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Design and development of 3D-printed microneedle arrays with hydrogel coating for local anesthesia

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Coating microneedle arrays (MNAs) with drug-loaded hydrogels offers a precise and minimally invasive strategy for the dermal and transdermal delivery of local anesthetics. Recent advances in additive manufacturing have improved the accuracy and accessibility of microneedle fabrication with high resolution, cost efficiency, and rapid prototyping. In this study, lidocaine-coated MNAs were developed to achieve rapid and effective local dermal anesthesia. Two microneedle geometries with identical heights, base dimensions, and inter-needle spacing were compared in terms of insertion efficiency, mechanical robustness, coating uniformity, drug loading, release behavior, and skin permeation.

Two hydrogel formulations with differing polymer concentrations were used for multilayer dip coating. The rheological characterization demonstrated viscoelastic behavior, with the optimized hydrogel exhibiting superior mechanical strength, adhesion, and spreadability, ensuring uniform and reproducible coating along microneedle shafts.

In vitro and ex vivo insertion studies showed consistent penetration depths without needle fracture or deformation under controlled compression mimicking the thumb pressure force. In vitro drug release studies demonstrated rapid lidocaine release followed by pH-driven non-monotonic diffusion behavior. Moreover, geometry-dependent performance was observed and proved that despite the higher drug loading due to the larger lateral surface, sharper geometry with mechanically stronger tips resulted in more efficient skin penetration, as confirmed by Raman mapping.

These findings demonstrate that 3D-printed hydrogel-coated MNAs can provide predictable, rapid and effective local anesthesia through optimized geometry and coating design.

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