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修复材料与牙体组织力学适配性的研究进展

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【摘要】 牙齿作为发挥咀嚼功能的主要器官，可承受无数次功能性接触，这与它的力学性能和组织结构密切相关。牙釉质和牙本质的硬度较高，并且它们具有梯度化的结构，这使得牙齿既能承受咬合力，又不致轻易折裂。当牙体组织缺损时，往往需要全冠修复体来恢复牙齿正常的形态与功能。常用的全冠修复材料有金属材料、陶瓷材料以及最近兴起的聚醚醚酮材料。金属材料在美学方面存在一定劣势，目前在临床上应用相对较少。不同组成成分的陶瓷材料在性能及美学上的表现有所差异，但弹性模量与硬度过高，在力学性能方面都超过了牙体组织，与牙体组织学力学性能不匹配。与此不同，聚醚醚酮材料的弹性模量低于牙体组织，与骨组织相似，但通过纤维增强等方式能够提高它的性能。当修复材料与牙体组织的力学性能并不完全适配时，两者之间的界面往往形成潜在的薄弱环节，最终影响修复的稳定性和长期效果。本文介绍了牙釉质和牙本质的力学性能以及相对应的结构特点，并在此基础上，分析现有修复材料的优势与局限性，进一步探究口腔全冠仿生设计的可能性。

【关键词】 牙釉质； 牙本质； 力学性能； 弹性模量； 断裂韧性； 冠修复； 聚醚醚酮； 碳纤维； 玻璃纤维； 羟基磷灰石

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Research progress on the mechanical compatibility of restorative materials with dental tissue

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【Abstract】 As the main means of mastication, teeth can withstand countless functional contacts. The mechanical properties of teeth are closely related to their tissue structure. Enamel and dentin have a high hardness and modulus of elasticity, and their graded structure allows them to withstand bite forces without being susceptible to fracture. When tooth tissue is defective, full crown restoration is often needed to restore the normal shape and function of the tooth. Metal materials, ceramic materials, and polyetheretherketone (PEEK) materials are commonly used for crown restoration. Metal materials have certain disadvantages in terms of aesthetics and are relatively rarely used in clinical practice. Ceramic materials with different compositions exhibit differences in performance and aesthetics, but their elastic modulus and hardness are much higher than those of dental tissue, resulting in mismatching mechanical properties. In contrast, the elastic modulus of PEEK is lower than that of tooth tissue and similar to that of bone tissue, but its properties can be improved by fiber reinforcement. Notably, when the mechanical properties of a restoration material and tooth tissue are not fully matched, the interface between them often forms a potential weak link, which ultimately affects the stability and long-term effect of the restoration. This article introduces the mechanical properties and corresponding structural characteristics of enamel and dentin. On this basis, the advantages and limitations of existing restoration mate-

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rials are analyzed, and the possibility of biomimetic design of full crowns is further explored.
【Key words】 enamel; dentin; mechanical properties; elastic modulus; fracture toughness; crown restoration; polyetheretherketone; carbon fiber; glass fiber; hydroxyapatite

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龋病、外伤、发育畸形等原因会造成牙体组织缺损，当剩余牙体组织不足以支撑牙齿正常行使功能时，往往需要全冠修复来恢复牙齿正常的形态与功能。目前全冠修复常用的口腔陶瓷材料在美观上可以满足临床应用的需要，但就力学性能而言，它与牙体组织并不完美契合，而力学性能的相对失衡也带来了一些临床问题，如修复体脱落、磨耗天然牙和饰瓷崩裂等。新兴材料的出现为冠修复提供了更多可能，在其中的聚醚醚酮（polyetheretherketone，PEEK）材料由于与骨组织相似的力学性能而备受关注。本文旨在回顾正常牙体硬组织的力学性能和常用于冠修复的口腔材料来探讨口腔全冠修复材料的仿生设计与发展可能。

1 牙体硬组织的力学性能

天然牙由牙釉质、牙本质、牙骨质以及牙髓组成。牙釉质覆盖在牙冠部的牙本质上，釉牙本质界（dento-enamel junction，DEJ）将两者分隔，牙釉质对内部结构起到保护作用。牙本质对外部的牙釉质和牙骨质起到一定的支持作用，同时保护着内部的牙髓组织。被覆于牙根部牙本质上的组织是牙骨质，它借牙周膜与牙槽骨相连，起着支撑牙齿的作用。牙齿是作为一个有机整体而发挥作用、行使功能。他们各自的力学性能和组织结构对牙齿行使功能以及修复体的设计应用有重要的作用。

1.1 弹性模量及硬度

弹性模量，又称为杨氏模量，是指在弹性状态下材料应力与应变的比值。材料的硬度是指衡量材料软硬程度的一种力学性能指标，它是表征材料的弹性、塑性形变强化、强度和韧性等一系列不同物理量组合的一种综合性能指标。

1.1.1 牙釉质 牙釉质的基本单位是釉柱，釉柱的基本单位是羟基磷灰石（hydroxyapatite，HAp）晶体[1]。从牙齿表面至釉牙本质界，它的弹性模量与硬度大致呈逐渐降低的趋势。这与釉柱的分布以及矿化程度相关。Niu等[2]通过共振超声光谱测得牙釉质的弹性模量为（71.7 ± 7.34）GPa。Lu等[3]将牙釉质分为靠近牙齿表层100 μm的外釉质层、靠近釉牙本质界100 μm的内釉质层以及位于其中的主体部分的“三明治结构”，用纳米压痕法测得由表及里三部分的硬度分别为（5.00 ± 0.22）GPa、（4.23 ± 0.18）GPa和（3.72 ± 0.35）GPa，弹性模量分别为（97.1 ± 2.95）GPa、（87.62 ± 2.50）GPa和（76.83 ± 5.71）GPa。这种变化趋势与内部釉质的结构有关。牙釉质中，HAp微晶以及釉柱都具有各向异性，靠近DEJ的釉柱多相互交叉，向着牙齿表面逐渐转化为与釉柱长轴一致的放射状[4]。内部相互交叉的结构起增韧作用，而与长轴方向平行负荷能力更强[5]。

1.1.2 牙本质 牙本质由牙本质小管、管周牙本质和管间牙本质组成。由DEJ至近牙髓处，它的弹性模量和硬度也呈逐渐减小的趋势。Kinney等[6]通过共振超声光谱测得牙本质弹性模量的范围为19 ~ 29 GPa。研究表明，力学性能的变化也与牙本质的组织结构密切相关[7]。靠近DEJ的牙本质小管较稀疏，而牙髓附近的较密集，同时随着不断向牙髓靠近，HAp的晶体颗粒也不断减小[8]。

1.2 断裂力学行为

1.2.1 断裂韧性 断裂韧性是反映牙釉质和牙本质抵抗裂纹的能力，是物体的固有特性。Hayashi-Sakai等[9]测得在中部的牙釉质断裂韧性要高于咬合面牙釉质的断裂韧性，这是由于中部的釉质釉柱走向不规则，呈弯曲样，因此裂纹在釉柱间的扩展受到抑制。针对牙本质，Ivancik等[10]将牙本质分为距釉牙本质界分别为0.5、2.5、3.5 mm的三部分测各自断裂韧性，内部牙本质的（2.2 ± 0.5）MPa·$m^{1/2}$显著低于中部的（2.7 ± 0.2）MPa·$m^{1/2}$和外部区域的（3.4 ± 0.3）MPa·$m^{1/2}$，这是因为外部牙本质相对胶原含量较高，从而增加了裂纹的闭合和裂纹尖端

应力强度的降低。

1.2.2　断裂行为　牙齿在不断的功能运动中，在牙釉质表层会产生微裂纹。而牙齿对这些裂纹具有一定的耐受性[11]。这种裂纹的耐受性与牙釉质和牙本质之间组织结构的变化有关。牙釉质内釉柱方向的转化会形成相互锁合的结构，同时弹性模量梯度会将施加的应力重定向，这使得裂纹进入内部釉柱交叉区后会因釉柱方向的改变而变慢，最后分叉并停止[12]。而当负荷过大或牙釉质磨耗严重时，裂纹可能会延续至牙本质。牙本质的抵抗机制与牙釉质相似，管周牙本质使得主裂纹发生偏转，继而终止裂纹[13]。因此即使裂纹进展到牙本质，往往也不会导致牙齿的劈裂。

牙釉质与牙本质的弹性模量、硬度和断裂韧性都呈现梯度性变化，这些梯度性的改变与牙釉质、牙本质本身组织结构的改变是相对应的，通过组织结构的变化使得富含羟基磷灰石晶体的脆性组织具有了良好的韧性[14]。

2　口腔全冠修复材料

口腔全冠主要有金属全冠[15]、烤瓷金属全冠[16]和陶瓷全冠[17]等。金属以及烤瓷全冠由于其在美观上的缺陷在临床上已较少使用。口腔陶瓷材料具有优异的美观性以及力学性能，是目前在临床上使用较多的全冠修复材料。近年来，高分子聚合物用作冠修复的优势也逐渐被发掘，如聚醚醚酮材料[18-19]。

2.1　口腔陶瓷材料

临床上常用的口腔陶瓷材料是玻璃陶瓷和氧化锆陶瓷。玻璃陶瓷是指一类含二氧化硅基的陶瓷，材料呈高度半透明性、仿生性和生物相容性，广泛用于嵌体、高嵌体以及冠修复。但它的不足在于固有脆性和低抗折裂性[20]。以二硅酸锂陶瓷材料为例，其维氏硬度为6.3 GPa，弯曲强度约262 ~ 360 MPa，断裂韧性为2.0 ~ 2.5 MPa·$m^{1/2}$[21]。针对玻璃陶瓷的现有不足，可通过离子交换强韧和氧化锆颗粒增强等方式来改善[22-23]。经改性后，氧化锆增强的玻璃陶瓷的弹性模量为60 ~ 108 GPa，硬度为4.5 ~ 6.8 GPa[24]。

氧化锆陶瓷具有良好的力学性能、热稳定性和化学稳定性而被广泛应用于冠桥修复，临床常用的氧化锆全瓷冠修复体弹性模量为200 GPa，抗折强度大于900 MPa，抗断裂韧性为9 ~ 10 MPa·$m^{1/2}$[25]。传统氧化锆多呈现白色，常需要饰面瓷来增加它的半透性。

对于陶瓷材料特别是氧化锆材料，修复失败的原因主要是饰瓷崩裂和修复体脱落[26]。Rodrigues等[27]认为饰瓷崩裂与饰瓷和基底冠之间的残余应力相关，同时修复体的几何设计、弹性模量、热膨胀系数以及基底冠与饰瓷比热差异等因素都是影响残余应力大小的关键因素。修复体脱落与粘接层的失效有关，Chen等[28]通过对陶瓷全冠修复体进行有限元分析发现应力集中冠颈部粘接界面，而且全冠的弹性模量越高，界面的应力越高，越易导致修复失败。氧化锆陶瓷存在的另一问题是会造成天然牙的磨耗的增加。一方面是由于氧化锆的硬度明显高于天然牙，另一方面是因为氧化锆是紧密结合的晶体结构，具有更强的抗表面降解性，而咬合时牙釉质的釉柱与其外层蛋白鞘之间更容易发生滑移[29]。

虽然口腔陶瓷材料在美观设计上具有优势，但是它与牙体组织相比，弹性模量与硬度过高，这种力学性能的不适配可能最终导致了修复的失败[30]。近年来，不少学者提出模拟牙齿结构来构建仿生牙釉质来作为修复体[31]。

2.2　聚醚醚酮

PEEK具有优异的力学性能，与口腔陶瓷材料相比，其优势在于弹性模量骨组织相似[32]。另外，它化学性能稳定，生物相容性良好，无细胞毒性和免疫原性。近年来，PEEK广泛应用于口腔种植[33-34]和口腔颌面外科[35-36]，也正被逐渐尝试作为全冠修复材料来使用。

Kimura等[37]对20例患者PEEK冠修复后6个月后进行随访，发现PEEK冠并未出现脱落、折裂、咀嚼力下降的现象，也未发现对牙龈边缘造成不利影响。Aldhuwayhi等[38]通过静态抗压以及动态抗疲劳实验证明PEEK相比于二硅酸锂，抗折断能力和抗咬合负荷能力更强。Abhay等[39]通过咀嚼模拟实验比较PEEK冠与氧化锆冠，发现PEEK冠对牙釉质的磨耗更少。PEEK较低的弹性模量和硬度，虽然使得应力分布更加均匀以及减少了天然牙磨耗的增加，但与牙体组织相比还有一定差距。为了提高它的力学性能，许多学者提出通过添加碳纤维和玻璃纤维以及羟基磷灰石颗粒的方式对聚醚醚酮进行了改进。

碳纤维和玻璃纤维由于具有良好的力学性能、无毒、耐磨性高等优势，而广泛地应用于材料的增强。碳纤维类型有不连续的短纤维和长纤维

以及连续纤维。一般在复合材料中，短碳纤维百分比为30 wt%，连续纤维为60 vol%[40]。Li等[41]通过注塑成型的方式分别合成了25 wt%短纤维和长纤维的PEEK复合材料，测得长碳纤维增强PEEK复合材料的拉伸强度和弯曲强度明显高于皮质骨。Kosmachev等[42]利用热压技术制作含60 vol%连续碳纤维增强的复合材料，观察到弯曲模量可达(59.5 ± 3.7)GPa。Gao等[43]通过模压成型的方式合成了30 wt%玻璃纤维增强的复合材料，测得它的硬度为7.8 GPa，明显高于PEEK本身，但是极限拉伸强度却不如PEEK。同时纤维的分布不均以及与PEEK基质浸润减弱都会影响复合材料的力学性能[44]。

羟基磷灰石具有良好的生物活性以及骨传导性而被用于生物材料[45]。Lai等[46]在PEEK中混入了2.5 wt%的HAp纳米粒子，测定复合材料的抗拉强度、冲击强度和抗弯强度分别比纯PEEK高18.5%、38.2%和5.7%，弯曲模量比纯PEEK高约30%。

3　总结和展望

了解正常牙体组织的结构和力学性能并以此为基础来制作设计全冠修复体是必不可少的，牙体组织与修复材料的力学性能对比总结见表1。

两种力学性能差异较大的材料相结合时，它们之间的界面往往会成为应力集中的薄弱区。全冠修复材料与牙齿本身的力学性能的适配性越强，那么经过修复后的牙齿在功能运动时更能作为一个整体发挥作用。虽然口腔陶瓷等修复材料可以满足美观方面的要求，在美观上符合仿生的概念，但它弹性模量与硬度较高、不具有与牙齿相似的层次结构。聚醚醚酮材料作为冠修复材料的优势恰好可以弥补陶瓷材料的劣势，然而它在临床上应用也受限于强度不足。通过多种方式可以构建复合材料来提高它的机械强度，使之更加接近牙体组织。然而，将聚醚醚酮作为冠修复材料仍需要更多病例来观察分析它的临床效果。牙釉质和牙本质的弹性模量和硬度均呈现梯度化递减的趋势，这一趋势与牙体组织的微观结构特点相符合。牙釉质釉柱在近釉牙本质界相互交错锁合，牙本质更高的弹性以及釉牙本质界的缓冲作用，可抵挡微裂纹的进展，防止牙齿劈裂。因此，应在牙体组织本身的力学性能与结构特点的基础上，构建层次更加多样的仿生修复材料，从而减少陶瓷材料的临床问题，能够更好地保护剩余牙体组织并延长修复体的寿命。

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表1　牙体组织与修复材料的力学性能对比

Table 1　Comparison of mechanical properties of dental tissue and restorative material

	Elastic modulus/GPa	Hardness/GPa	Fracture toughness/(MPa·$m^{1/2}$)	References
Enamel	71.7 ± 7.34	——	——	[2]
	Close to outer enamel surface: 97.1 ± 2.95 Main body of enamel: 87.62 ± 2.50 Close to EDJ: 76.83 ± 5.71	Close to outer enamel surface: 5.00 ± 0.22 Main body of enamel: 4.23 ± 0.18 Close to EDJ: 3.72 ± 0.35	——	[3]
Dentin	19-29	——	——	[6]
	Outer: 17.8 ± 3.1 Middle: 17.6 ± 2.7 Inner: 15.1 ± 2.2	Outer: 0.57 ± 0.15 Middle: 0.52 ± 0.15 Inner: 0.45 ± 0.15	——	[7]
	——	——	Inner: 2.2 ± 0.5 Middle: 2.7 ± 0.2 Outer: 3.4 ± 0.3	[11]
Glass ceramic	——	6.3	2.0-2.5	[23]
Zirconia-reinforced glass ceramic	60-108	4.5-6.8	——	[26]
Zirconia ceramic	200	——	9-10	[27]
Polyetheretherketone	3-4	——	——	[38]

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