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· 综述 ·

压电材料的抗菌性能及其在口腔医学领域的应用

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【摘要】 微生物感染是口腔疾病防治中的常见问题。抗生素疗法因其作用靶点单一、频繁使用易诱发耐药性等问题，在临床应用受限，亟需开发新型抗菌策略。刺激响应性抗菌材料能够通过外界刺激调控抗菌活性，具备远程可控性、局部精准治疗潜力以及不易诱发耐药性等优势。其中，基于机械力触发的压电材料因其独特的压电效应、良好的稳定性和生物相容性，在生物医学领域展现出显著的抗菌活性。研究表明，压电材料通过响应外力将机械能转化为电能，无需外电源即可发挥抗菌作用，其机制主要包括电场直接作用、活性氧的产生和免疫调节。压电材料在龋病、牙周炎、种植体周围炎等口腔感染性疾病治疗中的初步应用证实其稳定性、生物相容性和抗菌性，为临床转化奠定了基础。然而，其在复杂口腔微环境中的长期疗效及生物安全性仍需验证。未来研究应聚焦于优化材料制备工艺以提升抗菌效能与稳定性，深入探究抗菌机制，并系统评估其在不同类型口腔感染中的疗效与安全性。本文系统综述压电材料的抗菌作用、机制、稳定性、安全性及其在口腔医学领域研究进展，旨在为该领域的深入研究和应用提供理论依据。

【关键词】 刺激响应性；　压电材料；　压电效应；　抗菌作用；　抗菌机制；　稳定性；　安全性；　口腔医学

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Antibacterial properties of piezoelectric materials and their applications in stomatology

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【Abstract】 Microbial infections are a prevalent challenge in the prevention and treatment of oral diseases. Antibiotic therapy faces clinical limitations due to its single-target mechanism and tendency to induce resistance with repeated use, necessitating novel antibacterial strategies. Stimuli-responsive antibacterial materials, whose antimicrobial activity can be modulated by external stimuli, offer advantages such as remote controllability, potential for localized precision treatment, and a reduced risk of inducing resistance. Among these materials, mechanical force-triggered piezoelectric materials exhibit significant antibacterial activity in the biomedical field owing to their unique piezoelectric effect, excellent stability, and good biocompatibility. Research has shown that piezoelectric materials can convert mechanical energy into electrical energy in response to external forces, which enables antibacterial effects without requiring an external power source. The underlying mechanisms primarily include direct electric field effects, generation of reactive oxygen species, and immune modulation. Preliminary applications in treating oral infections (e.g., dental caries, periodontitis, and peri-implantitis) have confirmed their stability and biocompatibility, establishing a foundation for clinical trans-

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lation. However, long-term efficacy and biosafety in the complex oral microenvironment require further validation. Future research should focus on optimizing material preparation protocols to enhance antibacterial efficacy and stability, further investigating the underlying antimicrobial mechanisms, and systematically evaluating their therapeutic outcomes and safety profiles across various types of oral infections. This review summarizes the antibacterial effects, mechanisms, stability, safety, and research progress of piezoelectric materials in the stomatologic field, aiming to provide new insights for further research and application in this area.

【Key words】 stimuli-responsive; piezoelectric materials; piezoelectric effect; antibacterial activity; antibacterial mechanism; stability; safety; stomatology

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微生物感染严重威胁人类健康。抗生素的使用虽降低细菌感染相关疾病的发病率和死亡率，但其作用靶点单一、滥用易诱发耐药性等问题限制其临床应用[1-2]。金属离子、氧化物及季铵盐等传统抗菌剂虽在一定程度上缓解了耐药问题，却存在抗菌性能不可调控、抗菌作用与细菌感染严重程度不相关等不足[3-4]。因此，开发安全有效、具有响应性的新型抗菌药物成为当前研究热点。学者们研究发现多种材料能够响应内源性或外源性刺激（如温度、光、力等）产生电、热或化学物质，以增强其抗菌效果[5]。相较于传统抗菌材料，这类刺激响应性材料能够通过外界刺激调控抗菌活性，具备远程可控性、局部精准治疗潜力以及不易诱发耐药性等优势[6-7]。

压电材料是一类在机械力作用下于相对表面产生正负电荷的材料，其机械能与电能的相互转换现象称为压电效应[8-9]。相较于依赖特定波长光照或局部高温的光催化与光热催化抗菌材料，压电材料能直接利用机械力触发抗菌活性。这一机制有效克服了光热/光催化材料在组织穿透深度、光依赖性及对正常组织潜在热损伤等方面的局限性，展现出广阔的应用前景[10-11]。

凭借独特的压电特性与良好生物相容性，压电材料已在生物医学领域获得广泛应用[12]。值得注意的是，压电材料在口腔医学领域具备重要的应用潜力：日常功能活动（如咀嚼、刷牙）产生的机械力可触发其压电效应，实现按需抗菌，同时避免了光/热刺激可能带来的损伤风险。然而，目前该领域的研究报道仍相对有限。本文旨在系统综述压电材料的抗菌作用、机制、稳定性、安全性及其在口腔领域的研究进展，以期为相关研究及临床应用提供理论参考。

1　压电材料的抗菌作用

压电材料按化学组成可分为有机、无机及复合三大类。其中，有机压电材料的压电性主要源于聚合物结构取向，无机压电材料的压电特性则源自其晶体结构的非中心对称性[13]。复合压电材料是由压电组分与一种或多种其他组分复合而成，旨在协同优化综合性能的材料[14]。以下按此分类阐述各类压电材料抗菌作用。

1.1　有机压电材料的抗菌作用

有机压电材料，如聚偏二氟乙烯（polyvinylidene fluoride，PVDF）、聚L-乳酸［poly（l-lactic acid），PLLA］及其共聚物等，具有柔韧性、易加工性等优点[15-16]。PVDF的压电性主要来自其β相的全反式构象，提高β相含量可增强其压电特性[17]。研究表明，PVDF纳米纤维及其复合膜均能有效抑制大肠杆菌和金黄色葡萄球菌[18-19]。但PVDF不可降解，限制了其在体内应用[20]。研究发现生物可降解聚酯材料PLLA和聚-β-羟丁酸［poly（3-hydroxybutyrate），PHB］同样具有压电特性。压电PLLA纤维在形变时产生的强电场赋予织物良好抗菌性[21]，其薄膜在压电刺激下对表皮葡萄球菌表现出良好抗菌效果[22]。改性后的PHB对大肠杆菌和表皮葡萄球菌亦具有抑制作用[23]。这些可降解压电材料克服PVDF局限并为压电抗菌应用提供了新可能。

1.2　无机压电材料的抗菌作用

无机压电材料主要包括压电晶体和压电陶瓷。其中，压电陶瓷［如钛酸铅（$PbTiO_3$，PT）、钛酸钡（$BaTiO_3$，BTO）和铌酸钾（$KNbO_3$，KN）］通常具

有更优异的压电性能[24]。PT压电活性高，但铅元素的潜在生物毒性限制了其在生物医学领域的应用[25]。无铅压电陶瓷生物相容性良好，以BTO研究最为广泛。极化处理后BTO对金黄色葡萄球菌和大肠杆菌具有较好的抗菌效果[26]，将其负载于棉织物表面可赋予其优异的抗菌性能[27]。另有学者发现调控氧空位可优化BTO的压电催化活性和抗菌性能[28]。此外，Liu等[29]将BTO纳米粒嵌入水凝胶，利用超声触发压电催化效应产生活性氧（reactive oxygen species，ROS）发挥抗菌作用。

1.3　复合压电材料的抗菌作用

复合压电材料是由两种或两种以上不同物理性质的组分（至少一种为压电材料）复合而成的新型材料。通过形貌调控、构建异质结及贵金属修饰等组分优化策略，可协同提升其压电性能与力学性能，促进界面电荷转移，从而增强压电催化活性[30-32]。例如，铈（Ce）掺杂的中空BTO（hBT Ce）纳米粒在超声刺激下可高效破坏浮游菌和生物膜[33]；BTO与金（Au）纳米颗粒结合不仅提高电荷分离与迁移效率，增强抗菌效果，还促进感染伤口修复[34]。此外，BTO纳米粒表面修饰硒（Se）纳米粒形成BTO@SeNPs[35]、铌酸钾（$KNbO_3$）上沉积Au纳米颗粒合成$KNbO_3$@Au[36]、BTO纳米层插入TiO_2纳米棒和Au纳米颗粒形成的TiO_2/BTO/Au多层同轴异质纳米材料[37]等复合结构均显著提高了抗菌能力。

2　压电材料的抗菌机制

压电材料通过响应外力将机械能转化为电能，无需外电源即可发挥抗菌作用，其机制主要包括电场直接作用、ROS的产生和免疫调节（图1）。

2.1　电场的直接作用

压电材料在外力作用下产生的电场可通过以下机制发挥抗菌作用：①干扰细菌细胞膜静电平衡，抑制细菌黏附及生物膜形成。研究表明，含BTO的压电水凝胶在机械刺激下产生的电荷可下调细菌表面多糖生物合成基因（porP）和菌毛主要亚基蛋白基因（fimA）的表达，降低细菌黏附能力，减少生物膜形成[38]。②破坏细菌外部结构，增加细胞膜通透性，导致胞内物质泄漏，引发细菌死亡[39-40]。例如，铌酸钾钠陶瓷在高表面电势下可诱导K^+/Na^+外流，实现剂量依赖性杀菌[41]。极化处理的羟基磷灰石（hydroxyapatite，HA）/BTO复合材料通过中和膜负电荷、扰乱脂质双层致细菌膜破裂，抑制黏附并具杀菌效果[42]。③干扰细菌电子传递链，引发代谢紊乱[43]。压电效应产生的电势能够竞争性夺取细菌呼吸链电子，抑制ABC转运蛋白（ATP-binding cassette transporter）功能并激活氧化磷酸化通路，从而阻碍ATP合成，导致细菌能量代谢紊乱[44]。④诱导电穿孔效应：当局部电场强度超过阈值时，可击穿细菌细胞膜[45-46]。研究表明，具有鱼鳞状结构的氧化铝材料因其各向异性晶格特性而表现出增强的压电响应，在超声作用下能产生高强度局部电场，通过电穿孔作用协同杀灭多种微生物[47]。

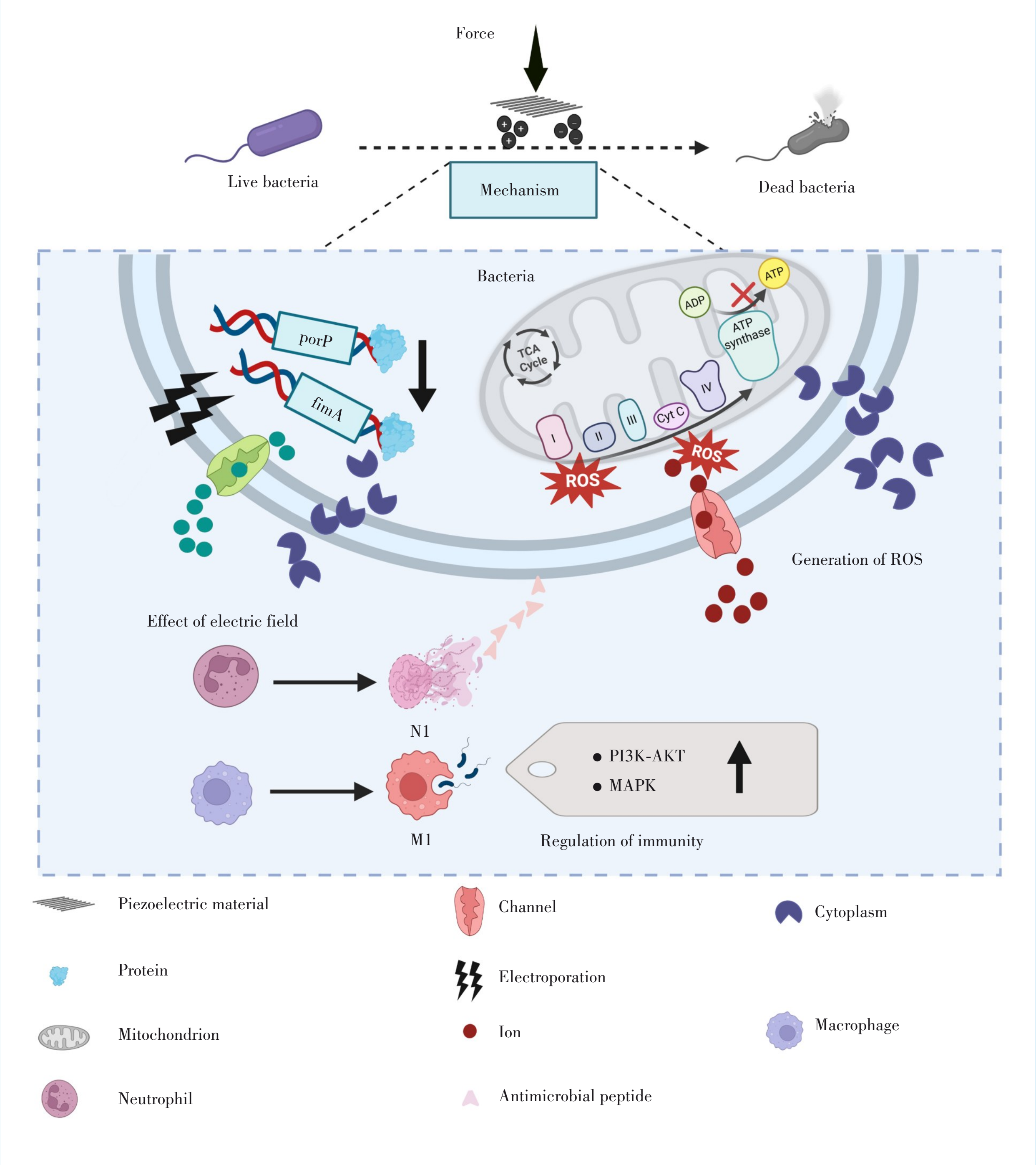
2.2　活性氧的产生

压电材料在机械刺激下产生的表面电荷可催化环境中的水分子和氧气发生氧化还原反应，生成具有强氧化性的ROS[48-50]。当ROS积累超过细菌清除能力时，会引发氧化应激反应导致细菌死亡[51-52]。过量的ROS能破坏细菌细胞膜的不饱和磷脂，引发脂质过氧化，增加膜通透性，导致胞内物质泄漏[53-54]。同时，ROS可下调核糖体、DNA及ATP合成相关基因表达[29, 55]。具有多孔网格结构的压电复合支架在超声刺激下产生的ROS可阻碍电子传递过程，抑制ATP合成，导致细菌能量代谢障碍而死亡[56-57]。该抗菌机制兼具可控性强与耐药风险低的优势：可通过调节外界刺激参数（频率、强度、持续时间）调控ROS生成量[58]；通过多靶点作用方式有效降低细菌耐药性风险[59]。然而，未经功能化的压电聚合物压电系数偏低，不足以驱动水/氧氧化还原生成ROS，其抑菌效应主要归因于表面电荷直接破坏细菌膜稳态，而非压电催化活性氧机制[22]。

2.3　免疫调节

巨噬细胞作为机体抗感染的第一道防线，其M1型极化在细菌清除中起关键作用[60]。然而，生物膜形成会显著抑制免疫细胞活性，阻碍细菌清除[61-62]。生物材料介导的免疫疗法为感染控制提供了新途径[63]。Li等[64]研究表明，钛植入物表面构建的压电纳米结构在超声驱动下可显著增强巨噬细胞对金黄色葡萄球菌的吞噬能力，其核心机制涉及磷脂酰肌醇3-激酶-蛋白激酶B（phosphatidylinositol 3-kinase-protein kinase B，PI3K-AKT）和丝裂原活化蛋白激酶（mitogen-activated protein kinase，MAPK）信号通路的激活。

进一步研究发现，压电复合支架在超声刺激下可激活补体和凝血级联通路、整合素信号通路



ROS: reactive oxygen species; PI3K-AKT: phosphatidylinositol 3-kinase-protein kinase B; MAPK: mitogen-activated protein kinase; ADP: adenosine diphosphate; ATP: adenosine triphosphate; TCA: tricarboxylic acid; Cyt C: cytochrome c; N1: N1 neutrophil; M1: M1 macrophage

Figure 1　Antibacterial mechanisms of piezoelectric materials

图1　压电材料的抗菌机制

和细胞因子-受体相互作用通路促进巨噬细胞M1极化，有效增强对骨感染细菌的清除能力[65]。Liu等[66]证实，经压电激活的巨噬细胞局部注射可有效清除耐药菌感染。此外，压电纳米催化与免疫激活的协同策略还能诱导中性粒细胞向N1型极化，通过促进抗菌肽释放和增强吞噬功能，协同清除生物膜感染[67]。然而，持续促炎极化可能抑制血管新生并延缓组织修复[68]。

目前，压电材料与免疫系统的相互作用机制仍处于探索阶段，未来需进一步阐明其分子通路

及调控网络。

3　压电材料的稳定性和安全性

3.1　稳定性

无机压电材料因其优异的压电性能和稳定性而备受关注[69]。Zhou等[70]通过结构设计，成功制备出高压电响应、高温度稳定性的材料，其压电系数超越传统压电单晶，展现出广阔的应用前景。Hua等[71]研究发现，在聚酰胺/BTO复合材料中，BTO的含量与压电性能呈线性正相关关系，同时材料的热稳定性也得到提升。另有研究表明，改性BTO/PVDF复合纳米纤维在1 000次循环测试中表现出稳定的输出电压，亦展现了优异的稳定性[72]。

3.2　安全性

压电材料因其优异的压电性能和良好的生物相容性，在生物医学领域展现出重要应用价值[73]。体外研究发现：压电材料对间充质干细胞、成纤维细胞和成骨细胞均未表现出明显细胞毒性[74-76]。体内研究进一步证实其安全性：小鼠关节腔内注射压电材料后，颗粒局限于关节腔，未引起系统性毒性或重要器官炎症[77-78]。犬下颌骨植入实验表明，BTO压电陶瓷涂层种植体不仅未诱发毒性反应，还能提高种植体稳定性[79]。

压电材料的选择性抗菌作用源于细菌与真核细胞在膜结构、电场耐受及氧化应激体系上的差异[22, 40]。细菌细胞膜因缺乏胆固醇且富含负电荷磷脂，其击穿电压低于哺乳动物细胞膜。此外，哺乳动物细胞直径更大，相同外源电场或压电电荷下跨，体积更大的哺乳动物细胞跨膜电位增幅较小，不易达到损伤阈值。

在氧化应激应对方面，细菌的抗氧化系统缺乏哺乳动物细胞的多级调控网络，因此在相同ROS暴露下更易发生氧化还原失衡，导致ROS介导的杀伤作用更显著[22, 80-81]。但某些细菌可通过适应性机制（如生物膜、抗氧化酶诱导）抵抗氧化压力[82]。

4　压电材料抗菌性能在口腔医学领域中的应用

压电材料作为一种新兴的刺激响应性材料，凭借其独特的压电性能、良好的稳定性和安全性，在口腔领域具有重要的应用价值。

4.1　龋病的治疗

龋病是牙菌斑生物膜引起的常见口腔感染性疾病，影响患者咀嚼功能及生活质量[83]。目前临床常规治疗方法存在机械清洁难以彻底清除生物膜，而抗菌药物易导致耐药性和口腔微生态失衡等不足[84-86]。研究表明，聚四氟乙烯驻极体牙刷在低频超声波作用下可通过压电催化产生ROS，发挥显著抗菌效果[87]。

HA-BTO纳米复合材料能有效抑制主要致龋菌变异链球菌生物膜形成，为抗菌防龋提供新策略[88]。针对传统充填材料缺乏抗菌性易导致继发龋的问题，BTO压电纳米粒作为复合树脂填料兼具抗菌与促矿化双重功能，有望提升充填治疗效果[89]。此外，聚偏氟乙烯-三氟乙烯与锶离子复合压电材料在咀嚼刺激下可模拟电生理微环境，招募牙髓干细胞并促进其分化，为牙本质缺损修复提供了一种原位再生策略[90]。

4.2　牙周病的治疗

牙周炎是一种以牙槽骨进行性破坏为特征的慢性炎症性疾病，可导致牙齿松动甚至脱落[91]。目前临床常规非手术治疗方法（包括洁治术、根面平整术及抗生素应用）存在局限性：一方面难以彻底清除牙周袋深部的菌斑生物膜，另一方面长期使用抗生素易导致细菌耐药性产生。

Roldan等[38]开发了含BTO压电材料的水凝胶，体内外实验表明该压电水凝胶可显著抑制牙龈卟啉单胞菌生物膜并减轻小鼠牙周炎症和促进骨再生，为非手术治疗提供新策略。引导骨再生（guided bone regeneration，GBR）是促进牙周骨形成的有效策略，但现有GBR膜存在机械强度有限及抗菌性能不足，易导致软组织侵入及感染。新型双层可降解压电GBR膜兼具良好机械性能与抗菌活性，超声刺激下能有效抑制牙龈卟啉单胞菌和金黄色葡萄球菌，在牙周炎动物模型中可有效控制感染并促进组织修复[92]。

此外，可降解压电Janus膜（具有非对称双面功能的薄膜）通过结构设计实现协同效应：外层PLLA有效抑制牙龈卟啉单胞菌，内层PLLA/明胶复合物兼具抗炎与促骨再生功能[93]。

4.3　牙列缺损的修复材料

义齿性口炎是可摘义齿佩戴者的常见并发症，与白色念珠菌感染密切相关[94]。现有抗真菌义齿材料（如抗生素、阳离子聚合物及纳米填料）存在细胞毒性、诱导耐药及破坏菌群稳态等缺点。Montoya等[95]研究表明，BTO压电纳米粒改性义齿基托材料在模拟咀嚼力作用下可触发压电催化产

生ROS，显著抑制白色念珠菌生物膜形成并降低代谢活力。

4.4 种植体周围炎的预防和治疗

种植体周围炎是导致种植失败的主要并发症，其传统抗生素治疗因耐药性问题而疗效受限。为此，学者们致力于种植体表面改性赋予其抗菌性能。Wu等[96]开发的银掺杂钛酸锶钡钙压电涂层抗菌率高达99%，且具有良好的生物活性。另有研究将BTO纳米颗粒嵌入壳聚糖薄膜以改性钛种植体表面，该涂层本身具抗菌性，且声波刺激可增强其抗菌效果[97]。近期研究提出压电抗菌与免疫调节协同策略：在钛植入物上添加压电水凝胶微球系统，利用超声驱动其产生ROS、下调生物膜基因，并通过激活免疫系统协同增强抗菌效果。这种无抗生素、无创且可按需调控的抗菌方法为种植体周围炎的防治提供了新思路[98]。

4.5 正畸治疗

正畸矫治过程中牙面清洁困难易致菌斑堆积，增加釉质白垩斑风险[99]。为应对隐形矫治器引起的牙釉质脱矿问题，学者合成了含压电BTO纳米粒的热塑性聚乙二醇-共环己烷-1，4-二甲醇对苯二甲酸酯复合材料，通过循环机械振动激活其压电效应。生物膜定量分析显示，该复合材料表现出显著抗菌活性，且抗菌效果随BTO浓度增加而增强[100]。另有研究将氧化锌纳米颗粒与PVDF复合于热塑性聚氨酯基底，利用咀嚼产生的应力激活涂层的压电效应。该涂层对多种口腔细菌的抗菌率超过90%，能有效减少细菌黏附与生物膜形成，从而预防釉质脱矿[101]。

5 总结与展望

压电材料能将机械刺激转化为电刺激，通过电场直接作用、ROS生成及免疫调节等途径实现可控的抗菌治疗。结合3D打印、数字化处理等先进制备技术，压电材料在精准与智能抗菌治疗领域展现出巨大潜力。然而，其临床转化仍面临诸多挑战：首先，抗菌机制尚未完全阐明。尽管ROS生成与细胞膜破坏已被确认是关键途径，但压电电荷与细菌相互作用的精确过程及分子机制仍不明确；其次，生物安全性有待提升，Sr^{2+}、Ba^{2+}等金属离子可能渗入组织，现有离子释放调控方法（如表面涂层、缓释系统）普遍存在相容性不佳、耐久性不足等问题，且材料长期毒性、靶向性及生物可降解性评估亦不充分；第三，应用设计较为单一。压电效应触发多依赖单一刺激源，与其他治疗方式的协同效应探索不足，且制备工艺常滞后于功能设计需求。

未来研究应聚焦：深化分子机制研究，阐明压电电荷与细菌的相互作用规律；通过微观结构优化提升压电系数与能量转换效率，以增强其在复杂口腔环境（如唾液冲刷、pH波动和咀嚼力等动态因素）中的耐用性；开发新型离子释放调控技术，保障生物安全性；强化多元组分协同设计并革新制备工艺，实现多功能集成；推进联合治疗模式探索与长期毒性评估，加速临床转化进程。

综上，压电材料在抗菌治疗领域前景广阔，需通过多维度创新破解现有挑战，方能推动其临床实际应用。

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