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3D-Printed Hollow Microneedles on Si Microfluidics for Healthcare

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Summary:

Hollow polymer microneedles (MNs), fabricated using two-photon polymerization (TPP), offer a painless means of penetrating the skin for interstitial fluid (ISF) extraction, enabling next-generation health monitoring. Integrated with a silicon-based microfluidic chip, the resulting wearable patch ensures consistent ISF sampling, mechanical durability, and biocompatibility—confirmed through both in vivo studies and surrogate testing. The system enables continuous biomarker monitoring for up to 72 hours without causing skin irritation or damage, highlighting its suitability for minimally invasive health applications.

Keywords: 3D printing, microfabricated hollow needles, wearables, microfluidics, silicon

Dermal ISF presents a promising alternative to traditional biomarker sampling methods [1], with MNs emerging as a minimally invasive solution for both ISF extraction and biomarker sensing due to their painless application [2]. However, the biocompatibility of sensing materials often limits the effectiveness of traditional MNs. Hollow MNs enhance versatility by separating the processes of sampling and sensing, enabling more advanced, real-time health monitoring and drug delivery systems. Recent advances in TPP have made it possible to fabricate hollow polymer MNs with complex, biocompatible geometries.

This work presents a wearable patch designed for skin penetration and ISF extraction, which integrates 18 polymer-based hollow MNs with a silicon microfluidic platform via additive manufacturing (Figure 1) [3]. The MNs are optimized for mechanical stability and minimized flow resistance, while the microfluidic chip ensures uniform ISF extraction through an equal-length arrangement, preventing temporal averaging. A clean-room fabrication process, combining micromachining and 3D printing, guarantees high precision with minimal variation in MN height and alignment, surpassing traditional manufacturing methods. FEM simulations and experimental tests confirm the MNs' resilience to compressive and shearing loads during skin penetration (Figures 2a and 2b). Despite the hollow design's inherent stress concentration, the MNs exhibit mechanical strength – approximately 400 mN per MN to induce failure – comparable to non-hollow designs [4], with negligible risk of fragmentation or detachment under real-world conditions.

The penetration capability and biocompatibility of the 3D-printed polymer MNs were evaluated through both skin surrogate and in vivo testing. The MN array showed consistent force-displacement behavior during ten repeated insertions and removals, with no performance degradation or damage (Figure 3), confirming its mechanical robustness and secure attachment to the microfluidic platform. In vivo tests conducted with the wearable (Figure 4) demonstrated painless insertion and rapid recovery, with minimal skin irritation and no adverse effects, highlighting the biocompatibility of the MN material. After 72 hours of continuous wear, the device showed no biofouling or MN degradation. Moreover, successful ISF extraction yielded approximately 1 µl of fluid within one hour, validating the device's functionality for continuous biomarker monitoring.

This adaptable platform, enabled by TPP, offers design flexibility for diverse skin conditions and analytes. Decoupling sampling from sensing provides a foundation for integrating novel sensing materials into a biocompatible platform with promising medical applications, such as continuously monitoring yet explored biomarkers.

References

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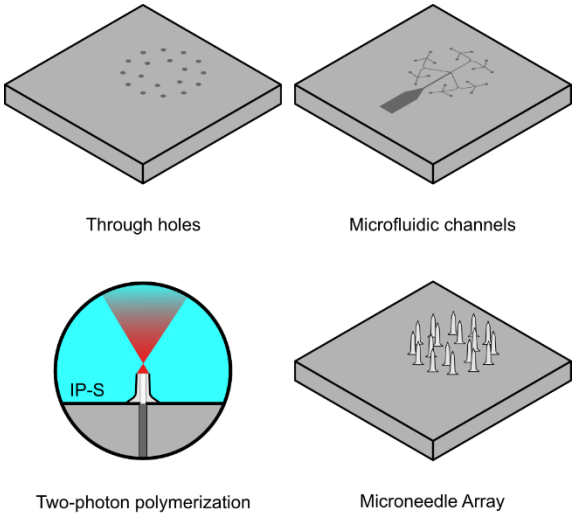

Fig 1. Fabrication process of the microfluidic chip and TPP printing of the 18-MN array. Adapted from [3].

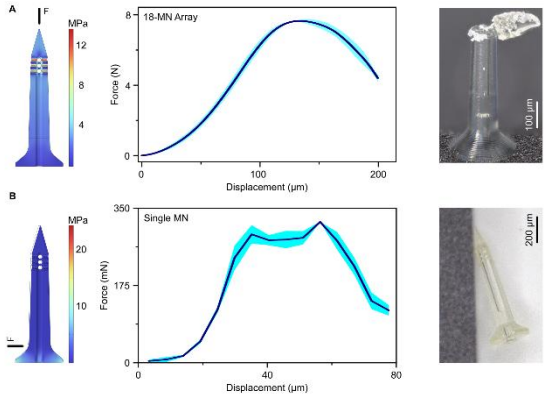

Fig. 2 ***(a)*** *FEM simulation and experimental mechanical testing under compressive load.* ***(b)*** *FEM simulation and mechanical testing under shear load; micrograph shows a representative MN after mechanical failure. Adapted from [3].*

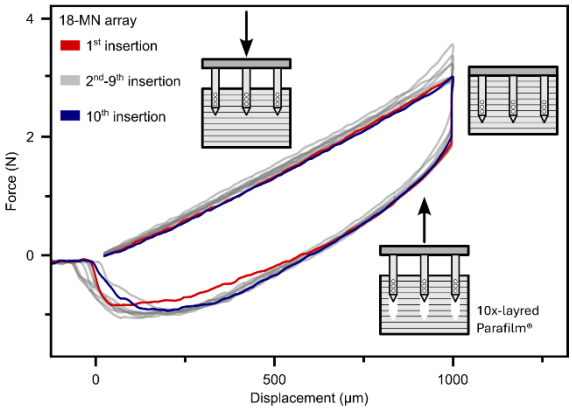

Fig 3. Repeated insertion test performed ten consecutive times on a skin surrogate to assess durability and performance. Adapted from [3].

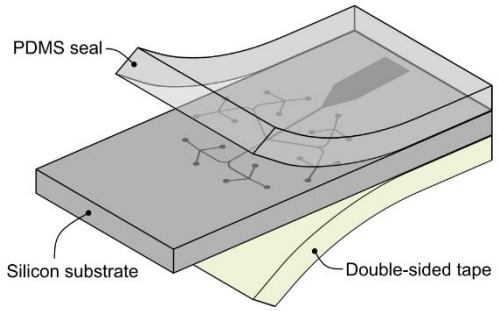

Fig 4. Wearable patch produced from the MN array. Adapted from [3].