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· 基础研究 ·

桩道预备时机对纤维桩粘接强度的影响

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【摘要】 **目的**　比较即刻桩道预备与延迟桩道预备对iRoot SP单尖法根管充填后纤维桩粘接强度和牙根抗折强度的影响，为临床桩道预备时机的选择提供实验依据。**方法**　获得单位医学伦理委员会审批及研究参与者书面知情同意。将72颗离体成人单根管前磨牙随机分为两组(每组36颗)：即刻桩道预备组(根管充填后立即进行桩道预备)和延迟桩道预备组(根管充填1周后进行桩道预备)。使用牙科显微镜观察两组桩道预备后桩道内壁清洁程度；扫描电子显微镜观察桩道预备后牙本质表面的超微结构特征；采用牙根抗折强度实验检测两组牙根抗折强度；采用薄片推出试验检测纤维桩的粘接强度，并在体视显微镜下观察分析粘接断裂模式。**结果**　牙科显微镜下，即刻桩道预备组牙本质表面较延迟桩道预备组更清洁。扫描电子显微镜下，即刻桩道预备组大部分牙本质小管开放，而延迟桩道预备组牙本质小管开放不全。即刻桩道预备组抗折强度为(2 872 ± 241.5)N，延迟桩道预备组为(2 934 ± 353.1)N，差异无统计学意义(t = −0.328，P = 0.751)。薄片推出试验显示，即刻桩道预备组的推出粘接强度(10.310 ± 2.907)MPa显著高于延迟桩道预备组(7.917 ± 2.429)MPa，差异具有统计学意义(t = 4.457，P < 0.001)。断裂模式分析显示，两组均主要表现为粘接剂-牙界面破坏。**结论**　使用iRoot SP单尖充填后，即刻桩道预备可获得优于延迟桩道预备的纤维桩粘接强度，且不影响牙根抗折强度。

【关键词】 iRoot SP；　单尖根管充填；　即刻桩道预备；　延迟桩道预备；　牙本质；　纤维桩；　粘接强度；　牙根抗折强度；　粘接剂-牙界面破坏

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Effect of post-space preparation timing on the bond strength of fiber posts　LAN Yuming, CHANG Zhen, FU Rui, HUANG Jiacheng.　Department of Oral Emergency, Hospital of Stomatology, Zhongshan City, Zhongshan 528400, China
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【Abstract】 **Objective**　To compare the effects of immediate versus delayed post-space preparation on the bond strength of fiber posts and the fracture resistance of roots after root canal obturation using iRoot SP and the single-cone technique, and to provide an experimental basis for the selection of the timing of clinical post-space preparation. **Methods**　This study was approved by the Medical Ethics Committee of the institution, and written informed consent was obtained from all participants. Seventy-two extracted human single-rooted premolars were randomly divided into two groups (n = 36 each): the immediate post-space preparation group (post-space preparation performed immediately after root canal obturation) and the delayed post-space preparation group (post-space preparation performed 1 week after root canal obturation). Cleanliness of the root canal walls was assessed with a dental microscope after preparation in both groups; the ultrastructural characteristics of the dentinal surface were examined via scanning electron microscopy; the fracture resistance of roots was measured with root fracture resistance tests; the bond strength of the fiber posts was measured with the thin-slice push-out test; and the bond failure modes were observed and analyzed under a stereomicroscope. **Results**　Under dental microscopy, the dentin surface of the immediate post-space preparation group appeared

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cleaner than that of the delayed post-space preparation group. Scanning electron microscopy revealed that most dentinal tubules remained open in the immediate post-space preparation group, while the tubules in the delayed post-space preparation group showed incomplete patency. The fracture resistance of the immediate post-space preparation group was (2 872 ± 241.5) N and that of the delayed post-space preparation group was (2 934 ± 353.1) N, with no statistically significant difference (t = −0.328, P = 0.751). The push-out bond strength of the immediate post-space preparation group (10.310 ± 2.907) MPa was significantly higher than that of the delayed post-space preparation group (7.917 ± 2.429) MPa, with a statistically significant difference (t = 4.457, P < 0.001). Analysis of failure modes showed that adhesive-to-dental interface failure was the predominant mode in both groups. **Conclusion** Following root canal obturation with iRoot SP using the single-cone technique, immediate post-space preparation yields superior fiber post bond strength compared to delayed post-space preparation, without compromising root fracture resistance.

【**Key words**】 iRoot SP; single-cone root canal obturation; immediate post-space preparation; delayed post-space preparation; dentin; fiber post; bond strength; root fracture resistance; adhesive-to-dental interface failure

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完善根管治疗后，对于因大面积缺损需行纤维桩修复的患牙，桩道预备最佳时机的选择是临床上常面临的一个关键问题。桩道预备必然会对已封闭的根管系统造成干扰，并在根管内壁形成玷污层，从而影响后续纤维桩的粘接效果[1]。桩道预备分为即刻桩道预备和延迟桩道预备，目前临床上虽多采用根管充填后1~2周的延迟预备，但也有研究指出，即刻预备能利用充填材料尚未完全凝固的条件，降低对根管形态的意外损伤[2]，且延迟桩道预备与即刻桩道预备所造成的根尖微渗漏无显著差异[3]，表明即刻桩道预备具有一定临床应用潜力。近年来，以iRoot SP为代表的生物陶瓷基封闭剂因其优异的生物相容性、低微渗漏和良好的生物活性，在单尖法根管充填中的应用日益广泛[4-5]。然而，在iRoot SP这一新型生物陶瓷材料逐渐普及的背景下，关于不同桩道预备时机对其所封闭根管中纤维桩粘接强度的影响，尚缺乏系统研究。为此，本研究旨在评估iRoot SP单尖法根管充填后，即刻桩道预备与延迟桩道预备对纤维桩粘接强度及牙根抗折强度的影响。通过牙科显微镜观察桩道内壁清洁程度、扫描电子显微镜分析牙本质表面超微结构，并结合牙根抗折强度实验及薄片推出试验检测力学性能，综合评价不同预备时机的临床效果。研究结果将为临床桩道预备时机的选择提供实验依据，对提高纤维桩修复的长期成功率具有重要价值。

1 资料与方法

1.1 主要仪器与试剂

Hanks溶液（H1020，索莱宝，中国）；ENDO MATE DT机用马达（Y141121，NSK，日本）；机用根管锉（Plex系列，欧罗德卡，中国）；iRoot SP根管封闭剂（24003Sp，IBC，加拿大）；35#/04锥度牙胶尖（Dentsply，美国）；玻璃离子水门汀（0530014002，常熟尚齿科材料有限公司，中国）；1%次氯酸钠溶液（朗力，中国）；P5超声治疗仪（JM1958-012166，Satelec，法国）；恒湿水浴箱（HH-W420，常州市亿能实验仪器厂，中国）；纤维桩及配套成型钻（DMG，德国）；Parabond自酸蚀粘接剂（7486，康特，瑞士）；双固化树脂水门汀LuxaCore Z Dual（213339，DMG，德国）；扫描电子显微镜（scanning electron microscope，SEM）（SU5000，日立，日本）；牙科显微镜（OMS2300，Zumax，德国）；体视显微镜（1213801S，三目，中国）；硬组织切片机（EXAKT300CP/400CS/AW，EXAKT公司，德国）；万能试验机（CMT5105，三思泰捷，中国）。

1.2 样本的准备

本研究遵循《赫尔辛基宣言》的原则，通过中山市口腔医院医学伦理委员会批准（批准号：2023年第21号）。本研究离体牙的收集获得患者的书面知情同意。选择2024年7月至2025年11月期间在中山市口腔医院就诊的成年患者，收集36例成年患者因正畸原因拔除的单根管前磨牙72颗。牙齿入组标准：新鲜、无龋、根部发育完全、根尖孔闭合、单根。样本离体后立即使用刮治器刮除牙齿表面牙周膜、牙结石和污物，浸泡于Hanks溶液中，4 ℃冷藏保存备用。

1.3 根管预备和根管充填

在流水冷却下，使用金刚砂车针于釉牙骨质界冠方2 mm处垂直牙体长轴截冠。常规拔髓后，以10号K锉疏通根管，以15号K锉插入根管，取尖

端到达解剖性根尖孔后回退1 mm的长度作为工作长度，并统一修整颈部断面，使所有样本工作长度标准化为16 mm。

根管预备采用ENDO MATE DT马达配合欧罗德卡机用镍钛器械系统，按标准程序预备至35#/04锥度，器械更换时以1%次氯酸钠溶液冲洗。预备完成后以灭菌蒸馏水超声荡洗。

干燥根管后，注入iRoot SP封闭剂，置入适配的35#/04牙胶尖，于根管口下2 mm处携热截断主尖并压实，以玻璃离子充填开髓孔。所有牙齿均拍摄X线片以确保充填质量良好。

1.4　实验分组

将72颗牙齿按随机数表分为2组，每组36颗。即刻桩道预备组：根管充填后立即进行桩道预备。延迟桩道预备组：根管充填后，将牙齿置于37 ℃、100%相对湿度的恒湿水浴箱储存1周[6]，随后再行桩道预备。

1.5　桩道预备及粘接纤维桩

使用低速手机及P钻进行桩道预备，深度至根尖保留5 mm根充材料，使用DMG纤维桩配套钻进行桩道成形，预备至绿色成型钻。在预备过程中，持续使用蒸馏水进行冲洗，以冷却桩道内壁。桩道预备后，使用灭菌水超声荡洗桩道，吸潮纸尖干燥，等待粘接备用。

纤维桩经75%乙醇浸泡2 min消毒，吹干备用。桩道内涂布Parabond自酸蚀粘接剂后，以双固化树脂水门汀LuxaCore Z Dual进行粘接。将纤维桩缓慢旋转就位于桩道内，确保树脂水门汀均匀分布，随后仔细清除从桩道冠方溢出的多余粘接剂。使用光固化灯从不同角度照射桩核冠部，光聚合40 s。

1.6　牙科显微镜观察桩道表面清洁度

每组随机取1个仅进行桩道预备、未粘接纤维桩的牙根样本进行牙科显微镜观察，流水冷却条件下，使用金刚砂车针沿牙体长轴截开，牙科显微镜下检查根管壁内剩余封闭剂情况。

1.7　扫描电子显微镜观察牙本质表面形态

每组随机取5个仅进行桩道预备、未粘接纤维桩的牙根样本进行SEM观察，在牙根的颊舌侧中线沿牙体长轴分别预备1条深达牙本质深层但未及髓腔的导向沟，用平口凿沿着导向钩将样本劈成两半，以暴露桩道内壁的牙本质。随后，选择较完整的一半样本进行干燥和喷金，然后在每个样本的桩道内壁牙本质表面随机选取3个点进行SEM观察，以评估两种桩道预备后桩道内壁牙本质的形态学变化。

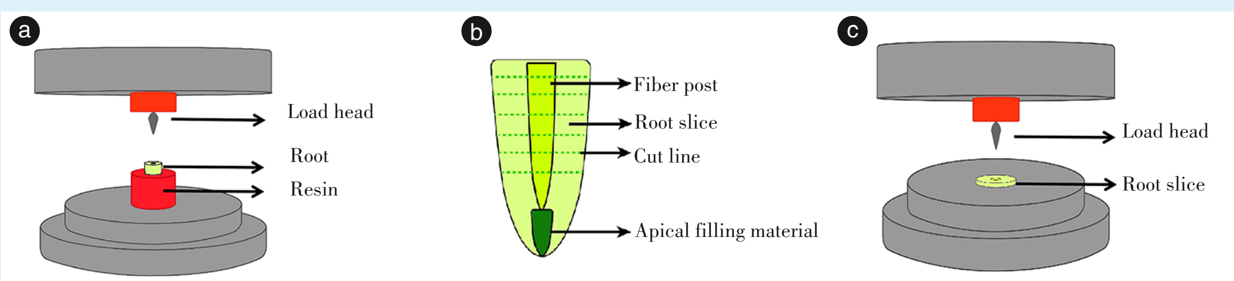
1.8　牙根抗折强度实验检测牙根抗折强度

取5 mL注射器套管，制备成长度为2 cm的圆柱形模具，内壁涂布分离剂，干燥后注入自凝树脂。从即刻预备组与延迟预备组各随机抽取5个完成纤维桩粘接的牙体样本，将根尖朝下垂直插入树脂，使牙根长度约1/3暴露于树脂外。模具竖直固定于万能试验机下，加载头垂直对准牙长轴，以2 mm/min的速度加压至牙根折裂，记录最大载荷(N)(图1a)。

1.9　薄片推出试验检测粘接强度

为评估纤维桩的粘接强度，取每组中剩余的25个已完成纤维桩粘接的样本用于推出实验。样本包埋固定后，使用硬组织切片机在距根尖5 mm处向冠方以垂直于桩道方向切割厚度1 mm的薄片，每样本制得6个试件，各组分别150个试件(图1b)。

将薄片水平置于万能试验机上，冠面向下，根面接触加载头。加载头尺寸匹配不同根段桩径，确保载荷仅作用于纤维桩且接触面积最大。以0.5 mm/min恒速加载至纤维桩脱出(图1c)，记录失效时最大载荷(N)。



a: schematic diagram of the root fracture strength test; b: schematic diagram of sample cutting; c: schematic diagram of the thin-slice push-out test. The figures were edited using Adobe Illustrator CC 2019. (Adobe Inc., San Jose, CA, USA)

Figure 1　Schematic diagrams of the root fracture resistance test and the thin-slice push-out test

图1　牙根抗折强度实验和薄片推出实验示意图

使用游标卡尺测量各薄片厚度(h)及桩冠、根端截面半径(R,r)。根据以下公式计算纤维桩与根管牙本质的粘接面积(S,单位mm^2):$S=\pi(R+r)\sqrt{(R-r)^2+h^2}$。推出强度(P,单位MPa)由以下公式求得:P= N/S。

1.10　体视显微镜下观察分析断裂模式

在体视显微镜下观察薄片推出实验中试件的粘接破坏模式,并对其进行归类分析。

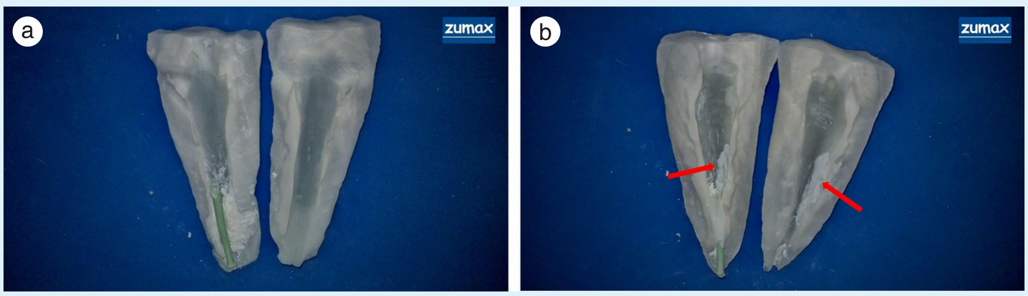
1.11　统计学方法

采用SPSS 27.0软件进行统计学分析。符合正态分布的计量资料用均数±标准差($\bar{x}\pm s$)表示,组间比较采用了独立样本t检验。正态性检验采用采用Shapiro-Wilk检验和Kolmogorov-Smirnov检验,方差齐性检验采用Levene检验。$P<0.05$为差异具有统计学意义。

2　结　果

2.1　不同桩道预备时机桩道内壁清洁程度分析

iRoot SP单尖法根管充填后,在不同时机行桩道预备。即刻桩道预备组桩道内壁清洁程度高,几乎无封闭剂残留(图2a);延迟桩道预备组桩道内壁可见部分残留封闭剂(图2b)。表明在本实验条件下,即刻桩道预备能获得更清洁的桩道内壁。



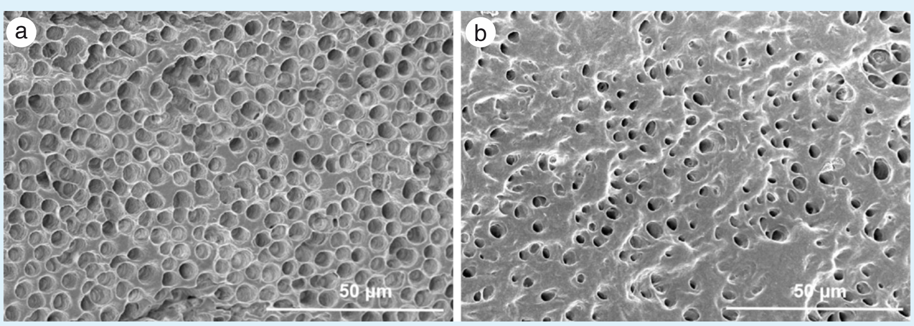
a: the immediate post-space preparation group, showing a clean post-space wall (×12.5); b: the delayed post-space preparation group; arrows indicate residual sealer on the post-space wall (×12.5), demonstrating lower cleanliness compared to the immediate post-space preparation group

Figure 2　Observation results of post-space walls under a dental microscope at different post-space preparation timings

图2　不同桩道预备时机桩道内壁的牙科显微镜观察结果

2.2　不同桩道预备时机牙本质表面形态分析

在使用iRoot SP单尖法根管充填后,对在不同时机(即刻与延迟)进行桩道预备的桩道内壁牙本质超微结构进行观察。SEM下可见,即刻桩道预备组的牙本质小管结构清晰,呈开放状态(图3a)。延迟桩道预备组的桩道内壁牙本质小管密度降低,且部分小管呈封闭或未开放形态(图3b)。表明在本实验条件下,即刻进行桩道预备更有利于维持牙本质小管的开放结构。



a: in the immediate post-space preparation group, dentinal tubules are almost entirely patent; b: in the delayed post-space preparation group, the post-space wall shows numerous dentinal tubule openings that appear constricted or partially occluded. SEM: scanning electron microscopy

Figure 3　Observation results of dentin surface morphology under SEM at different post-space preparation timings

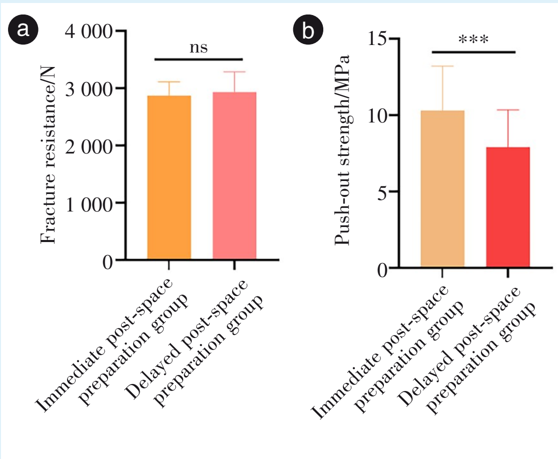
图3　不同桩道预备时机牙本质表面形貌的扫描电镜观察结果

2.3　不同桩道预备时机牙根抗折强度比较

即刻桩道预备组抗折强度为(2 872 ± 241.5)N,延迟桩道预备组抗折强度为(2 934 ± 353.1)N,差异无统计学意义(t=−0.328,P=0.751,图4a)。

2.4　不同桩道预备时机推出粘接强度比较

即刻预备组的推出粘接强度为(10.310±2.907)MPa，延迟预备组的推出粘接强度为(7.917±2.429)MPa，差异具有统计学意义(t=4.457，P<0.001)，即刻桩道预备组的粘接强度高于延迟桩道预备组(图4b)。



a: experimental results on the fracture resistance of tooth roots. Comparison of fracture resistance between the immediate and the delayed post-space preparation groups. No statistically significant difference in root fracture resistance was observed between the immediate and delayed post-space preparation groups. (ns: not significant, P > 0.05). b: the experimental results on bonding strength. Comparison of bonding strength between the immediate post-space preparation group and the delayed post-space preparation group shows that the immediate post-space preparation group exhibits significantly higher bonding strength than the delayed post-space preparation group, ***P < 0.001

Figure 4　Results of the root fracture resistance and push-out bond strength tests

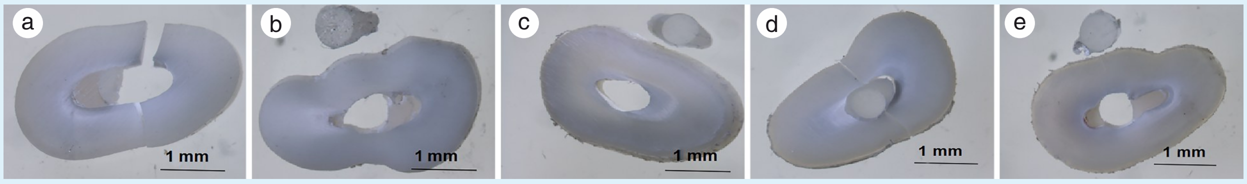
图4　牙根抗折强度实验和推出粘接强度的实验结果

2.5　体视显微镜下观察分析断裂模式

体视显微镜下观察各组试件的粘接破坏模式如图5所示，主要包括5种断裂模式：混合破坏(粘接破坏和任何类型的内聚破坏共同存在于同一样本中)、粘接剂内聚破坏、粘接剂-牙界面破坏、牙本质内聚破坏及纤维桩-粘接剂界面破坏。不同桩道预备时机的断裂模式分布如下：即刻桩道预备组(150个试件)中，混合破坏24例(16%)、粘接剂内聚破坏6例(4%)、粘结剂-牙界面破坏96例(64%)、牙本质内聚破坏6例(4%)，纤维桩-粘接剂面破坏18例(12%)；延迟桩道预备组(150个试件)中，混合破坏47例(31%)、粘接剂内聚破坏13例(9%)、粘接剂-牙界面破坏80例(53%)、牙本质内聚破坏3例(2%)，纤维桩-粘接剂界面破坏7例(5%)。结果表明，无论桩道预备时机如何，粘接剂-牙界面破坏均为两组中最主要的断裂模式。

3　讨　论

根管治疗通过预备、消毒及严密充填实现根管系统三维封闭，以控制感染与炎症[7-8]。其成功关键在于根管系统的封闭效果[9]，牙胶尖可充填根管主体[10]，但封闭剂在填补微隙、渗透侧副根管方面发挥着不可替代的作用[11-12]。近年来，以iRoot SP为代表的生物陶瓷类根管封闭剂在临床应用中备受青睐[13]，其具备优良的生物相容性[5, 14]、抑菌[15]、促成骨[16-17]和抗牙根折断性[18]，且固化后可生成羟基磷灰石与牙本质形成良好化学结合，达到较好的根管封闭效果[19-20]。故本研究选用其配合操作便捷的单尖法充填技术，以实现与根管解剖形态的紧密契合[21]。纤维桩因与牙本质相近的弹性模量及优异的抗疲劳性，已成为大面积缺损患牙修复的首选方案[22-24]。然而，纤维桩修复失败的主要原因是粘接失败[25-26]，且多发生于牙本质-粘接剂界面这一薄弱环节[27]，牙本质的清洁程度可直接影响纤维桩的粘接效果。桩道预备是纤维桩粘接前的关键步骤，而关于其预备时机(即刻或延迟)的临床选择仍存在争议。临床上大多数选择延迟桩道预备。即刻桩道预备仍存在部分争



a: mixed failur; b: adhesive cohesive failure; c: adhesive-to-dental interface failure; d: dentin cohesive failure; e: fiber post-to-adhesive interface failure

Figure 5　Representative images of the bond failure modes under a stereomicroscope

图5　体视显微镜下粘接断裂模式的代表图

议，虽有观点认为即刻桩道预备因慢机振动可能增加术后疼痛风险[28]，但亦有证据表明其虽可能伴发疼痛，却能显著减少根尖微渗漏及根管内残留物[29]，这表明即刻桩道预备具有一定临床应用潜力。

本研究旨在探讨 iRoot SP 单尖法充填后，不同桩道预备时机对牙根抗折及纤维桩粘接强度的影响。牙科显微镜凭借其放大系统，可清晰观察牙本质表面形态。扫描电子显微镜是评估牙本质清洁程度与牙本质小管开放状态的主要方法，能够直观反映不同处理方式对牙本质表面结构的影响[30]。鉴于牙本质表面清洁度是影响粘接效果的关键因素，本研究联合应用上述两种方法，系统评估了不同桩道预备时机对桩道清洁效果及牙本质表面形态的影响。牙科显微镜观察结果显示，即刻桩道预备组桩道壁内残留的封闭剂显著少于延迟桩道预备组，清洁程度更高。研究表明，近髓端牙本质小管直径约为 2.5 μm，而 iRoot SP 的颗粒直径约为 2 μm，但完全固化后具有轻微膨胀性[31]，Wang 等[18]使用 iRoot SP 充填根管 1 d 后，观察到 iRoot SP 在根管壁表面粘附良好，并进入小管内聚集、凝聚，形成复杂结构，几乎覆盖全部牙本质小管开口。

目前大多数关于纤维桩粘接的研究均采用自酸蚀粘接系统[6, 32]，因此本研究的样本进行桩道预备后使用自酸蚀粘接系统粘接纤维桩，随后进行后续的牙根抗折强度实验及薄片推出实验。牙根抗折强度实验分析表明，即刻桩道预备组与延迟桩道预备组的牙根抗折强度并无统计学差异，说明即刻桩道预备不会导致牙根抗折强度降低。薄片推出实验是检测纤维桩粘接强度的常用方法，其可靠性被广泛应用[33-34]。薄片推出实验结果表明，进行 iRoot SP 单尖法充填后，即刻桩道预备组相较于延迟桩道预备组展现出更强的纤维桩粘接效果。这一结果与 Machado 等[35]和 Vano 等[36-37]的基于环氧树脂类（AH Plus）或氧化锌丁香油酚类封闭剂的研究结论相反。上述研究支持延迟桩道预备可获得更高粘接强度，理由是即刻桩道预备会残留未凝固的封闭剂，从而污染进行纤维桩粘接的纸尖和毛刷，影响树脂粘接剂与牙本质面的的聚合。然而本研究结果表明，对于生物陶瓷类封闭剂 iRoot SP 而言，其理化特性与传统封闭剂截然不同，纤维桩的粘接实质上形成“桩—粘接剂—牙本质”复合体的过程[38]。该复合体的成功建立关键在于实现有效的机械固位与化学粘接，然而在临床中，对于某些如根管狭窄、存在峡部或有明显凹陷特殊形态的根管[39-40]，往往难以实现这种复合结构。iRoot SP 在未固化前呈现半流动性状态，在生理环境下 3 h 完成固化，并发生 0.2% 的膨胀，从而渗入牙本质形成严密充填[21, 31]，与牙本质间形成一定的粘接强度[41]。即刻桩道预备能在材料未完全固化前有效清洁桩道，有利于粘接剂与牙本质直接结合，而延迟桩道预备无法完全清理桩壁已固化的封闭剂，从而造成封闭剂的残留，导致粘接界面变成“桩-粘接剂-封闭剂”结构。本研究与 Nesello 等[42]研究结果一致，生物陶瓷封闭剂的残留影响树脂粘接剂与纤维桩间的粘接强度，这表明牙本质界面的清洁程度是决定纤维桩与牙本质间树脂粘接耐久性的关键因素，其对临床修复的长期成功率具有重要影响。在断裂模式分析中，无论桩道预备时机如何，两组试件均以粘接剂-牙本质界面破坏为主要破坏形式，表明纤维桩修复的失败仍主要归因于粘接界面的缺陷。因此，未来在致力于提高纤维桩粘接强度的同时，需进一步研究如何优化树脂粘接剂与牙本质之间的界面兼容性，或探索新型的界面处理技术（如激光、超声活化等），以实现树脂粘接剂与牙本质的直接、持久结合。

综上所述，对于需要采用桩（核）冠修复的牙髓病患牙，采用即刻桩道预备可能有助于提高纤维桩的粘接强度，从而提升修复长期成功率。但本研究存在一定局限性，如使用离体牙无法完全模拟口腔内复杂环境，观察时间较短，未能评估长期粘接稳定性。今后将扩大样本量，并结合临床随访进行深入验证。

【Author contributions】 Lan YM performed experiments, analyzed the data and drafted the manuscript. Chang Z, Fu R performed the experiments and revised the article. Huang JC designed the study and revised the article. All authors read and approved the final manuscript as submitted.

【Ethics Statement】 This study followed the principles of the Declaration of Helsinki and received approval from the Medical Ethics Committee of Zhongshan Stomatological Hospital (Approval No. 2023-021). This study was based on ex vivo dental samples from patients, all of whom provided written informed consent.

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