The Electrifying Future of Bone Regeneration: a Decade of Innovation from Xuliang Deng and Colleagues at the Peking University School of Stomatology

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Bone, a dynamic and complex tissue, possesses limited regenerative potential, which poses formidable challenges in orthopaedic surgery and clinical dentistry. In particular, for large bone defects beyond critical size, compromised physiological conditions due to comorbidities (i.e. osteoporosis and type 2 diabetes) or severe trauma, its intrinsic healing capacity often falls short, necessitating advanced therapeutic interventions. For decades, research on bone regeneration has predominantly focused on biomaterial design, growth factor delivery and cell-based therapies. More recently, a paradigm shift has occurred, recognising the critical role of the bioelectric microenvironment in orchestrating bone homeostasis and repair. At the forefront of this exciting field, the pioneering work of Professor Xuliang Deng and colleagues at Peking University School of Stomatology has systematically elucidated the intricate interplay between electrical signalling cues and bone regeneration, paving the way for novel electroactive biomaterial strategies. These are summarised by the accompanying review article,[1] which is published in this issue of the Chinese Journal of Dental Research.

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Over the past decade, Deng's research group has meticulously advanced our understanding from fundamental biophysical principles to sophisticated electroactive scaffold systems. Their foundational research, exemplified by their work in ACS Nano in 2016, highlighted the indispensable role of physiological electric potential in maintaining bone volume and quality.[2] They demonstrated that restoring this endogenous electrical microenvironment through electroactive nanocomposite membranes could significantly enhance bone regeneration, providing a strong mechanistic rationale for electroactive scaffold design.[2] This early work laid a critical theoretical foundation for the clinical application of electroactive biomaterials, particularly in dental practice.

A major contribution of Deng and colleagues in this field lies in their rigorous elucidation of the diverse bioelectric phenomena governing bone biology. They have shown how piezoelectricity, streaming potentials, transmembrane potentials and dielectric/ferroelectric effects collectively regulate cellular behaviour and matrix turnover.[1] Their compelling evidence suggests that the loss of these endogenous electrical signals at defect sites is a primary barrier to effective healing. Crucially, their research extends beyond merely enhancing osteogenesis. Through a series of comprehensive in vitro and in vivo studies, they have convincingly demonstrated that electrical microenvironment remodelling can concurrently promote osteogenesis, angiogenesis and neurogenesis, while also modulating immune responses, inhibiting osteoclast-mediated resorption and providing antibacterial protection.[1] Their insights into macrophage polarisation and osteo-immunomodulation have been particularly transformative,[3] integrating inflammation resolution, vascular ingrowth and bone formation into a unified, electro-regulated healing cascade.[1]

Addressing clinically challenging conditions has been another hallmark of their research. Deng's research group has made significant strides in demonstrating the positive efficacy of electroactive scaffolds in compromised physiological conditions arising from comorbidities such as type 2 diabetes, osteoporosis and periodontitis.[1] For instance, their 2021 study revealed that restoring the electrical microenvironment could enhance bone regeneration under diabetic conditions by modulating macrophage polarisation, specifically by

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attenuating proinflammatory M1 macrophage polarisation and promoting pro-healing M2 phenotypes.[3] Furthermore, their preclinical translational studies, such as the 2023 work published in the Journal of Materials Chemistry B, showcased the potential of ferroelectric nanocomposite membranes to enhance alveolar ridge regeneration in a mini-pig model, moving the field closer to realistic, disease-specific regenerative therapies.[4]

From a materials and technology standpoint, Deng and colleagues have developed an impressive portfolio of innovative platforms. They have progressed from passive electroactive materials to dynamically controllable, stimuli-responsive scaffolds that function as active bioelectronic interfaces. Key innovations include ferroelectric BTO/P (VDF-TrFE) systems, piezoelectric composites with tailored surface potentials and biodegradable piezoelectric Janus membranes with dual antibacterial and osteoinductive properties.[1] Their work has also explored magneto-responsive and ultrasound-responsive "smart" scaffolds, and nanocomposites capable of remote, on-demand modulation of surface charge.[1] A notable technological advance involves engineering heterogeneous surface potential distribution (HEPD) at the micro- and nanoscale. As reported in Advanced Materials in 2023, they demonstrated that HEPD induces a meshwork pattern of fibronectin adsorption, mimicking the heterogeneous extracellular matrix, which in turn enhances integrin clustering, focal adhesion maturation and mechanotransduction events driving osteogenic differentiation of mesenchymal stem cells.[5] This concept was further extended in Advanced Science in 2025, where they showed that HEPD promotes M2 polarisation of macrophages via activation of the PI3K-Akt signalling pathway, establishing a pro-angiogenic immune microenvironment that accelerates vascularisation and subsequent bone repair.[6] Their research also extended into 3D space with the fabrication of micropillar-patterned piezoelectric $BaTiO_3$ substrates, creating a 3D electrical microenvironment that markedly enhances BMSC adhesion, spreading, osteogenesis and osseointegration, as shown in Advanced Materials in 2025.[7] More recently, they developed a near infrared light–inducible pyroelectric nanocomposite membrane that promotes macrophage reprogramming for superior bone regeneration.[8]

What truly distinguishes Deng's work is the consistent connection between material design and clearly defined biological mechanisms. They have delved into molecular and cellular pathways, including voltage-gated Ca^{2+} influx, CaM/CaN/NFAT signalling, integrin-FAK-YAP/TAZ pathways, VEGF- and CGRP-mediated angio-neurogenesis, macrophage M1/M2 switching via PI3K-AKT and RhoA/ROCK, and the inhibition of osteoclastogenesis at molecular and cytoskeletal levels.[1] This mechanistic depth provides strong credibility to the notion that appropriately engineered electrical microenvironments can effectively replace, at least in part, the lost regulatory functions of healthy bone.

In conclusion, the research conducted by Xuliang Deng and colleagues has been instrumental in validating electrical microenvironment remodelling as a robust and versatile strategy for bone regeneration. Their systematic framework, spanning from macroscopic electrical biomimicry to micro-/nanoscale potential heterogeneity and 3D spatial remodelling, has provided profound insights into the underlying mechanisms governing electrical modulation of bone regeneration.[1] This body of work has advanced the field from conceptual proposals to experimentally grounded, multifunctional scaffold systems directly relevant to complex clinical scenarios. The translational potential of their innovations in orthopaedics, maxillofacial surgery and dentistry, particularly for aging and systemically compromised patient populations, is immense, promising an electrifying future for bone regenerative therapies.

References

1. Heng BC, Liu Y, Bai Y, et al. Remodeling the electrical microenvironment for facilitating bone regeneration: A decade of progress. Chin J Dent Res 2026;29:201–215.
2. Zhang X, Zhang C, Lin Y, et al. Nanocomposite membranes enhance bone regeneration through restoring physiological electric microenvironment. ACS Nano 2016;10:7279–7286.
3. Dai X, Heng BC, Bai Y, et al. Restoration of electrical microenvironment enhances bone regeneration under diabetic conditions by modulating macrophage polarization. Bioact Mater 2021;6:1124–1136.
4. Li Y, Meng Y, Bai Y, et al. Restoring the electrical microenvironment using ferroelectric nanocomposite membranes to enhance alveolar ridge regeneration in a mini-pig preclinical model. J Mater Chem B 2023;11:2721–2732.
5. Bai Y, Zheng X, Zhong X, et al. Manipulation of heterogeneous surface electric potential promotes osteogenesis by strengthening RGD peptide binding and cellular mechanosensing. Adv Mater 2023;35:2209769.
6. Cui Q, Zheng X, Bai Y, et al. Manipulation of surface potential distribution enhances osteogenesis by promoting pro-angiogenic macrophage polarization via activation of the PI3K-Akt signaling pathway. Adv Sci (Weinh) 2025;12:2414278.
7. Sun X, Guo Y, Zheng X, et al. Optimizing the electrical microenvironment provided by 3D micropillar topography on a piezoelectric BaTiO3 substrate to enhance osseointegration. Adv Mater 2025;37:2414161.
8. Guo Y, Wang Y, Guo Y, et al. NIR-inducible pyroelectric nanocomposite membrane promotes macrophage reprogramming for superior bone regeneration. Adv Funct Mater 2025;35(37):2502329. https://doi.org/10.1002/adfm.202502329.