surface of the dentin. Cooling water mist was not required during the experiment.

Results and Discussions A sub-pulse sequence mode erbium laser with high energy laser outputs of 80 sub-pulses per second was developed. When the sub-pulse widths were 50, 40, 30, and 20 μs, the maximum energy values were 671.1, 741.1, 814.1, and 798.8 mJ, respectively. The corresponding maximum slope efficiency was about 1.8% (Fig. 2). Through the experiment of dentin samples ablation, we found that the ablation mass would increase with decreasing sub-pulse widths. When the sub-pulse width was 20 μs, the mass of ablation was 90 mg after 60 s laser irradiation. When the sub-pulse width was 50 μs, the ablation mass was 62 mg. The ablation mass of the former was 45% higher than that of the latter (Fig. 4). Under conditions of 20 Hz repetition frequency, the samples were treated with the sub-pulse sequence mode laser at energy of 45 mJ. With decreasing sub-pulse width, the temperature rise in the pulp chamber decreased. When the pulse width was 50 μs, the temperature reached 42 ℃ within 25 s, but when the pulse width was set as 20 μs, the temperature reached 42 ℃ within 33 s (Fig. 5). In addition, the dentin samples were sprayed with gold and dehydrated to study the cavity structure after ablation before observation with a scanning electron microscope (SEM). When the sub-pulse widths were 20 μs and 30 μs, no carbonization, melting, or debris were observed on the surface of the pot hole, and the lower dental tubules were completely open. However, when the sub-pulse width reached 40 μs or 50 μs, no obvious melting and debris were observed by the scanning electron microscope, but the dentinal tubules were partially sealed (Fig. 6).

Conclusions　A sub-pulse sequence mode erbium laser at a high repetition frequency was developed, which obtained high energy laser outputs of 80 or 100 sub-pulses per second. The effects of sub-pulse width on erbium laser ablation in sub-pulse sequence mode were investigated. The pulse widths of the sub-pulse during ablation were set to 20, 30, 40 and 50 μs, respectively, and the pulse energy of the laser was maintained at 45 mJ. The influence of sub-pulse width on the ablation mass, the temperature rise in the pulp chamber, and the cavity microstructure were analyzed without cooling water mist. Results indicate that shorter sub-pulse widths can increase the ablation mass, reduce the temperature rise in the pulp chamber, prolong the operation time, and improve efficiency. In addition, improved cavity microstructure and more open dentinal tubules were obtained, which are both beneficial to adhesive repair and treatment.

Key words　laser optics; Er∶YAG laser; sub-pulse sequence mode; tissue ablation; dentin

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