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·基础研究·

表面处理对激光非破坏性拆除氧化锆修复体后牙本质再粘接效果的影响

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【摘要】 **目的** 探讨使用Er: YAG激光拆除修复体后，牙本质表面的变化及不同表面处理方式对牙本质再粘接效果的影响，为口腔临床操作提供参考。**方法** 本研究已通过单位伦理审查委员会批准。应用计算机辅助设计与计算机辅助制作(computer aided design and computer aided manufacturing，CAD/CAM)技术制作氧化锆试件(4 mm × 4 mm × 1.5 mm)102个。收集拔除人阻生第三磨牙110颗，制备牙本质块(4 mm × 4 mm × 2 mm)102个。将氧化锆试件与牙本质块用树脂水门汀粘接后，而后用Er: YAG激光拆除。随机选取3个拆除后的牙本质块，X射线能量色散谱仪(energy dispersive X-ray spectroscopy，EDX)分析牙本质表面元素组成。将拆除后牙本质块随机分成3组($n = 33$)，分别进行不同的表面处理：对照组(不做任何处理)、喷砂组(颗粒大小为50 μm Al_2O_3喷砂处理)、激光照射组(Er: YAG激光照射，参数为10 Hz，60 mJ，0.6 W)。各组随机选取3个牙本质块进行扫描电镜(scanning electron microscope，SEM)观察；各组剩余30个牙本质块使用光学体式显微镜，在20倍下观察牙本质表面残留的树脂，用树脂残留指数(adhesive remnant index，ARI)法计分。而后使用树脂水门汀按照标准程序与3组经过不同表面处理的牙本质块再粘接，形成牙本质-树脂粘接试件($n = 30$)，每组再分为两个亚组进行老化($n = 15$)，其中一亚组进行37 ℃恒温水浴 24 h，另一亚组 37 ℃恒温水浴24 h后再接受5 000次冷热循环，测量各组微剪切粘接强度，并分析断裂模式。比较3组牙本质表面ARI组间差异及粘接强度、断裂模式的组间差异以及组内老化前后差异。**结果** Er: YAG激光拆除氧化锆，牙本质表面未见明显损伤，但牙本质内C元素及Si元素显著增加。经过不同表面处理后，喷砂、激光照射组ARI低于对照组($P < 0.05$)，而喷砂组与激光照射组间ARI差异无统计学意义($P > 0.05$)。牙本质表面形貌也呈现出差异：对照组牙本质表面可见牙本质表面残留大量树脂；喷砂组残留树脂较少，牙本质表面粗糙，可见牙本质小管；激光照射组牙本质表面可见块状残留树脂。经37 ℃恒温水浴 24 h后，对照组、喷砂组、激光照射组粘接强度分别是(6.13 ± 2.40)MPa、(9.39 ± 2.00)MPa、(5.85 ± 1.44)MPa，喷砂组粘接强度显著高于其他2组($P < 0.05$)；经37 ℃恒温水浴 24 h并接受5 000次冷热循环后，对照组、喷砂组、激光照射组粘接强度分别为(5.39 ± 0.83)MPa、(8.45 ± 1.20) MPa、(4.84 ± 1.43)MPa，喷砂组粘接强度显著高于其他2组($P < 0.05$)。对照组、喷砂组、激光照射组经37 ℃恒温水浴 24 h后，5 000次冷热循环前后粘接强度均无统计学差异($P > 0.05$)。对照组、喷砂组、激光照射组均未出现内聚断裂，断裂模式主要为粘接断裂，5 000次冷热循环前后，喷砂组混合断裂频率均高于其他2组($P < 0.05$)。**结论** Er: YAG激光拆除氧化锆未对牙本质造成损伤，但拆除后牙本质表面会残留大量树脂。通过50 μm Al_2O_3喷砂处理可以有效去除这些残留树脂，从而改善牙本质再粘接效果。

【关键词】 喷砂； 氧化锆； 牙本质； Er: YAG激光； 粘接强度； 牙本质粘接；冷热循环老化； 树脂残留指数

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Effect of surface treatment on dentin rebonding after laser non-destructive removal of zirconia prosthesis

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【**Abstract**】　**Objective**　To investigate the changes of dentin surface and the effects of different surface treatments on the rebonding effect following non-destructive restoration removal by an Er:YAG laser and to provide reference for oral clinical operation. **Methods**　This study was approved by the ethics review committee of the unit. Using computer-aided design and computer-aided manufacturing (CAD/CAM) technology, 102 zirconia specimens (4 mm × 4 mm × 1.5 mm) were fabricated. In total, 110 impacted third molar teeth were extracted, and 102 dentine blocks (4 mm × 4 mm × 2 mm) were prepared. The zirconia specimen and dentin blocks were bonded with resin cement before removal with an Er:YAG laser. Three disassembled dentin blocks were randomly selected, and the components of dentin surface elements were analyzed by energy dispersive X-ray spectroscopy (EDX). The removed dentin blocks were randomly divided into three groups (n = 33) based on the different surface treatments: control group (no treatment), sandblasting group (50 μm, Al_2O_3 sandblasting), and laser irradiation group (Er: YAG laser irradiation, parameters were set to 10 Hz, 60 mJ, 0.6 W). Three dentin blocks were randomly selected in each group for scanning electron microscopy (SEM) observation, and the residual resin on dentin surface of remaining 30 dentin blocks in each group were observed under an optical microscope at 20 times magnification. Scores were obtained using the adhesive remnant index (ARI) method. Three groups of dentin blocks (n = 30) that underwent different surface treatments were rebonded with resin cement according to standard procedures and then divided into two subgroups for aging (n = 15). One subgroup was subjected to a 37 ℃ water bath for 24 h, and the other subgroup was subjected to 5 000 thermal cycles after a 37 ℃ water bath for 24 h, and the microshear bonding strength of each group was measured. The microshear bonding strength of each group was measured, and fracture modes were analyzed. The differences of dentine surface ARI between the three groups, as well as the inter-group differences in fracture mode, and bonding strength, and the intra-group differences before and after aging were compared between the three groups. **Results**　When zirconia was removed by Er: YAG laser, there was no obvious damage on the dentin surface, but C and Si elements in dentin increased significantly. After different surface treatments, the ARI scores of the sandblasting and laser irradiation groups were lower than those of the control group (P < 0.05), while ARI was not significantly different between the sandblasting and laser irradiation groups (P > 0.05). The dentin surface morphology was also different. There was a large amount of residual resin on the dentin surface of the control group. In the sandblasting group, the residual resin was lower, the dentin surface was rough, and the dentin tubules were visible. A large amount of residual resin was observed on the dentin surface of the laser irradiation group. After 24 h of water bath at 37 ℃, the bonding strengths of the control group, sandblasting group, and laser irradiation group were (6.13 ± 2.40) MPa, (9.39 ± 2.00) MPa, and (5.85 ± 1.44) MPa, respectively, and the bonding strength of the sandblasting group was significantly higher than that of the other two groups (P < 0.05). After being subjected to 24 h of water bath at 37 ℃ and 5 000 thermal cycles, the bonding strengths of the control group, sandblasting group, and laser irradiation group were (5.39 ± 0.83) MPa, (8.45 ± 1.20) MPa and (4.84 ± 1.43) MPa, respectively. The bonding strength of the sandblasting group was significantly higher than that of the other two groups (P < 0.05). There was no significant difference between the control group, sandblasting group, and laser irradiation group before and after 5 000 thermal cycles following 24 h of water bath at 37 ℃ (P > 0.05). In the control group, sandblasting group, and laser irradiation group, cohesive fracture was not observed. The fracture mode was mainly adhesive fracture. Before and after 5 000 thermal cycles, the frequency of mixed fracture in the sandblasting group was significantly higher than that in the other two groups (P < 0.05). **Conclusion**　Er: YAG laser removal of zirconia does not damage dentin, but a large amount of resin remains on the dentin surface after removal. The sandblasting process can effectively remove these residual resins, thereby improving the dentine rebonding effect.

【**Key words**】　sandblasting;　zirconia;　dentin;　Er: YAG laser;　bonding strength;　dentin bonding;　thermal cycle;　adhesive remnant index

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近年来，氧化锆修复体因其卓越的机械性能与美学特性，在口腔修复领域的应用日益广泛[1]。然而，治疗后，患者可能因继发龋、牙髓疾病[2]或修复体崩瓷[3]等问题，需要对氧化锆修复体进行拆除。传统上，口腔修复医生倾向于使用破坏性拆除方式进行拆除[4]。虽然，破坏性拆除简单易行，但却存在牙体二次损伤、修复体无法二次利用等不足[4]，给患者带来额外的精神负担和经济负担。随着氧化锆材料的不断进步[5]，中红外波长的掺铒钇铝石榴石激光（erbium-doped yttrium aluminium garnet，Er: YAG）被证实能有效且完整地拆除氧化锆修复体，为修复体的再粘接与二次利用开辟了新途径。特别是随着氧化锆半透明性的提升[1]，波长为2 940 nm（接近水分子吸收峰）的Er: YAG激光[6]，能够穿透氧化锆修复体，作用于粘接界面的水门汀、水及树脂单体[7]，通过微爆破效应实现非破坏性拆除[8]。有研究提出，激光非破坏性后，牙本质表面残留的树脂粘接剂经历热消融、碳化等特殊变化[9]。然而，关于这些残留树脂对牙本质再粘接强度的影响，国内外研究结论不一。多数观点认为，残留树脂会干扰牙本质的酸蚀与渗透过程，甚至阻碍树脂的聚合反应，从而降低再粘接强度[10]。但也有不同观点，如Zortuk等[11]指出牙本质表面残余树脂对其再粘接强度无明显影响。同时，Bavbek等[12]则认为，目前尚无完全去除牙本质表面残留树脂的有效方法。

本研究旨通过比较喷砂处理和激光照射对Er: YAG激光拆除氧化锆修复体后牙本质再粘接强度的影响，寻找氧化锆修复体再粘接时可能的最佳牙本质表面处理方式，为口腔临床操作提供参考。

1　材料和方法

1.1　材料与仪器

氧化锆（Organical CAD/CAM）和切削机（R+K CAD/CAM Technologie GmbH，德国）；树脂水门汀（RelyX Ultimate）和通用型粘接剂（Single Bond Universal）（3M，美国）；慢速硬组织切割机（Isomet，Buehler，美国）；双波长激光治疗仪（M021-5AF/1，Fotona，斯洛文尼亚）；万能材料试验机（AGS-X，Shimadzu，日本）；光固化灯（Elipar S10，3M，美国）；Al_2O_3颗粒（50 μm，Renfert，德国）；碳化硅水磨砂纸（400、600、1 000、2 000目，Starcke，德国）；喷砂枪（Danville，Microetcher ⅡA，美国）；扫描电镜（QUANTA 450，FEI，美国）；X射线能量色散谱仪（energy dispersive X-ray spectroscopy，EDX）（Xplore30，Oxford，英国）；冷热循环仪（TC-501F（Ⅲ），苏州威尔，中国）；光学体式显微镜（MM400，NIKON，日本）。

1.2　试件制备

本项研究经福建医科大学附属口腔医院生物医学研究伦理委员会批准（审批号：2021福医口伦理审字第37号），共收集110颗因阻生拔除的无龋坏完整第三磨牙（福建医科大学附属口腔医院口腔颌面外科门诊提供），去除牙周软组织，浸泡于生理盐水中，4 ℃储存。使用慢速硬组织切割机在流水冷却下分离离体牙冠根，暴露冠部牙本质，制备4 mm × 4 mm × 2 mm表面无裂痕、缺陷的牙本质块102个。用自凝树脂包埋牙本质形成直径10 mm、高5 mm的圆柱体试件，暴露牙本质，流水冲洗下碳化硅水磨砂纸由粗到细逐一标准化牙本质表面（600、1 200、2 000目）[13]。

应用计算机辅助设计与计算机辅助制作（computer aided design and computer aided manufacturing，CAD/CAM）技术制作4 mm × 4 mm × 1.5 mm的氧化锆试件102个，并在流水冲洗下碳化硅水磨砂纸由粗到细逐一标准化（400、600、1 000目）氧化锆表面[14]。用50 μm Al_2O_3在2.5 bar压力下距氧化锆表面离10 mm进行喷砂处理10 s，使用无水乙醇超声荡洗5 min，吹干备用[14]。

1.3　粘接试件及拆除

按照产品说明书要求，使用通用型粘接剂和树脂水门汀粘接氧化锆试件与牙本质块，在10 N的恒定压力下，先光照固化3 ~ 5 s，探针去除多余的水门汀，再光照固化20 s[14]。使用Er: YAG激光（参数设置为10 Hz，220 mJ，2.2 W，水气比为4∶4），中短脉冲（medium short pulse，MSP）模式对氧化锆进行拆除[9]，拆除过程中，激光手柄的激光纤头距离氧化锆表面1 mm，并与试件表面成90°，激光束呈叠瓦状匀速、缓慢照射，直至氧化锆脱离。

1.4　拆除氧化锆后牙本质表面EDX分析

拆除氧化锆后牙本质表面EDX分析：随机选取3个牙本质块置于2.5%戊二醛固定2 h，磷酸盐缓冲液（phosphate buffered saline，PBS）漂洗3次，乙醇梯度脱水，冷冻干燥后24 h，真空溅射镀金，进行表面元素组成EDX分析。

1.5　牙本质表面处理及分组

将拆除下的99个牙本质块随机分成3组（n = 33），分别予以下处理，对照组：不做表面处理；喷砂组：喷砂处理方式为喷砂机使用50 μm Al_2O_3颗

粒，在压力为3 bar条件下，距离牙本质表面2 mm喷砂20 s[15]，而后荡洗10 s；激光照射组：Er: YAG激光照射参数设置为10 Hz，60 mJ，0.6 W[16]，水气比为6∶4，MSP模式，光纤头垂直并距离牙本质表面1 mm，激光束呈叠瓦状匀速、缓慢照射1 min。

1.6 牙本质表面观察

各组随机抽取3个牙本质块置于2.5%戊二醛固定2 h，PBS漂洗，乙醇梯度脱水，冷冻干燥后24 h，真空溅射镀金，使用扫描电镜（scanning electron microscope，SEM）加速电压5 kV下观察牙本质表面。各组剩余30个牙本质块使用光学体式显微镜，20倍下观察牙本质表面残留的树脂，用树脂残留指数（adhesive remnant index，ARI）法计分，0分：无树脂残留于牙本质表面；1分：＜50%的树脂残留于牙本质表面；2分：＞50%的树脂残留于牙本质表面；3分：牙本质表面完全被树脂覆盖[17]。

1.7 再粘接试件制备

将直径1 mm，高1 mm的树脂柱（RelyX Ultimate，3M，美国）与3组经过不同表面处理的牙本质块再粘接，获得对照组、喷砂组、激光照射组试件（$n = 30$）。采用随机数字表法各组选取1/2试件为37 ℃恒温水浴24 h（24 h组），剩余1/2试件经过37 ℃恒温水浴24 h后再接受5 000次冷热循环（冷水5 ℃ ± 0.5 ℃、热水55 ℃ ± 0.5 ℃，冷热水池中各停留30 s）（24 h+5 000 TC组）[18]，测量各组微剪切粘接强度并分析断裂模式。

1.8 微剪切粘接强度测试

微剪切粘接强度测试及断裂模式分析：将试件夹持于实验器具上，安装在万能试验机上，试件的粘接界面与加载头水平距离小于0.5 mm，加载力与粘接界面平行，加载速度为0.5 mm/min，直至粘接界面断裂[19]。微剪切粘接强度的计算公式为：P=F/A，其中P为微剪切粘接强度（MPa）；F为最大剪切力（N）；A为粘接面积（mm^2）[20]。

1.9 断裂模式分析

使用光学体式显微镜在20倍下观察再粘接试件的断裂界面。断裂模式分为3类：粘接断裂；内聚断裂；混合断裂。

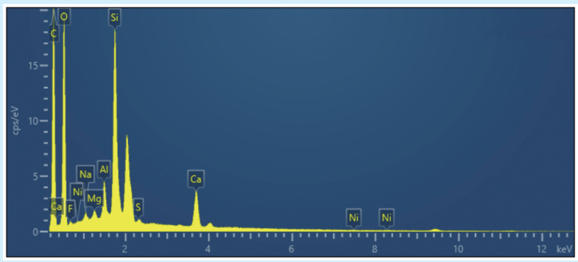
1.10 统计学分析

使用SPSS 25.0统计软件（IBM，美国）进行分析，采用Kruskal-Wallis检验和Mann-Whitney *U*检验比较3组树脂残留指数（ARI）组间差异及断裂模式差异。微剪切粘接强度结果用均数±标准差表示，Kolmogorov-Smirnov检验证实数据符合正态分布，Levene检验证实数据方差齐。采用双因素方差分析比较各组间微剪切粘接强度的差异，对冷热循环前后微剪切粘接强度使用配对*t*检验进行组内两两比较。检验水准为双侧$\alpha = 0.05$。

2 结 果

2.1 Er: YAG激光拆除氧化锆后牙本质表面EDX分析

Er: YAG激光拆除氧化锆后牙本质表面EDX分析见图1，牙本质表面主要元素分别为C元素（52.02 wt%）、O元素（38.35 wt%）及Si元素（5.02 wt%）。



The contents of main elements on dentin surface were C (52.02 wt%), O (38.35 wt%), and Si (5.02 wt%). EDX: energy dispersive X-ray spectroscopy

Figure 1 EDX of the dentin surface after zirconia debonding by Er: YAG laser

图1 Er: YAG激光拆除氧化锆后牙本质表面EDX分析

2.2 不同表面处理方式牙本质表面形貌观察

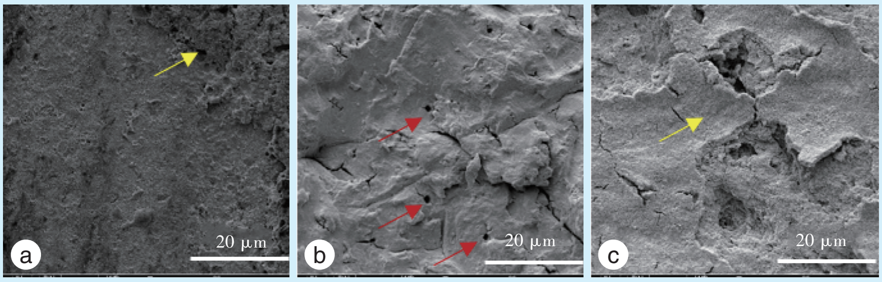
各组树脂残留指数见表1。各组表面处理后牙本质表面形貌SEM观察见图2。喷砂组、激光照

表1 不同表面处理方式牙本质表面树脂残留指数

Table 1 The adhesive remnant index of dentin surfaces with different surface treatments $n = 30$

Groups	ARI=0	ARI=1	ARI=2	ARI=3	Total	*
Control	0	0	25	5	30	a
Sandblasting	6	24	0	0	30	b
Laser irradiation	0	30	0	0	30	b
P	< 0.001					
χ^2	78.893					

Kruskal-Wallis and Mann-Whitney *U* tests; *: identical letters indicate no statistically significant differences among surface treatments ($P > 0.05$), different letters denote statistically significantly differences ($P < 0.05$). Control group: no treatment was performed; sandblasting group: 50 μm Al_2O_3 sandblasting; laser irradiation group: Er: YAG laser irradiation, parameters were set to 10 Hz, 60 mJ, 0.6 W. ARI: adhesive remnant index. ARI=0: no adhesive; ARI=1: less than 50% of adhesive remaining; ARI=2: more than 50% of adhesive remaining; ARI=3: 100% of adhesive remaining



Yellow arrow: the adhesive remnant; red arrow: dentin tubule. a: a large amount of residual resin was found on the dentin surface of control group. b: the residual resin was almost removed, the dentin surface of sandblasting group was rough, and dentin tubules were visible. c: massive residual resin was found on the dentin surface of the laser irradiation group. SEM: scanning electron microscopy. Control group: no treatment was performed; sandblasting group: 50 μm Al_2O_3 sandblasting; laser irradiation group: Er: YAG laser irradiation, parameters were set to 10 Hz, 60 mJ, 0.6 W

Figure 2　SEM observations of the dentin surface with different surface treatments

图 2　不同表面处理方式牙本质表面形貌扫描电镜观察

射组分别与对照组树脂残留指数差异有统计学意义（$P < 0.05$），而喷砂组与激光照射组间树脂残留指数无统计学差异（$P > 0.05$）。其中对照组牙本质表面可见牙本质表面残留大量树脂；喷砂组残留树脂较少，牙本质表面粗糙，可见牙本质小管；激光照射组牙本质表面可见块状残留树脂。

2.3　不同表面处理方式再粘接试件微剪切粘接强度的比较

各组粘接试件微剪切强度比较结果见表 2。不同表面处理方式微剪切强度存在差异，差异有统计学意义（$P < 0.05$）；相同表面处理方式冷热循环前后差异无统计学意义（$P > 0.05$）；表面处理方式与冷热循环对试件微剪切强度影响无交互作用（F=0.056，$P > 0.05$）。

2.4　不同表面处理方式再粘接试件断裂模式分析

各组断裂模式分析见表 3。各组均未出现内聚断裂，断裂模式主要为粘接断裂。喷砂组断裂模式与其他两组之间存在统计学差异：无论是否冷热循环，喷砂组混合断裂频率均较其他组较高（$P < 0.05$）。

表 2　不同表面处理方式再粘接试件微剪切粘接强度比较

Table 2　Comparison of microshear bonding strength of rebonding specimens with different surface treatments

$\bar{x} \pm s$, MPa, n = 15

Groups	Aging time*		F	P
	24 h	24 h+5 000 TC		
Control	6.13 ± 2.40^{Aa}	5.39 ± 0.83^{Aa}	9.846	0.268
Sandblasting	9.39 ± 2.00^{Ba}	8.45 ± 1.20^{Ba}	4.003	0.130
Laser irradiation	5.85 ± 1.44^{Aa}	4.84 ± 1.43^{Aa}	0.300	0.064
F	42.992		–	–
P	< 0.05		–	–

*: identical uppercase superscript letters within the same column indicate no statistically significant differences among surface treatments ($P > 0.05$), different uppercase superscript letters within the same column indicate statistically significantly differences ($P < 0.05$); identical lowercase superscript letters within the same row indicate no statistically significant differences among aging treatments ($P > 0.05$), different lowercase superscript letters within the same row indicate statistically significantly differences ($P < 0.05$); there was no interaction between surface treatment and thermal cycling on microshear bonding strength (F= 0.056, $P > 0.05$); 24 h: 24 hours of storage in water at 37 ℃; TC: thermal cycling, the specimens were thermocycled in 5 ℃ - 55 ℃ water baths with a holding time of 30 s. Control group: no treatment was performed; sandblasting group: 50 μm Al_2O_3 sandblasting; laser irradiation group: Er: YAG laser irradiation, parameters were set to 10 Hz, 60 mJ, 0.6 W

表 3　不同表面处理方式再粘接试件的断裂模式

Table 3　Failure modes of rebonding specimens with different surface treatments　n = 15

Groups	Adhesive failure		Cohesive failure		Mixed failure		*	
	24 h	24 h+5 000 TC	24 h	24 h+5 000 TC	24 h	24 h+5 000 TC	24 h	24 h+5 000 TC
Control	13	12	0	0	2	3	a	a
Sandblasting	8	9	0	0	7	6	b	b
Laser irradiation	14	15	0	0	1	0	a	a
P			–				0.020	0.026
χ^2			–				7.794	7.333

24 h: 24 hours of storage in water at 37 ℃; TC: thermal cycling, the specimens were thermocycled in 5 ℃ - 55 ℃ water baths with a holding time of 30 s. *: identical letters show no statistically significant differences among treatments ($P > 0.05$); different letters show statistically significantly differences ($P < 0.05$). Control group: no treatment was performed; sandblasting group: 50 μm Al_2O_3 sandblasting; laser irradiation group: Er: YAG laser irradiation, parameters were set to 10 Hz, 60 mJ, 0.6 W

3 讨　论

Er: YAG激光以其独特的拆除能力，在氧化锆修复体的移除中展现出显著优势。其工作原理在于，激光能够穿透氧化锆材料，精准作用于粘接剂层，通过引发微爆破效应，有效破坏粘接界面，实现修复体的脱粘接。这一过程与传统破坏性拆除方法，如使用车针、取冠器等物理手段，形成了鲜明对比。在激光作用下，这些残留树脂经历热消融与光消融[7]，呈现发白甚至碳化现象[21]，可能构成一道屏障，阻碍粘接剂的有效渗入与树脂的完全聚合，进而影响再粘接效果。以往的研究多集中于牙本质表面处理方式对其粘接强度的影响，而本项研究聚焦于Er: YAG激光拆除后牙本质再粘接问题，从多个维度深入探讨了不同表面处理方式及冷热循环对粘接效果的影响。据文献报道，牙本质表面主要化学成分包括C、Ca、P和O元素[22]。本项研究结果显示，激光拆除后牙本质表面C元素及Si元素显著增加，这一变化可归因于激光拆除后残留树脂水门汀（主要成分为C元素及Si元素）的影响，这也证明激光拆除发生于树脂水门汀与修复体之间的界面，导致牙本质表面残留大量树脂水门汀[21]。在粘接实验中，本研究选择微剪切粘接实验方法，以最大限度避免因粘接物质内聚破坏而导致的实验结果偏差[12]。同时，参考前人研究，本项研究选择50 μm Al_2O_3，3 bar压力下距离牙面2 mm喷砂处理牙本质表面。有研究表明，5 000次冷热循环大致相当于体内6个月的使用时间[23]。同时，Comino-Garayoa等[24]的研究指出，5 000次以上冷热循环对修复体粘接强度的影响与5 000次冷热循环相比，无显著性差异。因此，本研究选择5 000次作为冷热循环测试的次数，以模拟临床中修复体在口腔温度变化下的使用情况。

实验结果显示，在冷热循环前后，喷砂组相较于其他组均展现出更为优异的粘接效果。通过SEM观察，喷砂处理后，牙本质表面残余树脂能够被有效清除，表面呈粗糙状，且牙本质小管清晰可见并处于开放状态。牙本质经喷砂处理后，断裂模式中混合断裂频率增加，这与Falcon等[25]的研究结果相近。de Oliveira等[26]比较27 μm Al_2O_3在3.45 bar距离牙面2 mm喷砂及Er: YAG（4 Hz，200 mJ，0.8 W）激光对不同粘接系统条件下牙本质粘接性能的影响，结果表明喷砂处理牙本质获得粘接强度是Er: YAG激光处理组的1.5倍以上。以往的研究指出粘接断裂模式多发生于物质间粘接强度较低时，而混合断裂模式多发生于物质间粘接强度较强时[27]。本项研究结果喷砂组较对照组、激光照射组获得更佳粘接效果，这可能与喷砂处理不仅能够有效清除牙本质表面树脂，而且产生粗糙、不规则形貌的牙本质表面，甚至使牙本质小管重新开放，增大树脂突与牙本质的接触面积有关[28]。因此，本研究认为对激光拆除后的牙本质表面进行喷砂处理是有效提高牙本质再粘接强度的一种方法。

鉴于树脂对激光展现出的高度吸收特性，激光技术成为了一种潜在的手段，用于清除牙体表面的树脂残留[29]。与喷砂处理方式不同，激光照射具有热效应，通过消融作用去除牙本质表面玷污层，使牙本质小管开放、形成不规则表面[30]，可能有利于牙本质再粘接。有学者提出，Er: YAG激光照射去除牙体表面树脂的效果优于常规技术[29]，但激光照射去除牙体表面树脂的效果可能与激光参数设置有关[31]。前期预实验中，相同频率（10 Hz）不同能量条件下（60、90、120 mJ）Er: YAG激光去除牙本质表面树脂，结果表明3组间牙本质再粘接强度差异无统计学意义。Nahas等[16]比较相同频率（10 Hz）不同能量条件下（40、60、80、100、120 mJ）Er: YAG激光对牙本质层的热影响，发现60 mJ条件下对牙本质有机基质的热消融最小。因此，本项研究最终选择低能量（10 Hz，60 mJ，0.6 W）的Er: YAG激光参数进行实验。然而，SEM结果显示，在Er: YAG激光照射拆除后的牙本质表面仍有树脂残留，并未出现Er: YAG激光能有效去除牙本质残留树脂的现象，这可能由于Er: YAG激光照射过程中人工控制其移动，导致Er: YAG激光未能全方位照射再粘接区域。此外，本研究微剪切强度测试结果显示，Er: YAG激光照射未能改善牙本质再粘接性能，这与Zortuk等[11]的实验结果相似。

研究结果显示，冷热循环前后各组试件的再粘接强度无统计学差异，这与Madrigal等[32]的研究结果相似。此外，牙本质的再粘接强度还可能受到其他多种生物学和临床因素的共同影响，例如细菌的污染等[33]。同时，粘接剂、水门汀类型[34]也可能对研究结果产生显著影响。边缘封闭性也是影响牙本质再粘接强度的重要因素[35]。本课题组计划在后续研究中进行深入探讨和验证。

综上所述，本研究结果提示，激光非破坏性拆

除修复体虽未造成牙本质损伤，但牙本质表面残留大量树脂。50 μm Al_2O_3喷砂能够改善激光拆除修复体后牙本质再粘接效果。

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