

Development and Application of Piezoelectric Films for Enhancing Bone Growth

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INTRODUCTION: Bone tissue possesses inherent piezoelectric properties that convert mechanical stress into electrical signals, playing a crucial role in skeletal development and fracture healing. Traditional orthopedic implants often face challenges such as delayed healing or non-union, whereas piezoelectric materials can simulate the electromechanical characteristics of bone tissue, thereby potentially promoting osteogenesis and tissue regeneration. This study developed a piezoelectric polyvinylidene fluoride (PVDF) nanofiber film through electrospinning, annealing, and poling processes, designed as a bioactive coating for orthopedic implants (e.g., bone screws) to accelerate bone healing. Specifically, we evaluated the scaffold's material properties, in vitro osteogenic effects on MC3T3-E1 preosteoblasts, and in vivo healing potential in a rat femoral defect model.

METHODS: PVDF powder was dissolved in an 18 wt% DMF:acetone (3:7) solvent mixture. Electrospinning was conducted using a custom apparatus with a syringe pump flow rate of 1 mL/h, applied voltage of 22-25 kV, and collector distance of 15 cm, producing nanofibrous mats approximately 100-150 μm thick (Fig 1). Subsequently, the mats were annealed at 110°C for 2 hours to enhance crystallinity, followed by contact poling at 2 kV and 130°C for 30 minutes to induce piezoelectricity. To further enhance the piezoelectric properties of nanofiber film, 20 wt% barium titanate (BaTiO₃) nanoparticles were incorporated into the PVDF solution prior to electrospinning.

Material characterization included scanning electron microscopy (SEM) for morphology and fiber diameter analysis, Fourier-transform infrared spectroscopy (FTIR) for β -phase content quantification, tensile testing on a universal machine at a crosshead speed of 5 mm/min, water contact angle measurement for hydrophobicity assessment, and piezoelectric coefficient (d_{33}) determination using a d_{33} meter.

In vitro studies involved culturing MC3T3-E1 preosteoblasts (density: 5×10^4 cells/cm²) on sterilized scaffolds in osteogenic medium (α -MEM supplemented with 10% FBS, 50 $\mu\text{g}/\text{mL}$ ascorbic acid, and 10 mM β -glycerophosphate). Cell migration was evaluated via wound healing assay (scratch width: $\sim 500 \mu\text{m}$) at 0, 12, 24, and 48 hours, with migration rates quantified using ImageJ software. Mineralization was assessed after 14 and 21 days using Alizarin Red S staining.

In vivo experiments utilized 6-8 week-old male Sprague-Dawley rats ($n=10$, body weight 250-300 g) under IACUC-approved protocols. A partial femoral fracture model was established by creating a 2 mm defect in the mid-diaphyseal region, stabilized with titanium pins (diameter: 1.5 mm). Pins were either uncoated (control, $n=4$), coated with pure PVDF ($n=4$), or coated with PVDF+20wt%BaTiO₃ ($n=2$). After 60 days of healing, femurs were harvested, and maximum failure load were evaluated via three-point bending tests on a material testing system (span: 20 mm, loading rate: 1 mm/min).

RESULTS: The electrospun PVDF scaffolds exhibited a uniform, bead-free nanofibrous morphology with fiber diameters ranging from 90 to 200 nm (mean: 150 ± 50 nm). FTIR spectra revealed a moderate β -phase fraction of 43-48%, essential for piezoelectric activity. Porosity exceeded 60% (mean: $65 \pm 5\%$), facilitating nutrient diffusion. Mechanical testing indicated a tensile strength of approximately 25 MPa (Young's modulus: 150-200 MPa), suitable for implant coating applications. Water contact angles ranged from 114° to 132°, indicating moderate hydrophobicity that supports initial cell attachment without excessive repulsion. The piezoelectric coefficient d_{33} was measured at 56-60 pC/N, confirming robust electromechanical responsiveness under static conditions.

The *in-vitro* study showed the piezoelectric scaffolds significantly enhanced MC3T3-E1 migration compared to non-poled controls, with wound closure rates increasing by 30-50% at 24 hours ($p=0.002$). Mineralization assays showed a 1.5-2-fold increase in calcium deposition at 21 days (optical density: 0.45 ± 0.05 vs. 0.25 ± 0.03 in controls, $p<0.01$), indicative of promoted osteodifferentiation (Fig 2).

The *in-vivo* study showed the three-point bending tests demonstrated superior biomechanical recovery in PVDF-treated groups. Maximum load in the control group was 120 ± 15 N, compared to 150 ± 20 N in PVDF-coated ($p=0.045$) and 160 ± 18 N in PVDF/BaTiO₃-coated groups. Stiffness values followed a similar trend. Statistical comparisons confirmed significance between injured vs. healthy femurs ($p=0.0232$), with PVDF groups trending toward healthy benchmarks (Fig 3).

DISCUSSION: The developed piezoelectric PVDF scaffolds exhibited favorable biomimetic properties, including a porous architecture mimicking the extracellular matrix and intrinsic piezoelectricity that generates micro-electrical cues under physiological loading. The enhanced β -phase crystallinity post-poling contributed to the observed d_{33} values, aligning with literature reports on PVDF for tissue engineering (e.g., 40-70 pC/N in optimized films). *In vitro* results underscore the scaffold's ability to stimulate preosteoblast migration and mineralization without exogenous electrical stimulation, potentially via piezopotential-induced activation of calcium channels and osteogenic pathways, as supported by prior studies on piezoelectric biomaterials.

The superior mechanical outcomes in PVDF-coated implants of *in vivo* study suggest accelerated fracture healing, likely due to enhanced osteoconduction and electromechanical signaling that promotes progenitor cell recruitment and matrix deposition. The addition of BaTiO₃ further amplified piezoelectricity, leading to ductile fracture behavior and improved load-bearing capacity, consistent with composite enhancement theories. However, limitations include the small sample size ($n=2$ for doped group), potential variability in rat healing rates, and the absence of long-term degradation assessments. Compared to conventional titanium implants, this scaffold offers a non-invasive augmentation strategy, but future investigations should incorporate larger cohorts, micro-CT for volumetric analysis, and clinical-scale testing to validate translational potential.

SIGNIFICANCE: This piezoelectric PVDF scaffold represents a novel, biocompatible approach to mitigate delayed bone healing in orthopedic implants, with potential to reduce revision surgeries and improve patient outcomes through enhanced osseointegration.

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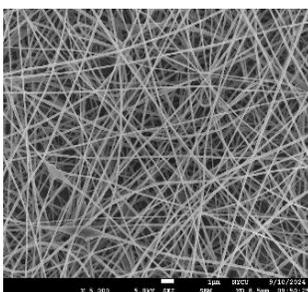


Fig 1: PVDF fibers made by Electrospinning

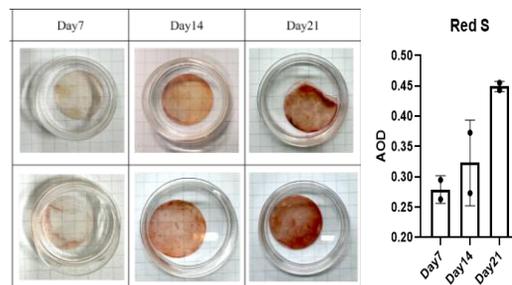


Fig 2: Mineralization assays of MC3T3-E1

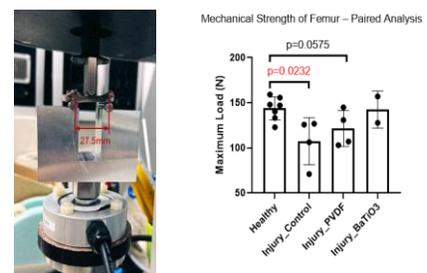


Fig 3: Three-point bending tests of bone