综 述

引用格式：*J. Inorg. Mater.*, 2026, **41(6):** 751
**DOI:** 10.15541/jim20250441

# 可注射无机材料及其生物医学应用

王金文[1,2], 杨 振[2], 周 欢[2], 夏 丹[1], 杨 磊[1,2]

(河北工业大学 1. 材料科学与工程学院; 2. 生命科学与健康工程学院, 河北省生物医学材料与智能诊疗重点实验室, 健康科学与工程中心, 天津 300130)

**摘 要:** 随着医工交叉领域和生物医学新兴研究方向的迅速发展, 可注射医用材料因其在微创手术等领域的应用优势, 在组织修复与再生、医学影像、疾病精准诊疗及微创化治疗等前沿领域得到广泛关注, 并形成了一系列创新性医疗器械产品。在各类可注射医用材料中, 无机材料因其独特的材料生物学特性、流变学性能以及自固化等特点, 在微创骨科、肿瘤诊疗、组织替代与修复等领域展现出巨大的应用潜力和前景。本文综述了可注射无机材料的相关概念、原理及其在生物医学领域的最新进展。首先, 介绍了无机材料可注射性的基本概念、原理及其调控因素(包括无机材料颗粒的几何特征、体系的液固比、液相黏度及材料体系的物理化学反应等); 然后, 从临床应用角度阐述了可注射无机材料在硬组织修复、医学影像诊断、肿瘤治疗、皮肤和整形等领域的应用现状和研究进展, 并分析了其优势和不足; 最后, 探讨了当前面临的挑战及未来发展趋势。本文有望为推动医用无机材料的应用研究和临床转化提供有益参考, 进而促进相关医疗器械产品的技术创新和研发。

**关 键 词:** 无机材料; 可注射性; 生物医学; 微创手术; 综述

**中图分类号:** R318 **文献标志码:** A **文章编号:** 1000-324X(2026)06-0751-13

# Biomedical Applications of Injectable Inorganic Biomaterials

WANG Jinwen[1,2], YANG Zhen[2], ZHOU Huan[2], XIA Dan[1], YANG Lei[1,2]

(1. School of Materials Science and Engineering, Hebei University of Technology, Tianjin 300130, China; 2. Center for Health Science and Engineering, Hebei Key Laboratory of Biomaterials and Smart Theranostics, School of Health Sciences and Biomedical Engineering, Hebei University of Technology, Tianjin 300130, China)

**Abstract:** The rapid advancement at the interface of medicine and engineering, as well as emerging biomedical research, has led to a new research area of injectable biomaterials. Owing to their advantages in minimally invasive surgery, injectable biomaterials have been extensively investigated for biomedical research fields such as tissue repair and regeneration, medical imaging, precision diagnosis and therapy, and other minimally invasive therapies. Furthermore, many injectable biomaterials have been successfully translated into medical devices and products.

**收稿日期:** 2025-10-31; **收到修改稿日期:** 2026-01-19; **网络出版日期:** 2026-01-22
**基金项目:** 国家自然科学基金(82025025); 国家重点研发计划(2023YFC2412300); 国家自然科学基金联合基金(U23A6008); 河北省自然科学基金(H2022202007); 国家自然科学基金(32571559)
National Natural Science Foundation of China (82025025); National Key Research and Development Program of China (2023YFC2412300); Joint Funds of the National Natural Science Foundation of China (U23A6008); Natural Science Foundation of Hebei Province (H2022202007); National Natural Science Foundation of China (32571559)
**作者简介:** 王金文(1997–), 男, 博士研究生. E-mail: wangjinwen166@126.com
WANG Jinwen (1997–), male, PhD candidate. E-mail: wangjinwen166@126.com
**通信作者:** 夏 丹, 副教授. E-mail: xiad@hebut.edu.cn; 杨 磊, 教授. E-mail: ylei@hebut.edu.cn
XIA Dan, associate professor. E-mail: xiad@hebut.edu.cn; YANG Lei, professor. E-mail: ylei@hebut.edu.cn

Among injectable biomaterials, inorganic materials possess distinctive materiobiological properties, rheological properties, and unique self-setting behaviors, making them highly promising for biomedical applications including minimally invasive orthopedics, cancer theranostics, and tissue substitution and repair. This review aims to introduce the basics of injectable inorganic materials and summarize their latest research advances and application progress. Firstly, the fundamental concepts and governing principles of injectability are introduced, along with a discussion of key regulatory factors (*e.g.*, geometric properties of the particles, liquid-to-solid ratio of the system, liquid phase viscosity, and physicochemical reactions). Secondly, clinically oriented research and development progress in inorganic injectable biomaterials are summarized, covering areas such as hard tissue repair, medical imaging diagnosis, cancer therapy, dermatology, and plastic surgery. Advantages and limitations of these materials are also analyzed. Finally, the key challenges and future research directions for injectable inorganic biomaterials are discussed. This article is expected to provide valuable references for advancing application-oriented research and facilitating the clinical translation of injectable inorganic biomaterials, thereby promoting the technological innovation and development of related medical devices.

**Key words:** inorganic material; injectability; biomedicine; minimally invasive surgery; review

生物医用无机材料，如生物陶瓷、生物玻璃及其复合材料，因其优异的生物相容性、力学性能和生物化学性质，已广泛应用于骨[1-3]、牙齿[4-5]、皮肤[6]及心血管[7-8]等组织的修复与重建，同时在软/硬组织的修复与替代、疾病的诊断与治疗等方面发挥了重要作用。随着临床治疗理念和医疗技术的不断革新，基于传统医疗器械的开放式手术或治疗模式正快速向侵入性和破坏性更小、组织修复速度更快、病人康复效果更佳的微创诊疗技术发展。这一趋势对开发适配微创诊疗技术需求的可注射或可微创递送的生物医用材料提出了迫切需求。

无机材料具有相变特性、光学特性、力学特性和多样结构选择性等优势，近年来在可注射微创治疗[9-10]、组织填充[11-12]、靶向递送[13-14]和影像诊断[15-16]等领域得到了广泛关注。可注射无机材料的形态多为微米级或纳米级颗粒，通常需要与液体介质混合来实现微创递送(图 1)。最典型的可注射无机材料是以磷酸钙骨水泥为代表的一类自固化材料，这类材料与液体接触后会发生水合反应或自固化反应，实现材料固态-可注射态-固态的转变。通过控制组分比例、固液比和温度等参数可有效调控无机材料可注射态的维持时间及流变学特性，从而满足其在不同应用场景下的注射及操作时间要求[17-18]。

与自固化材料不同，其它无机材料颗粒缺少自发相转变的特性，需要分散在流体介质中形成悬浮液或胶体，依托流体介质才能注射。因此，这类无机

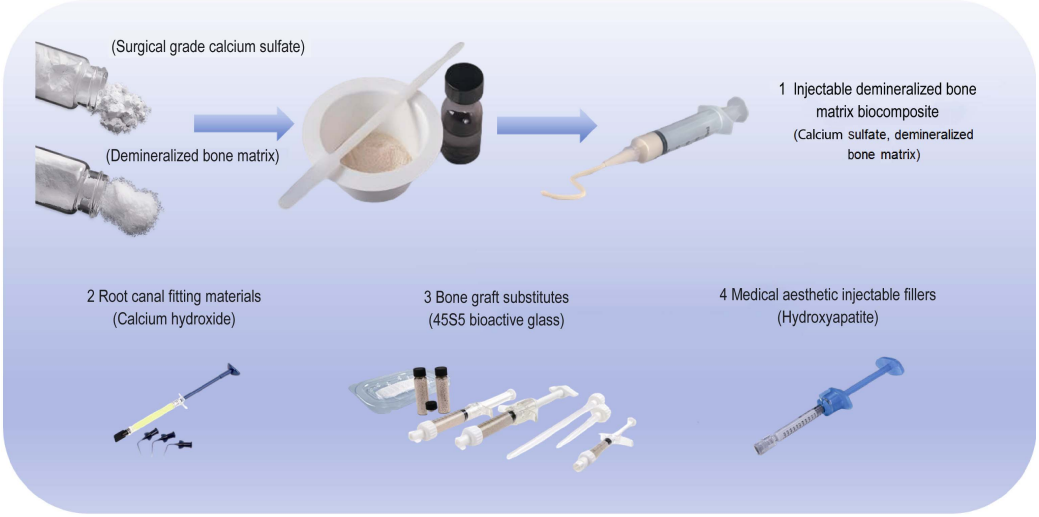


图 1 目前临床使用的可注射无机材料产品及其典型成分

Fig. 1 Current injectable inorganic materials for clinical use and their typical components

材料本身更接近于功能单元或药物载体, 不具有直接可注射性[19]。另外, 该类材料与流体介质的选择与搭配比较灵活, 极大地拓宽了可注射无机材料的应用范围, 形成了针对组织或细胞的活性元素释放[20-21]、结构支撑[22]、力学刺激[23]、光动力治疗[24]、药物靶向递送[25-26]、电磁性能调控[27-28]等一系列诊疗新方法。

鉴于该领域的快速发展, 本文将系统阐述可注射无机材料的基本概念、优势及相关特性, 重点总结近年来其在硬组织修复、医学影像诊断、肿瘤治疗、皮肤和整形等领域的应用进展, 最后分析其发展挑战及趋势。

# 1　无机材料的可注射性

## 1.1　可注射性的概念

Bohner 等[29]曾将可注射性定义为材料体系在注射过程中保持均匀性的能力。然而, 目前对于无机材料的可注射性尤其是无机悬浮颗粒体系(固体颗粒分散在液相介质中形成的多相体系)仍没有严格的定义。根据已有研究, 可以从注射率和注射力两方面对无机材料的可注射性进行量化评价。注射率是指能够从注射器中推出的材料质量与装载总质量的比值; 注射力则是指从注射器推出材料所需要的推注力值, 通常取连续推注力曲线上的最大值或平均值。一般而言, 较高的注射率和/或较小的注射力意味着更佳的可注射性。目前部分典型糊剂(例如羟基磷灰石及磷酸三钙等)在不引入添加剂的情况下, 其注射率一般为 30%~80%, 且显著受材料体系液固比及颗粒性质影响, 因此可注射性较差, 难以满足临床需求[30-31]。在实际应用中, 往往通过引入添加剂或优化颗粒性质(例如颗粒尺寸、粒径分布及颗粒形状等), 将注射率提升到 90%以上[32], 同时控制注射力低于 50 N[10, 33], 以适应临床操作。

无机材料可注射性与材料体系的物理参数密切相关, 主要涉及以下参数。(1)颗粒几何特征: 主要包括无机颗粒的形状、尺寸以及粒径分布等。(2)液固比: 注射体系中液相与固相的体积比或质量比。(3)堆积分数 $\varphi$: 液固体系中固体颗粒体积与体系总体积的比值(式(1))。$\varphi_{max}$ 为体系的最大堆积分数, 与体系中固体颗粒的粒径分布相关, 对应的液相量为形成糊剂所需的最少液相量。(4)液相黏度 $\mu_l$: 对注射过程中材料的均匀性具有显著影响。(5)液相穿透压 $P_{PS}$: 液相通过无机颗粒网络所需的压力(式 2)[34]。

$$\varphi = \frac{V_s}{V_{total}} \tag{1}$$

$$P_{PS} = \frac{Q\mu_l L}{kA} \tag{2}$$

其中, $V_s$ 为固体颗粒体积; $V_{total}$ 为总体积; $Q$ 为流量; $L$ 为液相流经颗粒介质的长度; $A$ 为液相流经颗粒介质的面积; $k$ 为渗透率(液相穿透颗粒介质的能力)。

除此之外, 无机材料体系内的物理化学反应(如磷酸钙、硫酸钙遇水后的固化反应等)也是影响可注射性的重要因素。这些因素的相互作用关系比较复杂, 是目前该领域的研究前沿。下面将简要总结上述因素的研究进展。

## 1.2　影响无机材料可注射性的因素

### 1.2.1　颗粒几何特征及液固比

一般在可注射无机材料的浆料体系中, 堆积分数 $\varphi$ 与最大堆积分数 $\varphi_{max}$ 之间的差值越大则越易于注射。在无机材料颗粒粒径、形状等性质不变的情况下, $\varphi$ 与液固比直接相关, 液相越多则 $\varphi$ 越小, 体系的流动性和可注射性就越强。同时, $\varphi_{max}$ 越大表示颗粒堆积越密集, 颗粒间空隙越小, 颗粒网络对液相的锁定能力越强, 注射过程中液相与固相的分离(即相分离)就越难发生, 可注射性就越强。Bohner 等[29]和 Alves 等[35]使用不同液固比的磷酸钙糊剂(0.35、0.6、0.87 mL/g)进行实验, 结果表明相同注射条件下, 提高液固比可以增加磷酸钙糊剂的挤出量, 从而提高注射率(图 2(a))。因此, 控制体系 $\varphi_{max}$ 与 $\varphi$ 之间的差值可以调控可注射性。

除液固比外, 颗粒尺寸、形状及粒径分布也会显著影响无机材料 $\varphi$。研究表明, 当颗粒尺寸单一分布时, 体系的 $\varphi_{max}$ 通常小于 0.64; 而当颗粒粒径呈多尺寸分布时, 较小的颗粒可以充填到大颗粒构成的网络空隙中形成更致密的堆叠(图 2(b, c)), 从而提升 $\varphi_{max}$[36]。图 2(d)是球形颗粒为双峰分布时, 大、小颗粒体积比对 $\varphi_{max}$ 影响的模拟结果, 当 30%的小颗粒与 70%的大颗粒混合时, $\varphi_{max}$ 达到峰值 0.83 左右[36-39]。引入更小尺寸的颗粒还可进一步增大 $\varphi_{max}$。因此, 颗粒的尺寸分布对无机浆料的可注射性具有至关重要的作用。Tadier 等[40]使用 156、390 μm 两种尺寸的玻璃珠粒与 $\beta$-TCP 颗粒混合进行实验, 发现多种不同粒径混合的浆料体系具有更好的可注射性。

对于单一粒径来说, 颗粒越小则材料体系的可注射性越好。这是由于粒径越小, 颗粒的比表面积越大, 对体系中液相迁移的阻力越强, 从而减小渗

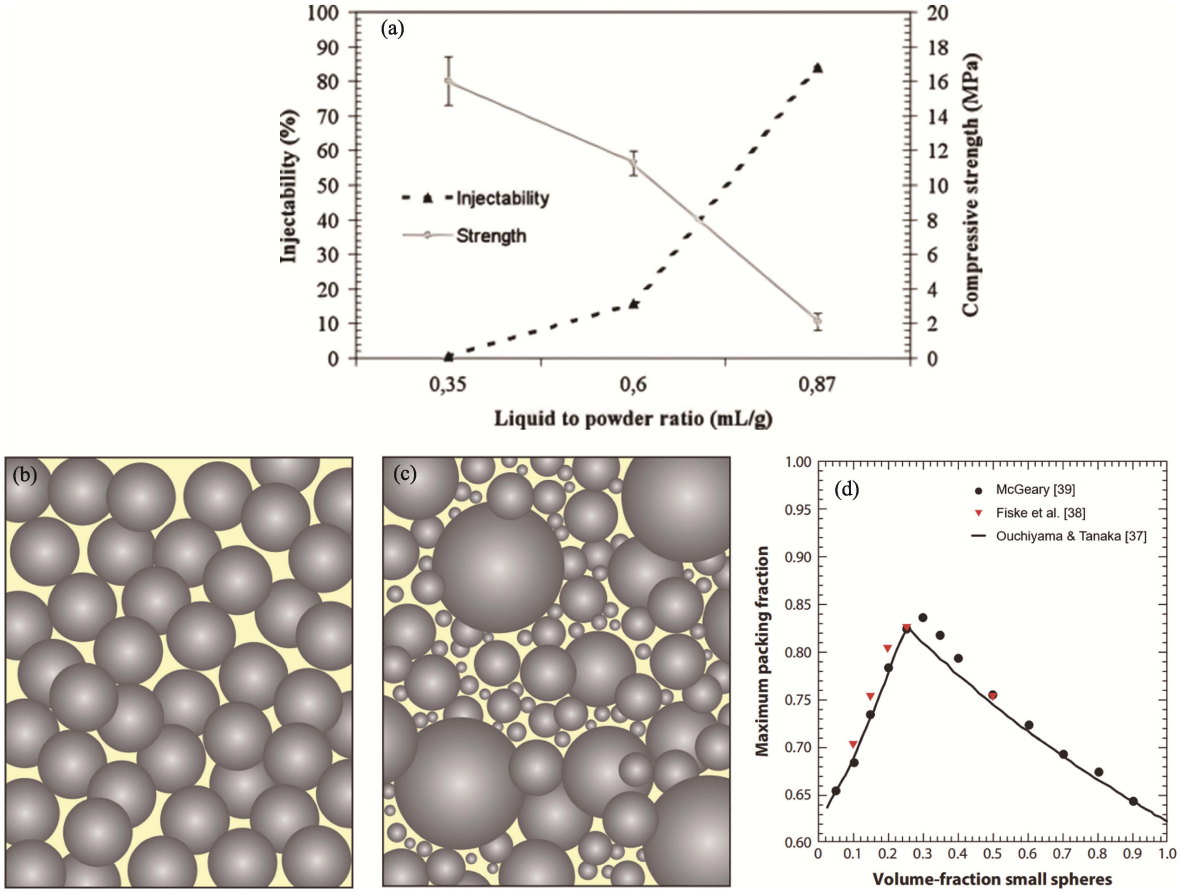


图 2 无机材料体系的液固比及颗粒堆积状态对可注射性的影响[35-39]

Fig. 2 Effects of liquid-to-solid ratio and particle packing on the injectability of inorganic materials[35-39]

(a) Effect of liquid-to-solid ratio on injectability[35]; (b) Packing state of particles of a single size[36]; (c) Packing state of particles of multiple sizes[36]; (d) Bimodal size distribution *versus* $\varphi_{max}$[36]. Experimental maximum packing fraction data from Fiske *et al.*[38] and McGeary[39] for a bimodal size distribution (diameter ratio $\alpha_p = D_2/D_1 = 20$ ($D_1$: diameter of small particles; $D_2$: diameter of large particles; $\alpha_p$: diameter ratio of particles)) *versus* the small-to-large particle concentration ratio were compared with the predictions of the Ouchiyama & Tanaka[37] model

透率及相分离。同时，小颗粒更易发生滑动，易于通过注射器的狭窄出口，从而提升可注射性。然而，粒径过小容易引发团聚，对材料可注射性产生不利影响[41]。

此外，无机材料颗粒的几何形状也会影响可注射性。一般而言，相较于不规则颗粒，球形颗粒因其滚动性更好而具有更佳的可注射性；不规则或多边形颗粒的棱角容易互相锁住，增大摩擦，往往需要更大的力来打破其互锁结构使体系发生流动，因此可注射性较差[42-43]。

### 1.2.2 液相黏度

液相黏度对无机材料体系的注射率及注射力均有影响。当液相黏度较低时，无机颗粒网络对液相的锁定能力弱，液相容易穿过颗粒网络而发生相分离，导致部分固相材料无法从注射器中挤出，在注射器内形成滤饼，降低注射率。适当提高黏度可加强对液相的锁固，减少相分离，提升注射率与均匀性。液相通过粉末网络所需要的压力 $P_{PS}$ 与液相黏度成正比(式(2))[34]，高黏度意味着相分离更难发生，材料的均匀性更强，因此注射率更高。

基于这一原理，不少研究通过提高液相黏度来增强可注射材料体系的注射率。以磷酸钙骨水泥为例，Liu 等[44]通过引入纤维素醚来改善磷酸钙骨水泥的可注射性，且液相黏度越高，对注射率的促进效果越好(图 3(a))。Alves 等[35]在磷酸钙骨水泥中引入不同浓度的羧甲基纤维素、琼脂聚合物及海藻酸钠来提高液相黏度，结果表明所有复合骨水泥体系的注射率相较于低液相黏度的对照组都得到显著改善。此外，该团队[45]在磷酸钙骨水泥中加入不同类型的淀粉，发现引入淀粉显著改善了磷酸钙骨水泥体系的注射率、抗溃散能力及固化后的力学强度。

然而，随着液相黏度的进一步升高，其对材料体系可注射性的影响会进入不同阶段。此时，虽然材料体系在注射过程中保持较好的均匀性，但体系内部不同组分间的摩擦力升高，导致材料体系流动

性变差, 与注射器壁的摩擦也会升高, 增大了注射力, 反而降低了可注射性。以药物注射的相关研究为例, Wu 等[46]使用聚乙烯醇、羧甲基纤维素等物质进行注射实验, 发现过高的液相黏度会导致注射力增加和可注射性变差(图 3(b))。综上所述, 液相黏度对无机材料可注射性的影响不是单一的, 必须将其控制在合理范围内以确保材料体系具备所需的可注射性。

### 1.2.3　物理化学反应

固相与液相之间存在物理化学反应的无机材料或无机复合材料体系, 尤其是具有自固化行为的体系(如硫酸钙、磷酸钙骨水泥及交联固化水凝胶等), 反应后其黏度或屈服应力会急剧上升, 进而丧失流动性和可注射性。这类可注射无机材料临床使用时往往需要经过混合、注射(进入体内)及固化三个步骤。在注射期, 混合后的材料需保持良好的流动性以便从注射器中顺利推出; 而当注射完成后, 则需要其在体内尽快完成固化, 形成固定形状或结构。此类材料的反应启动方式可分为自发反应和非自发反应。自发反应(例如磷酸钙、硫酸钙骨水泥)从粉体和液剂混合时开始, 一直到固化完成时结束, 因此需要在反应进程中确定一个能够满足临床注射操作时间需求的窗口期(如微创手术中植入体内的操作时间)。Khairoun 等[47]将此窗口期称为“面团期”(如磷酸钙骨水泥像面团一样容易塑形), 也有临床医生称为“拉丝期”(如磷酸钙骨水泥在手指间搓揉出现拉丝现象)。研究显示在磷酸钙骨水泥中加入缓凝剂可延长“面团期”或“拉丝期”, 从而有更长的时间来适配不同手术使用场景[48]。Şahin 等[49]在磷酸钙骨水泥中引入柠檬酸, 其吸附在 $\alpha$-TCP 晶体及磷灰石晶核上可抑制晶核的形成及生长, 从而延长“面团期”(磷酸钙骨水泥的流变性质随时间变化如图 3(c)所示)。此外, 材料体系中的颗粒尺寸、结晶度、温度及液固比等都可以影响磷酸钙骨水泥的“面团期”或“拉丝期”[50]。

与自固化反应不同, 非自发反应是指依赖外媒或外场刺激触发的固化或者相变反应, 例如复合温敏性或光固化性水凝胶的无机材料体系, 其在温度变化及光源的影响下发生凝胶化反应。注射前, 这类无机复合材料体系呈现低黏度、高流动性的溶胶

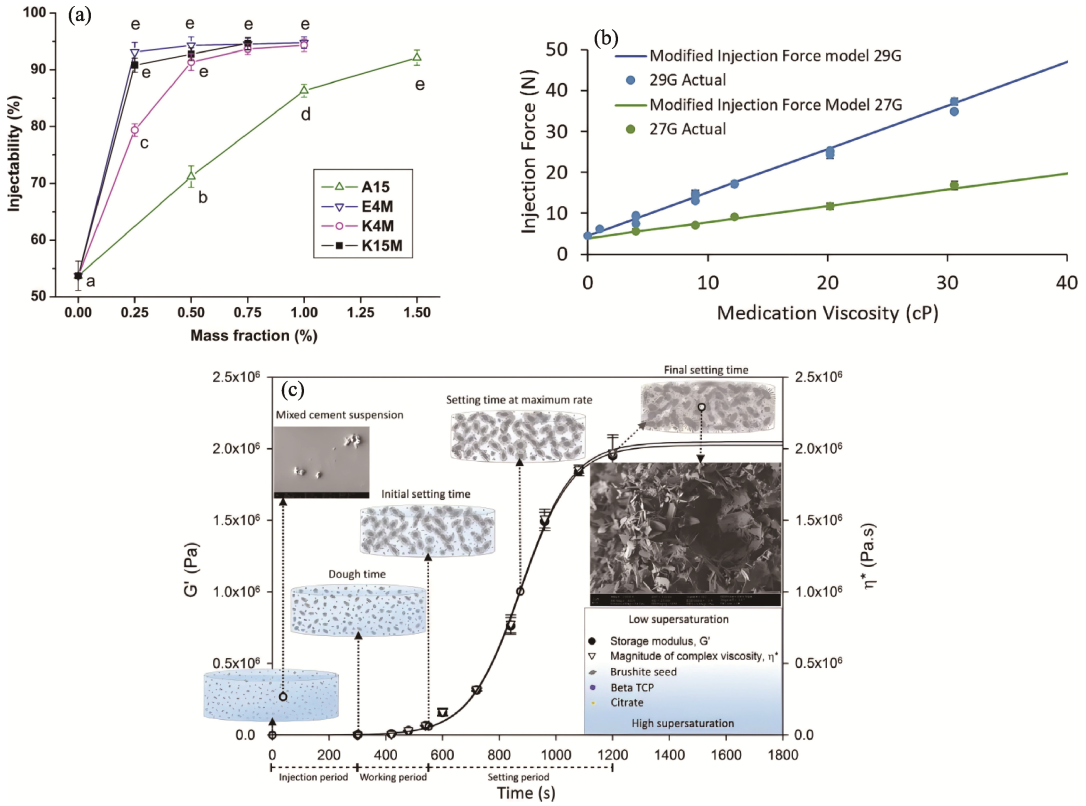


图 3　液相黏度对无机材料可注射性的影响及磷酸钙骨水泥在固化过程中的流变学行为[44, 46, 49]

Fig. 3　Effect of liquid-phase viscosity on the injectability of inorganic materials and the rheological behavior of calcium phosphate bone cement during setting[44, 46, 49]

(a) Injectability of calcium phosphate bone cement with different cellulose ether composites (A15, E4M, K4M, and K15M represent different grades of cellulose ether, with the viscosity relationship of A15 < E4M = K4M < K15M)[44]; (b) Injection force of solutions with varying viscosities in 27G and 29G-1 mL syringes[46]; (c) Schematic of calcium phosphate bone cement setting kinetics and linear viscoelastic properties over time[49]

状态，可注射性高；注射后，通过施加特定的外媒或外场刺激(如温度、紫外光灯)，触发其快速发生原位溶胶-凝胶转变，并迅速实现原位固化，完成对生物组织缺损部位的填充或结构支撑[51]。非自发反应的材料体系由于具有分离的可注射阶段和固化阶段，临床适配性很强，但需要复合特定的响应性材料和外媒或外场刺激，这对实际应用提出了额外条件甚至产生限制。

综上，构建一个理想的可注射无机材料体系需要考虑多重因素。既需要平衡颗粒性质和液相黏度等因素来设计具有良好流变学特性的体系，也需要考虑材料体系的反应动力学，从而为临床操作提供一个安全及可预测的窗口期，最终为病人带来更好的治疗效果。

## 2 可注射无机材料在生物医学领域的应用

### 2.1 硬组织修复

在骨科与口腔修复领域，基于磷酸钙骨水泥、硫酸钙骨水泥、高可塑性生物陶瓷-高分子复合材料等可注射无机材料的微创技术可显著减少开放式手术造成的组织创伤、降低术后并发症发生率，并实现不规则组织损伤部位的结构填充与功能重建，促进硬组织修复再生[52-53]。

可注射无机材料体系的设计需要适配具体临床术式和治疗需求。例如，在治疗骨质疏松性椎体压缩性骨折中，植入材料需要能够通过微创器械注射至椎体填充部位，以恢复塌陷组织的力学支撑，并原位诱导新骨形成(图 4(a~e))[54-55]。在口腔牙槽骨的保护与再生中，植入材料需具有优异的促骨形成能力，抵抗牙槽骨的吸收与萎缩。相关研究表明，复合使用磷酸钙骨水泥与生物活性玻璃可以修复成年小型猪牙槽骨缺损，术后 12 周，新生骨可以完全替代骨水泥实现再生(图 4(f, g))[56]。而在慢性骨髓炎等感染性骨缺损治疗中，则需要材料提供持续的抗菌功能，建议使用具有抗生素缓释能力的可注射无机材料。例如在一项儿童足跟组织缺损合并创伤性跟骨骨髓炎治疗中，植入载抗菌药物硫酸钙的修复材料有效减轻了患儿疼痛，抑制炎症反应，并促进术后康复和骨愈合(图 4(h))[57]。而在口腔科的根管治疗中，使用以氢氧化钙为主要成分的糊剂可创造高碱性环境(pH 12.5)，破坏微生物细胞膜[58]。

研究表明，微创植入材料的降解速率需匹配骨代谢及其生成速率[59]。因此，对于降解过快的无机材料，常通过与生物惰性或降解速度较慢的材料复合来控制其降解速度(如将降解过快的硫酸钙与降解较慢的磷酸钙复合)[60]；而对于降解速度过慢的材料，则通过引入可降解聚合物或增大材料孔隙率的方法来调节其组织长入速度(如在 $\beta$-TCP 支架中制造孔隙来加速降解)[61]。

此外，无机材料还能作为多功能集成平台用于硬组织修复。Fan 等[62]使用硼酸盐生物活性玻璃复合磁热纳米粒子构建了一种可注射的磁热生物活性系统用于骨肉瘤的治疗，其中生物活性玻璃降解产生的离子及碱性环境可以激活 TNF 信号通路，抑制骨肉瘤细胞的生长并降低骨肉瘤细胞的高温耐受性，配合磁热疗法促使骨肉瘤细胞死亡。

目前，可注射无机材料在骨科及牙科领域已经衍生了众多临床产品，如表 1 所示[63-74]。

### 2.2 肿瘤治疗

在肿瘤治疗领域，可注射无机材料可作为局部化疗药物载体实现精准的靶向给药，并结合自身的光热协同效应增强疗效。例如，介孔二氧化硅纳米粒子[75-76]和氧化石墨烯[77]等具有大比表面积的无机纳米材料可在负载化疗药物后直接注射至肿瘤部位持续释放药物，显著提高肿瘤局部药物浓度，在增强抗肿瘤效果的同时有效降低全身毒性反应[78]。Du 等[79]通过将多种蛋白质(EGFP、mAbH3 和 DNase I)包裹在二氧化硅纳米胶(BSNPs)内，并在胶囊表面修饰不同的核定位信号肽(NLS)，精准定位肿瘤细胞核，原位释放的蛋白药物水解细胞核内的 DNA，抑制小鼠肿瘤生长。

无机纳米粒子在光热治疗应用领域主要被用作光热转化剂(如过渡金属硫元素、氧化物及氧化石墨烯等碳基材料)及纳米光敏剂(如二氧化钛及氧化锌等)等[80]。Liu 等[81]在纳米氧化石墨烯(NGO)上负载金纳米粒子(AuNPs)(用于增强光热转化效果)，并通过修饰巯基聚乙二醇叶酸(SH-PEG1000-FA)提高了靶向能力。在该载体上负载光敏剂亚甲基蓝(MB)或抗癌药物 5-氟尿嘧啶(5-Fu)，制备出两种光热-光动力(NGO-AuNPs-FA/MB)及光热-化疗(NGO-AuNPs-FA/5-Fu)协同作用的治疗平台，可用于靶向药物的传递及癌症的局部治疗(图 5(a, b))。Sun 等[82]开发了一种多功能治疗纳米材料组件，可以在肿瘤环境中原位生成硫化铜纳米点，并在近红外二区(NIR-Ⅱ)的照射下对结直肠癌进行特异性治疗。除光热治疗外，研究人员还使用可注射的磁热制剂进行磁热治疗。其核心机制是磁性纳米粒子(MNPs)可在交变

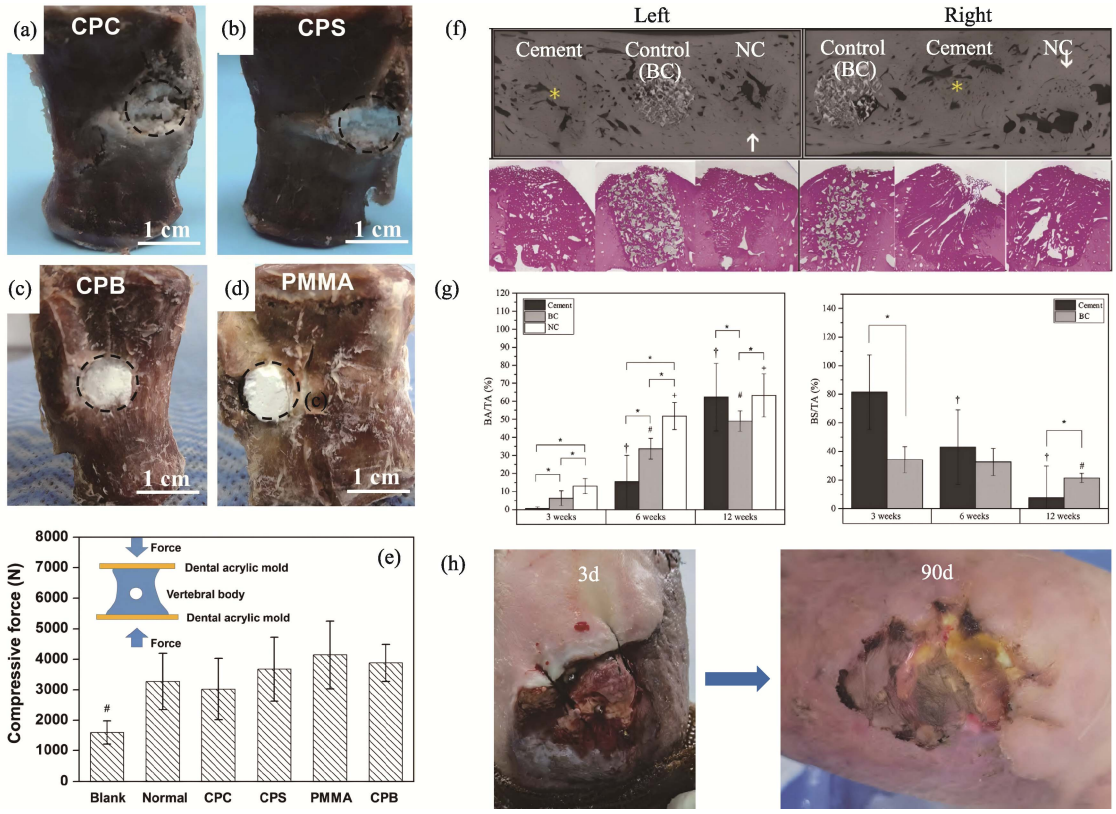


图 4　可注射无机材料在骨及口腔修复中的应用[55-57]

Fig. 4　Applications of injectable inorganic materials in orthopedics and dentistry[55-57]

(a-d) Filling of sheep vertebrae with different bone cements (CPC is calcium phosphate bone cement, CPS is a composite bone cement of CPC and starch, CPB is a composite bone cement of CPS and barium sulfate, and PMMA is polymethyl methacrylate bone cement)[55]; (e) Compressive strength of a complete vertebra and vertebrae filled with different bone cements[55]; (f) XMT axial view of the 12 weeks mandibular specimen (top) and corresponding buccal-lingual section histological images (down)[56]; (g) Percentage of bone area to tissue area (BA/TA) at different time points (left), and the percentage of bone substitute to tissue area (BS/TA) (right)[56]; (h) Recovery of the affected area in a pediatric patient after combined treatment with a rational skin flap repair and absorbable calcium sulfate load-bearing medication[57]

**表 1　骨科及口腔科硬组织修复领域中的可注射无机材料产品示例[63-74]**

**Table 1　Examples of injectable inorganic materials for hard tissue repair in orthopedics and dentistry[63-74]**

| Product | Major component | Application |
|---|---|---|
| Self-setting calcium phosphate cement (Rebone)[63] | Calcium phosphate | Non-load-bearing bone filling and root canal filling |
| HydroSet (Stryker)[64] | Calcium phosphate | Cranial defect filling |
| Pro-Dense (Stryker)[65] | Calcium phosphate, calcium sulfate | Bone defect filling and repair |
| AlloMatrix (Stryker)[66] | Demineralized bone matrix, calcium sulfate | Bone defect filling and repair |
| DBX®Putty (DePuy Synthes)[67] | Demineralized bone matrix | Bone defect filling and repair |
| Drillable bone void filler (DePuy Synthes)[68] | Calcium phosphate | Bone defect filling and repair |
| FIBERGRAFT™ Bioactive glass (DePuy Synthes)[69] | 45S5 bioactive glass | Bone graft substitute |
| Calcium sulfate bone substitute (R&L Medical)[70] | Calcium sulfate | Bone defect filling and repair |
| Inductigraft (Baxter)[71] | Calcium phosphate, silicate | Bone graft substitute |
| Bone graft material-boneswift (Medgen Life Sciences)[72] | Hydroxyapatite | Filling of orthopedic trauma and non-structural spinal defects |
| Vitapex (Morita)[73] | Calcium hydroxide | Root canal filling |
| KP-Root SP (Kevin Peter)[74] | Zirconia, silicate, calcium phosphate, calcium hydroxide | Root canal filling |

磁场的作用下产生热量，杀伤肿瘤细胞，达到治疗效果。Jang 等[83]通过将 Mg 掺杂到 $\gamma$-$Fe_2O_3$ 超顺磁纳米颗粒中，制得可注射 $Mg_{0.13}$-$\gamma$-$Fe_2O_3$，其固有损耗功率约为传统商用 $Fe_3O_4$ 的 100 倍。在外加交流磁场下，$Mg_{0.13}$-$\gamma$-$Fe_2O_3$ 表现出卓越的磁热转换能力，有效消除了肿瘤(图 5(c~e))。

无机材料除了通过药物递送或光热及磁热效应直接杀伤肿瘤细胞之外，还可以作为栓塞剂用于肿瘤治疗，即通过导管动脉灌注将无机材料注入肿瘤的供血动脉中，阻塞血管腔，切断肿瘤组织的供给，从而诱导组织坏死。无机纳米材料与传统的栓塞材料(聚乙烯醇(PVA)等)相比，其优势在于纳米尺度与显影性。纳米尺度的材料可以到达并阻塞更末梢的微血管，实现更彻底的栓塞，从而有效防止建立侧支循环。例如，由二氧化硅填充颗粒、三氧化二铋与聚二甲基硅氧烷复合而成的 NeoCast，经微导管注射后，展现出卓越的远端血管穿透性，实现了持久且彻底的血管闭塞(图 5(f))[84]。同时无机栓塞剂材料带来的成像能力，可使医生能够更精准地定位治疗区域，以获得更好的治疗效果。例如，氧化铁纳米颗粒在栓塞的同时可作为磁共振成像(MRI)对比剂，实时监控治疗过程[85-86]。这种将栓塞功能与显影等附加能力一体化的材料设计，彰显了无机纳米材料在提升肿瘤栓塞治疗方面的潜力。

## 2.3 医学成像与诊断

可注射无机材料在成像与诊断领域的应用主要是通过微创注射的方式将其作为造影剂或者监测器件递送至目标区域，实现监测。以显影剂为例，研究人员使用超顺磁性氧化铁纳米材料(SPIO)、聚乙二醇(PEG)复合抗表皮生长因子受体(EGFR)单克隆抗体制备的纳米粒子系统可以显著增强 MRI 的灵敏度，监测大鼠模型中 EGFR 表达过的肺癌细胞[87]。此外，一些含有高原子序数元素[88-89](例如钡、碘等)的无机材料，可以与周围组织形成高对比度，配合计算机断层扫描(CT)和超声成像来进行监测。例如碘造影剂常被用于心血管疾病的诊断，含碘造影剂经静脉注射后，随血液流经心脏腔室及血管，在 X 光或 CT 下能够呈现出清晰的高密度影像，将被检测区域可视化，从而实现监测诊断。在生物材料中直接添加造影剂，能赋予材料可视性，实现术中定位和术后监测。本团队[90]在磷酸钙骨水泥中加入硫酸钡，制备出的骨水泥材料在 X 光下能够清晰显影，为医生在手术过程中提供了实时影像反馈。此外，本团队还针对硫酸钡难以降解，在植入部位产生占位及破骨效应而影响骨修复进程的问题，开发了新型多聚磷酸锶显影剂以代替硫酸钡[91]。研究结果表明，引入多聚磷酸锶不仅赋予磷酸钙骨水泥良好的显影性以确保材料可视化，而且相较于硫酸钡表现

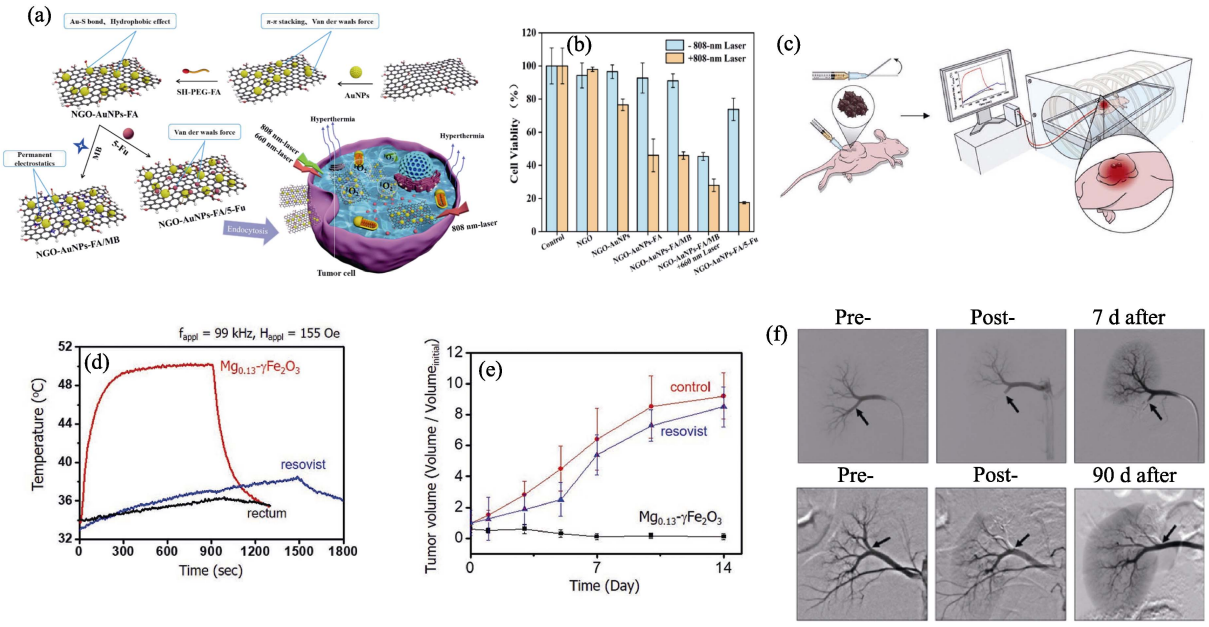


图 5 可注射无机材料在肿瘤治疗中的应用[81, 83-84]

Fig. 5 Applications of injectable inorganic materials in tumor therapy[81, 83-84]

(a) Schematic of the preparation process and synergistic therapy for NGO-AuNPs-FA/MB and NGO-AuNPs-FA/5-Fu[81]; (b) Viability of HeLa cells with or without near-infrared (NIR) irradiation[81]; (c) Magnetic hyperthermia of tumors using $Mg_{0.13}$-$\gamma$-$Fe_2O_3$[83]; (d) Temperature-rise profiles under different treatments[83]; (e) Relative tumor volumes under different treatments[83]; (f) Embolization performance of the NeoCast embolic agent in porcine renal vasculature after 7 and 90 d[84]

出更优的促成骨及抑制破骨的性能, 促进了更高质量的新骨再生。同时将传统的“显影”升级为“显影-生物活性调控”一体化, 解决了传统惰性显影剂与骨再生目标不匹配的难题。

除了显影剂之外, 通过将具有监测功能的器件注射到目标区域也可以实现诊断与监测。例如, 将羟基石墨烯(GOH)复合 PVA 及多糖生物聚合物制备的水凝胶器件(Alg-PBA/PVA/GOH), 可以基于电信号的变化监测细菌及手部运动(图 6(a~e))[92]。此外, 使用 NdFeB@$SiO_2$ 永磁微粒与 PVA/海藻酸钠构建互穿网络, 制备的磁性水凝胶器件(MagLabel-IH)具有持久剩磁(图 6(f, g)), 可在胃肠道肿瘤术前通过内镜进行黏膜下注射, 并在术中配合电磁传感阵列与电磁探针使用, 对肉眼难以看见的腔内肿瘤进行毫米级实时定位、切缘标定与重建规划[93]。

## 2.4　皮肤与整形修复

皮肤作为人体外部环境和内部稳态间的重要屏障, 其再生修复能力极易受到内外因素干扰, 进而引发衰老及一系列问题。同时, 由组织畸形或创伤导致的组织缺损, 不仅会损害患者外观, 更会影响患者心理健康及自我感知。

生物活性玻璃凭借其微创注射、功能离子缓释等性质, 在皮肤修复领域展现出一定潜力。其不仅能够作为支架促进细胞的迁移及组织再生, 还能通过释放 Ca[94]、Si[95]、Mg[96]及 Zn[97]等离子, 发挥抗菌及调控血管生成的作用, 尤其在复杂创面(例如糖尿病伤口、烫伤伤口)的修复中表现优异。例如, 使用掺 Mg 的生物活性玻璃与小细胞外囊泡(sEVs)组成的包囊簇(EPPM)复合水凝胶系统(EPPMO), 能够实现对 sEVs 及 $Mg^{2+}$的靶向递送, 增加 sEVs 在细胞中的摄取, 并促进巨噬细胞的 M2 型极化、抑制炎症反应以及促血管生成, 从而加速糖尿病伤口的愈合(图 7(a))[98]。此外, 基于金纳米颗粒, 负载白细胞介素-4(IL-4)并辅以肌成纤维细胞膜制备出的仿生可注射纳米平台, 具备抗菌、免疫微环境调控及组织再生诱导的功能, 能够加速难治性皮肤创面愈合进程并优化组织重塑的质量[99]。

在医疗美容领域, 可注射皮肤填充剂因其较小的皮肤损伤和即时的填充效果, 被应用于面部褶皱填充、软组织缺损修复、面部及下颌部增大、鼻修复和非对称面部畸形矫正等整形外科手术。其中, 以羟基磷灰石注射制剂为代表的可注射无机填充剂已成为可注射医美材料领域的重要组成部分。此类填充材料以羟基磷灰石微球为主要成分, 交联透明质酸钠凝胶或羧甲基纤维素钠等为流体介质, 辅以磷酸盐缓冲溶液或甘油改善其可注射性, 并通过添加少量药物(如盐酸利多卡因等)降低注射后的局部组织反应, 从而实现对面部的填充整形(图 7(b))[100-102]。目前, 临床产品所使用的羟基磷灰石主要是粒径分布在 25~45 μm 范围的规则形貌微球(图 7(c))[103]。这种粒径设计旨在提供理想的填充效果, 同时能够在局部刺激成纤维细胞合成 I 型和 III 型胶原蛋白, 实现长期的局部组织重塑(图 7(d~f))[104]。国际美容整形外科学会(International

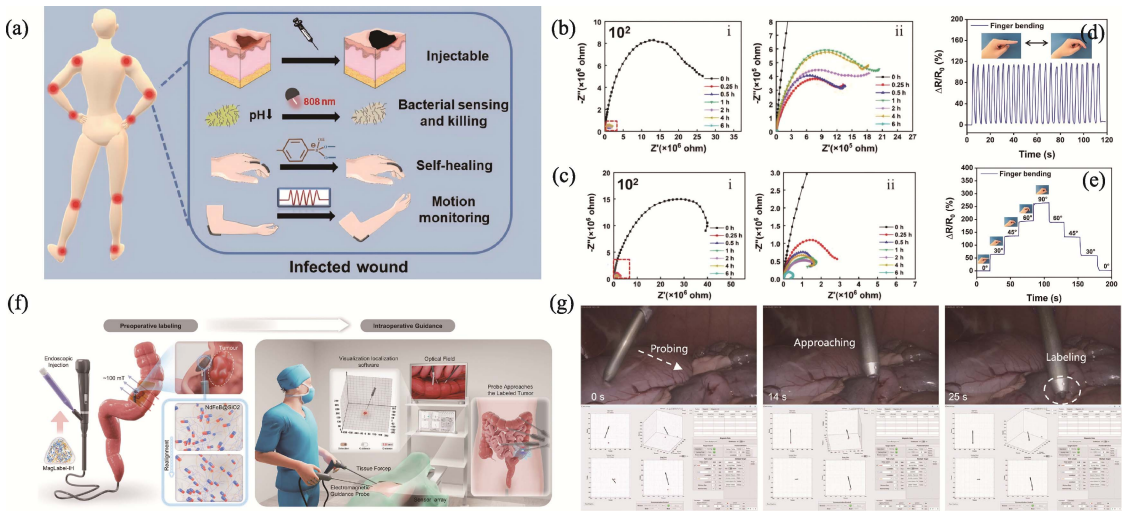


图 6　可注射无机材料在医学监测和诊断中的应用[92-93]

Fig. 6　Applications of injectable inorganic materials in medical sensing and diagnostics[92-93]

(a) Schematic illustration of the functions of the Alg-PBA/PVA/GOH hydrogel[92]; (b, c) Impedance spectra of Alg-PBA/PVA/GOH hydrogel after incubation with *E. coli* (b) and *S. aureus* (c) suspensions for different times[92]; (d, e) Alg-PBA/PVA/GOH hydrogel monitoring human finger bending (d) and index finger bending from 0° to 90° (e)[92]; (f) Surgical electromagnetic localization of intraluminal gastrointestinal neoplasms using MagLabel-IH[93]; (g) Electromagnetic guidance probe used to gradually approach the tumor site labeled with MagLabel-IH, and ultimately mark the intestinal segment containing the tumor during laparoscopic procedure in rabbits[93]

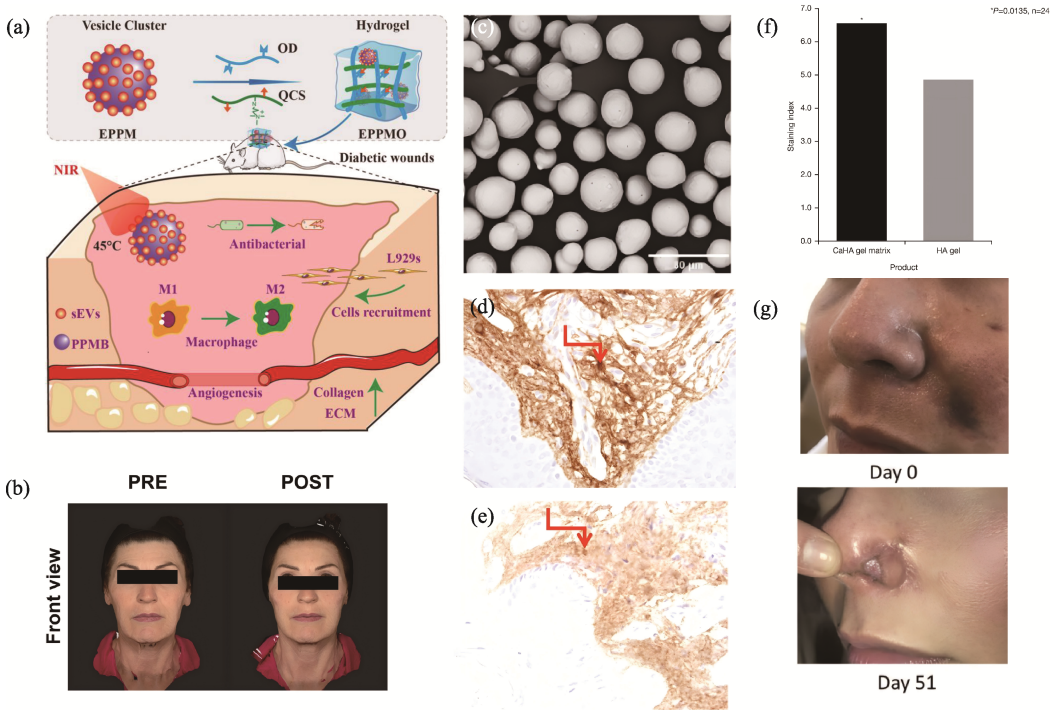


图 7 可注射无机材料在皮肤修复及面部填充中的应用[98, 102-104, 107]

Fig. 7 Applications of injectable inorganic materials in skin repair and facial filling[98, 102-104, 107]

(a) Schematic diagram of the preparation process of EPPMO hydrogel[98]; (b) Before-and-after comparison using a calcium hydroxylapatite facial filler[102]; (c) Calcium hydroxylapatite microspheres[103]; (d, e) Type I collagen staining 9 months after treatment with calcium hydroxylapatite filler (d) and hyaluronic acid gel (e)[104]; (f) Intensity of type I collagen staining 9 months after treatment with calcium hydroxylapatite filler or hyaluronic acid gel[104]; (g) Facial artery embolization with ischemia of the nasal ala following injection of calcium hydroxylapatite filler in the nasolabial fold near the pyriform aperture[107]

Society of Aesthetic Plastic Surgery, ISAPS)的数据显示，全球羟基磷灰石注射填充产品使用量年均复合增长率达 16%，展现出广阔的市场前景。

尽管羟基磷灰石在硬组织填充和修复中的生物安全性已得到了充分验证[105]，但其在医学美容领域的临床安全仍存在争议。如前文所述，羟基磷灰石类注射填充材料对微球的形貌和粒径有明确要求，以降低填充材料对注射部位组织的刺激[106]。同时，目前羟基磷灰石类注射填充材料仅被允许注射至真皮深层或皮下部位，不可注射至浅层皮肤、眼周、口周和血管中，以避免造成局部炎症反应、视力损伤、栓塞等灾难性后果。但即便存在上述约束条件，临床使用中依然存在由羟基磷灰石填充剂引起的局部红肿、结节、增生和蜂窝组织炎等不良反应的案例(图 7(g))[107]。因此，国内监管部门一直对羟基磷灰石类可注射填充材料的审批和引进保持谨慎态度，直到 2025 年才批准相关产品引进到医美领域。

## 3 挑战与展望

本文系统回顾了可注射无机材料的研究进展及其在生物医学领域的应用，介绍了材料可注射性的概念、调控因素及其在骨科、口腔科、肿瘤、医学成像、皮肤与整形等多个领域的应用研究前沿。然而，可注射无机材料的研究虽然取得了很多进展，但将前沿技术转化为安全有效的临床产品仍面临一系列重大挑战。首先，可注射材料的性能需与复杂临床需求精准匹配。这涉及可注射性、力学性能、降解性及长期生物安全性等多种性能的协同调控。材料的可注射性要满足不同临床治疗的多样性，而植入后其力学性能又需要满足基本的力学支撑并动态匹配组织再生的过程。其降解速率需匹配新生组织的再生速率，实现二者同步。在生物安全性方面，不仅要确保材料及降解产物的无毒性，还要关注其长期植入后与神经、血管及其它组织的整合情况。其次，材料的智能化与集成化设计。未来材料应从单一功能的被动响应转变为能根据病变部位的特定微环境(pH、温度、酶表达及活性氧水平等)进行特定响应，在时间和空间上实现材料性能的动态精准调控，从而获得更好的组织修复效果。

未来可注射无机材料的发展关键在于深化跨学科交叉融合并加速转化医学研发进程。例如，整合材料组分设计与 3D 打印、基因工程、人工智能等先进技术，有望构建新一代材料设计和治疗技术体

系。但是，这一系列的材料与技术都要经过临床试验乃至长期检验才能够惠及患者，更需要加强产-学-研-医的深度融合，同时推动材料制备工艺的标准化与规模化，建立可靠的评价模型和临床验证方法，最终加速可注射无机材料产品的落地，服务人民生命健康。

## 参考文献:


[1] LI N Y, WANG J Y, FENG G X, *et al*. Advances in biomaterials for oral-maxillofacial bone regeneration: spotlight on periodontal and alveolar bone strategies. *Regenerative Biomaterials*, 2024, **11:** rbae078.

[2] LU G H, ZHAO G, WANG S, *et al*. Injectable nano-micro composites with anti-bacterial and osteogenic capabilities for minimally invasive treatment of osteomyelitis. *Advanced Science*, 2024, **11(12):** 2306964.

[3] MOFARRAH M, JAFARI-GHARABAGHLOU D, FARHOUDI-SEFIDAN-JADID M, *et al*. Potential application of inorganic nano-materials in modulation of macrophage function: possible application in bone tissue engineering. *Heliyon*, 2023, **9(6):** e16309.

[4] VOLPONI A A, ZAUGG L K, NEVES V, *et al*. Tooth repair and regeneration. *Current Oral Health Reports*, 2018, **5(4):** 295.

[5] ALMULHIM K S, SYED M R, ALQAHTANI N, *et al*. Bioactive inorganic materials for dental applications: a narrative review. *Materials*, 2022, **15(19):** 6864.

[6] MA J G, WU C T. Bioactive inorganic particles-based biomaterials for skin tissue engineering. *Exploration*, 2022, **2(5):** 20210083.

[7] LUO X M, QIAO Z H, LIU Y, *et al*. Inorganic bioactive materials regulating myocardial regeneration. *Journal of Inorganic Materials*, 2025, **40(8):** 871.

[8] SUHAG D. Handbook of biomaterials for medical applications, Volume 2. Singapore: Springer Nature, 2024**:** 105–139.

[9] HAN F, LIU Z, WEI Q, *et al*. Minimally invasive implantable biomaterials for bone reconstruction. *Engineering*, 2025, **46:** 23.

[10] NGUYEN M, KARKANITSA M, CHRISTMAN K L. Design and translation of injectable biomaterials. *Nature Reviews Bioengineering*, 2024, **2(10):** 810.

[11] SCARDUA N, ROVARIS D P, MOREIRA K M S, *et al*. Supraperiosteal technique protocol for forehead filling with a mixture of calcium hydroxyapatite and hyaluronic acid: double-blind, randomized controlled clinical trial. *Journal of Cosmetic Dermatology*, 2024, **23(12):** 4116.

[12] ZERBINATI N, RAUSO R, GONZALEZ P, *et al*. *In vitro* evaluation of collagen production on human fibroblasts treated with hyaluronic acid peg cross-linked with micromolecules of calcium hydroxyapatite in low concentration. *Journal of Biological Regulators and Homeostatic Agents*, 2017, **31(2 Suppl. 2):** 87.

[13] LI C, WANG J C, WANG Y G, *et al*. Recent progress in drug delivery. *Acta Pharmaceutica Sinica B*, 2019, **9(6):** 1145.

[14] KHAN M, ONG Z Y, WIRADHARMA N, *et al*. Advanced materials for co-delivery of drugs and genes in cancer therapy. *Advanced Healthcare Materials*, 2012, **1(4):** 373.

[15] CHENG Z S, QUE H Y, CHEN L, *et al*. Nanomaterial-based drug delivery system targeting lymph nodes. *Pharmaceutics*, 2022, **14(7):** 1372.

[16] TANG C Y, ZHOU K X, WU D, *et al*. Nanoparticles as a novel platform for cardiovascular disease diagnosis and therapy. *International Journal of Nanomedicine*, 2024, **19:** 8831.

[17] XU H H, WANG P, WANG L, *et al*. Calcium phosphate cements for bone engineering and their biological properties. *Bone Research*, 2017, **5(1):** 17056.

[18] FATHI M, KHOLTEI A, YOUBI S E, *et al*. Setting properties of calcium phosphate bone cement. *Materials Today: Proceedings*, 2019, **13:** 876.

[19] SHARMA A, KOKIL G R, HE Y, *et al*. Inorganic/organic combination: inorganic particles/polymer composites for tissue engineering applications. *Bioactive Materials*, 2023, **24:** 535.

[20] HOUAOUI A, SZCZODRA A, LALLUKKA M, *et al*. New generation of hybrid materials based on gelatin and bioactive glass particles for bone tissue regeneration. *Biomolecules*, 2021, **11(3):** 444.

[21] OSADA N, TERADA A, MAEDA H, *et al*. Tuning of ion-release capability from bio-ceramic-polymer composites for enhancing cellular activity. *Royal Society Open Science*, 2019, **6(9):** 190612.

[22] MÎRȚ A L, FICAI D, OPREA O C, *et al*. Current and future perspectives of bioactive glasses as injectable material. *Nanomaterials*, 2024, **14(14):** 1196.

[23] ABBASI R, SHINEH G, MOBARAKI M, *et al*. Structural parameters of nanoparticles affecting their toxicity for biomedical applications: a review. *Journal of Nanoparticle Research*, 2023, **25(3):** 43.

[24] YI G, HONG S H, SON J, *et al*. Recent advances in nanoparticle carriers for photodynamic therapy. *Quantitative Imaging in Medicine and Surgery*, 2018, **8(4):** 433.

[25] HUANG K W, HSU F F, QIU J T, *et al*. Highly efficient and tumor-selective nanoparticles for dual-targeted immunogene therapy against cancer. *Science Advances*, 2020, **6(3):** eaax5032.

[26] GAO J J, XIA Z T, GUNASEKAR S, *et al*. Precision drug delivery to the central nervous system using engineered nanoparticles. *Nature Reviews Materials*, 2024, **9(8):** 567.

[27] WEI H P, CUI J J, LIN K L, *et al*. Recent advances in smart stimuli-responsive biomaterials for bone therapeutics and regeneration. *Bone Research*, 2022, **10(1):** 17.

[28] ZHANG Y G, HABIBOVIC P. Delivering mechanical stimulation to cells: state of the art in materials and devices design. *Advanced Materials*, 2022, **34(32):** 2110267.

[29] BOHNER M, BAROUD G. Injectability of calcium phosphate pastes. *Biomaterials*, 2005, **26(13):** 1553.

[30] HABIB M, BAROUD G, GITZHOFER F, *et al*. Mechanisms underlying the limited injectability of hydraulic calcium phosphate paste. *Acta Biomaterialia*, 2008, **4(5):** 1465.

[31] O'NEILL R, MCCARTHY H O, CUNNINGHAM E, *et al*. Extent and mechanism of phase separation during the extrusion of calcium phosphate pastes. *Journal of Materials Science: Materials in Medicine*, 2016, **27(2):** 29.

[32] MONTUFAR E B, MAAZOUZ Y, GINEBRA M P. Relevance of the setting reaction to the injectability of tricalcium phosphate pastes. *Acta Biomaterialia*, 2013, **9(4):** 6188.

[33] ROBINSON T E, HUGHES E A B, BOSE A, *et al*. Filling the gap: a correlation between objective and subjective measures of injectability. *Advanced Healthcare Materials*, 2020, **9(5):** 1901521.

[34] O'NEILL R, MCCARTHY H O, MONTUFAR E B, *et al*. Critical review: injectability of calcium phosphate pastes and cements. *Acta Biomaterialia*, 2017, **50:** 1.

[35] ALVES H L R, DOS SANTOS L A, BERGMANN C P. Injectability evaluation of tricalcium phosphate bone cement. *Journal of Materials Science: Materials in Medicine*, 2008, **19(5):** 2241.

[36] KALYON D M, AKTAŞ S. Factors affecting the rheology and processability of highly filled suspensions. *Annual Review of*

*Chemical and Biomolecular Engineering*, 2014, **5:** 229.
[37] OUCHIYAMA N, TANAKA T. Porosity of a mass of solid particles having a range of sizes. *Industrial & Engineering Chemistry Fundamentals*, 1981, **20(1):** 66.
[38] FISKE T J, RAILKAR S B, KALYON D M. Effects of segregation on the packing of spherical and nonspherical particles. *Powder Technology*, 1994, **81(1):** 57.
[39] MCGEARY R K. Mechanical packing of spherical particles. *Journal of the American Ceramic Society*, 1961, **44(10):** 513.
[40] TADIER S, GALEA L, CHARBONNIER B, *et al*. Phase and size separations occurring during the injection of model pastes composed of *β*-tricalcium phosphate powder, glass beads and aqueous solutions. *Acta Biomaterialia*, 2014, **10(5):** 2259.
[41] JACK V, BUCHANAN F J, DUNNE N J. Particle attrition of *α*-tricalcium phosphate: effect on mechanical, handling, and injectability properties of calcium phosphate cements. *Proceedings of the Institution of Mechanical Engineers Part H: Journal of Engineering in Medicine*, 2008, **222(1):** 19.
[42] ISHIKAWA K. Effects of spherical tetracalcium phosphate on injectability and basic properties of apatitic cement. *Key Engineering Materials*, 2003, **240/241/242:** 369.
[43] RUBIO-HERNÁNDEZ F J, CEREZO-AIZPÚN I, VELÁZQUEZ-AVARRO J F. Mineral additives geometry influence in cement pastes flow. *Advances in Cement Research*, 2011, **23(2):** 55.
[44] LIU W Z, ZHANG J T, WEISS P, *et al*. The influence of different cellulose ethers on both the handling and mechanical properties of calcium phosphate cements for bone substitution. *Acta Biomaterialia*, 2013, **9(3):** 5740.
[45] LIU H L, GUAN Y, WEI D L, *et al*. Reinforcement of injectable calcium phosphate cement by gelatinized starches. *Journal of Biomedical Materials Research Part B: Applied Biomaterials*, 2016, **104(3):** 615.
[46] WU L K, LI H, WANG Y Y, *et al*. Advancing injection force modeling and viscosity-dependent injectability evaluation for prefilled syringes. *European Journal of Pharmaceutics and Biopharmaceutics*, 2024, **197:** 114221.
[47] KHAIROUN I, BOLTONG M G, DRIESSENS F C, *et al*. Some factors controlling the injectability of calcium phosphate bone cements. *Journal of Materials Science: Materials in Medicine*, 1998, **9(8):** 425.
[48] DESPAS C, SCHNITZLER V, JANVIER P, *et al*. High-frequency impedance measurement as a relevant tool for monitoring the apatitic cement setting reaction. *Acta Biomaterialia*, 2014, **10(2):** 940.
[49] ŞAHIN E, KALYON D M. The rheological behavior of a fast-setting calcium phosphate bone cement and its dependence on deformation conditions. *Journal of the Mechanical Behavior of Biomedical Materials*, 2017, **72:** 252.
[50] ZHANG J T, LIU W Z, SCHNITZLER V, *et al*. Calcium phosphate cements for bone substitution: chemistry, handling and mechanical properties. *Acta Biomaterialia*, 2014, **10(3):** 1035.
[51] MELLATI A, AKHTARI J. Injectable hydrogels: a review of injectability mechanisms and biomedical applications. *Research in Molecular Medicine*, 2018, **6(4):** 1.
[52] CHEN X, YUAN Y, TAN Y Q, *et al*. Strategic study on the development of inorganic non-metallic biomaterials. *Journal of Inorganic Materials*, 2025, **40(5):** 449.
[53] DAI H, HOSSEINPOUR S, HUA S, *et al*. Advances in porous inorganic nanomaterials for bone regeneration. *Nano TransMed*, 2022, **1(1):** e9130005.
[54] GAO C X, LIU H L, YANG H L, *et al*. Fabrication and characterization of injectable calcium phosphate-based cements for kyphoplasty. *Materials Technology*, 2015, **30(B4):** B256.
[55] LIU H L, LIU B, GAO C X, *et al*. Injectable, biomechanically robust, biodegradable and osseointegrative bone cement for percutaneous kyphoplasty and vertebroplasty. *International Orthopaedics*, 2018, **42(1):** 125.
[56] D'ONOFRIO A, HILL R G, KENT N W, *et al*. Development of a novel formulation of bioactive glass based calcium phosphate cement for bone grafting. *Advanced Functional Materials*, 2024, **34(36):** 2401953.
[57] 宋东建, 甘君龄, 苏萌, 等. 可吸收载抗菌药物硫酸钙与生物骨水泥链珠膜诱导在儿童足跟组织缺损合并创伤性跟骨骨髓炎中的效果比较. 中国合理用药探索, 2024, **21(7):** 61.
[58] BEST S, AMMONS C L, KARUNANAYAKE G A, *et al*. Outcome assessment of teeth with necrotic pulps and apical periodontitis treated with long-term calcium hydroxide. *Journal of Endodontics*, 2021, **47(1):** 11.
[59] WEI S, MA J X, XU L, *et al*. Biodegradable materials for bone defect repair. *Military Medical Research*, 2020, **7(1):** 54.
[60] LI X D, YAN D W, REN H H, *et al*. Fabricating biodegradable calcium phosphate/calcium sulfate cement reinforced with cellulose: *in vitro* and *in vivo* studies. *Journal of Materials Chemistry B*, 2023, **11(2):** 303.
[61] WANG W W, ZHOU X Q, WANG H Y, *et al*. Fabrication and evaluation of PCL/PLGA/*β*-TCP spiral-structured scaffolds for bone tissue engineering. *Bioengineering*, 2024, **11(7):** 732.
[62] FAN M K, LIU C Y, ZHANG Y Y, *et al*. A strategy for challenging tumorous bone regeneration by borosilicate bioactive glass boosting moderate magnetic hyperthermia. *Nature Communications*, 2025, **16:** 8057.
[63] 自固化磷酸人工骨-自固化磷酸钙骨水泥. [2026-01-15]. https://www.weigaoholding.com/Product/info.html?cate=48&id=269.
[64] HydroSet. [2026-01-15]. https:www.stryker.com/us/en/craniomaxillofacial/products/hydroset.html.
[65] Pro-Dense. [2026-01-15]. https://www.stryker.com/us/en/trauma-and-extremities/products/prodense.html.
[66] AlloMatrix. [2026-01-15]. https:/www.stryker.com/us/en/trauma-and-extremities/products/allomatrix.html.
[67] DBX® Demineralized Bone Matrix. [2026-01-15]. https://www.jnjmedtech.com/en-US/product/dbx-demineralized-bone-matrix-trauma.
[68] Drillable Bone Void Filler. [2026-01-15]. https://www.jnjmedtech.com/en-US/product/drillable-bone-void-filler.
[69] FIBERGRAFT™ Bioactive Glass. [2026-01-15]. https://www.jnjmedtech.com/en-US/product/fibergraft-bioactive-glass.
[70] Calcium Sulphate. [2026-01-15]. https://rnlmedical.com/product/calcium-sulphate-antibiotic-carrier/.
[71] INDUCTIGRAFT. [2026-01-15]. https://advancedsurgery.baxterhealthcare.co.uk/inductigraft.
[72] COD 医材汇. [2026-01-15]. https://mp.weixin.qq.com/s/CxeJ_POLKJSI-rTwIqnOQ.
[73] 森田 Vitapex. [2026-01-15]. https://www.yae920.com/p/goods/etails? goodsId=198.
[74] KP-Root SP. [2026-01-15]. https://kevinpetertech.com/zh/rticular?case=productDetails&id=158.
[75] LIU J L, LIU J Y, WANG Y X, *et al*. Bioactive mesoporous silica materials-assisted cancer immunotherapy. *Biomaterials*, 2025, **315:** 122919.
[76] ZHOU S, ZHONG Q, WANG Y, *et al*. Chemically engineered mesoporous silica nanoparticles-based intelligent delivery systems for theranostic applications in multiple cancerous/non-cancerous diseases. *Coordination Chemistry Reviews*, 2022, **452:** 214309.
[77] GU Z J, ZHU S, YAN L, *et al*. Graphene-based smart platforms for

combined cancer therapy. *Advanced Materials*, 2019, **31(9):** 1800662.
[78] SHI Z Q, ZHOU Y, FAN T J, *et al*. Inorganic nano-carriers based smart drug delivery systems for tumor therapy. *Smart Materials in Medicine*, 2020, **1:** 32.
[79] DU W, DU S B, DONG X, *et al*. Biodegradable silica nanocapsules enable efficient nuclear-targeted delivery of native proteins for cancer therapy. *Biomaterials*, 2023, **294:** 122000.
[80] ZHANG X, WANG S, CHENG G H, *et al*. Light-responsive nanomaterials for cancer therapy. *Engineering*, 2022, **13:** 18.
[81] LIU F, XU C F, LI J L, *et al*. Nanoarchitectonics of versatile platform based on graphene oxide for precise and enhanced synergistic cancer photothermal-photodynamic/chemotherapy. *Journal of Molecular Structure*, 2023, **1294:** 136499.
[82] SUN X X, LIANG X Y, WANG Y K, *et al*. A tumor microenvironment-activatable nanoplatform with phycocyanin-assisted *in-situ* nanoagent generation for synergistic treatment of colorectal cancer. *Biomaterials*, 2023, **301:** 122263.
[83] JANG J T, LEE J, SEON J, *et al*. Giant magnetic heat induction of magnesium-doped $\gamma$-$Fe_2O_3$ superparamagnetic nanoparticles for completely killing tumors. *Advanced Materials*, 2018, **30(6):** 1704362.
[84] PHAM Q P, GROOM II J V, SADASIVAN C, *et al*. An *in situ* curing, shear-responsive biomaterial designed for durable embolization of microvasculature. *Advanced Healthcare Materials*, 2025, **14(15):** 2404011.
[85] ZHANG D M, ZHANG J, BIAN X L, *et al*. Iron oxide nanoparticle-based $T_1$ contrast agents for magnetic resonance imaging: a review. *Nanomaterials*, 2024, **15(1):** 33.
[86] STAMPFL U, SOMMER C M, BELLEMANN N, *et al*. Multimodal visibility of a modified polyzene-F–coated spherical embolic agent for liver embolization: feasibility study in a porcine model. *Journal of Vascular and Interventional Radiology*, 2012, **23(9):** 1225.
[87] WANG Z L, QIAO R R, TANG N, *et al*. Active targeting theranostic iron oxide nanoparticles for MRI and magnetic resonance-guided focused ultrasound ablation of lung cancer. *Biomaterials*, 2017, **127:** 25.
[88] LUSIC H, GRINSTAFF M W. X-ray-computed tomography contrast agents. *Chemical Reviews*, 2013, **113(3):** 1641.
[89] HSU J C, NIEVES L M, BETZER O, *et al*. Nanoparticle contrast agents for X-ray imaging applications. *Wiley Interdisciplinary Reviews-Nanomedicine and Nanobiotechnology*, 2020, **12(6):** e1642.
[90] TIAN Y X, LIU H L, HE L W, *et al*. Calcium phosphate-based composite cement: impact of starch type and starch pregelatinization on its physicochemical properties and performance in the vertebral fracture surgical models *in vitro*. *Journal of Biomedical Materials Research Part B: Applied Biomaterials*, 2021, **109(12):** 2068.
[91] 唐子牛, 褚凤成, 吴康, 等. 兼具显影与成骨功能多聚磷酸锶在磷酸钙骨水泥中的应用. 中国组织工程研究, 2024, **28(22):** 3539.
[92] SHAN M Y, CHEN X, ZHANG X Y, *et al*. Injectable conductive hydrogel with self-healing, motion monitoring, and bacteria theranostics for bioelectronic wound dressing. *Advanced Healthcare Materials*, 2024, **13(11):** e2303876.
[93] GU J N, SUN Y X, ZHANG T Y, *et al*. Enhancing remanent magnetization of injectable hydrogels improves realtime transluminal localization of tumor in hollow soft viscera. *Bioactive Materials*, 2026, **55:** 410.
[94] KAWAI K, LARSON B J, ISHISE H, *et al*. Calcium-based nanoparticles accelerate skin wound healing. *Public Library of Science One*, 2011, **6(11):** e27106.
[95] DUAN W, GAO Y, XU R R, *et al*. Engineering dual-driven pro-angiogenic nanozyme based on porous silicon for synergistic acceleration of burn infected wound healing. *Materials Today Bio*, 2025, **31:** 101522.
[96] WANG R Y, LI C Y, ZHANG Y X, *et al*. Injectable, conductive MXene@$Mg^{2+}$ hydrogel with photothermal antibacterial and angiogenic properties for bacteria-infected wound healing. *Chemical Engineering Journal*, 2025, **514:** 163472.
[97] QIAN Y N, ZHENG Y J, JIN J, *et al*. Immunoregulation in diabetic wound repair with a photoenhanced glycyrrhizic acid hydrogel scaffold. *Advanced Materials*, 2022, **34(29):** 2200521.
[98] WANG Z T, SUN Z P, ZHU S L, *et al*. A multifunctional hydrogel loaded with magnesium-doped bioactive glass-induced vesicle clusters enhances diabetic wound healing by promoting intracellular delivery of extracellular vesicles. *Bioactive Materials*, 2025, **50:** 30.
[99] JIA Q, DING Y J, SU Z W, *et al*. Cell membrane-camouflaged nanoparticles activate fibroblast-myofibroblast transition to promote skin wound healing. *Biofabrication*, 2025, **17(1):** 015036.
[100] LIU S, SONG L, HUANG S W, *et al*. Hydroxyapatite microspheres encapsulated within hybrid hydrogel promote skin regeneration through the activation of calcium signaling and motor protein pathway. *Bioactive Materials*, 2025, **50:** 287.
[101] PAVICIC T, SATTLER G, FISCHER T, *et al*. Calcium hydroxyapatite filler with integral lidocaine CaHA (+) for soft tissue augmentation: results from an open-label multicenter clinical study. *Journal of Drugs in Dermatology*, 2022, **21(5):** 481.
[102] PROIETTI I, SPAGNOLI A, FAVARONI A, *et al*. HArmonyCa™ hybrid filler to restore connective tissue: an Italian real-life retrospective study. *Journal of Cosmetic Dermatology*, 2024, **23(12):** 3883.
[103] AGUILERA S B, MCCARTHY A, KHALIFIAN S, *et al*. The role of calcium hydroxylapatite (radiesse) as a regenerative aesthetic treatment: a narrative review. *Aesthetic Surgery Journal*, 2023, **43(10):** 1063.
[104] YUTSKOVSKAYA Y, KOGAN E, LESHUNOV E. A randomized, split-face, histomorphologic study comparing a volumetric calcium hydroxylapatite and a hyaluronic acid-based dermal filler. *Journal of Drugs in Dermatology*, 2014, **13(9):** 1047.
[105] WANG Q, YAN H Y, XIAO J X. Recent progress of dermal implants for aged skin rejuvenation: a review. *Journal of Materials Chemistry B*, 2025, **13(36):** 11126.
[106] KARATAS E, KOC K, YILMAZ M, *et al*. Characterization and comparative investigation of hydroxyapatite/carboxymethyl cellulose (CaHA/CMC) matrix for soft tissue augmentation in a rat model. *ACS Omega*, 2024, **9(29):** 31586.
[107] VAN LOGHEM J, FUNT D, PAVICIC T, *et al*. Managing intravascular complications following treatment with calcium hydroxylapatite: an expert consensus. *Journal of Cosmetic Dermatology*, 2020, **19(11):** 2845.