Supplementary Information

A Wearable 3D-Printed Hollow Microneedle Device for Pressure-Driven Interstitial Fluid Collection and Testing

Nedim Hacıosmanoğlu[1,2], Emre Ece[1,2], Fatih Inci[1,2]#

[1] UNAM-National Nanotechnology Research Center, Bilkent University, 06800, Ankara, Turkey

[2] Institute of Materials Science and Nanotechnology, Bilkent University, 06800, Ankara, Turkey

Corresponding author: finci@bilkent.edu.tr

ORCID ID: 0000-0002-9918-5038

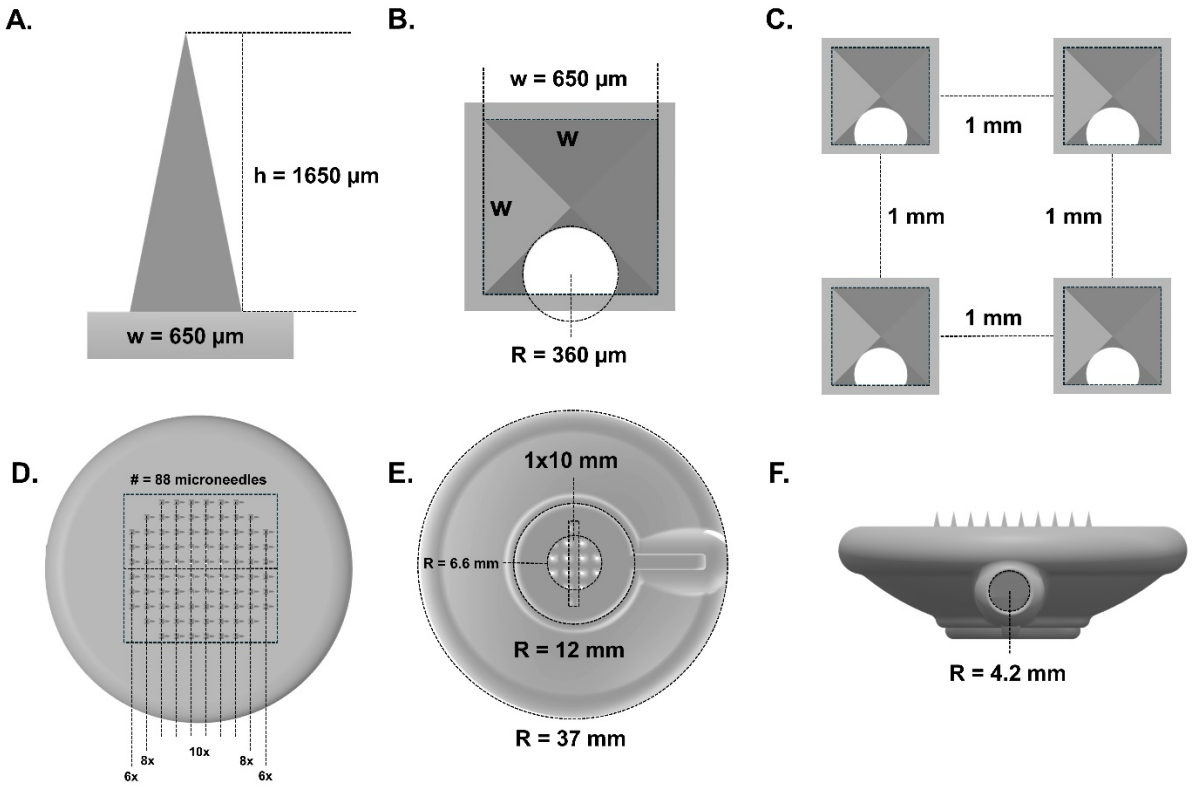

Fig. S1 µHolloSense design and dimensions, (A) MN design (side), (B) MN and bore design (top), (C) Multiple MN separation, (D) MN orientation (top), (E) Buffer and LFA port dimensions, and (F) Syringe port orientation.

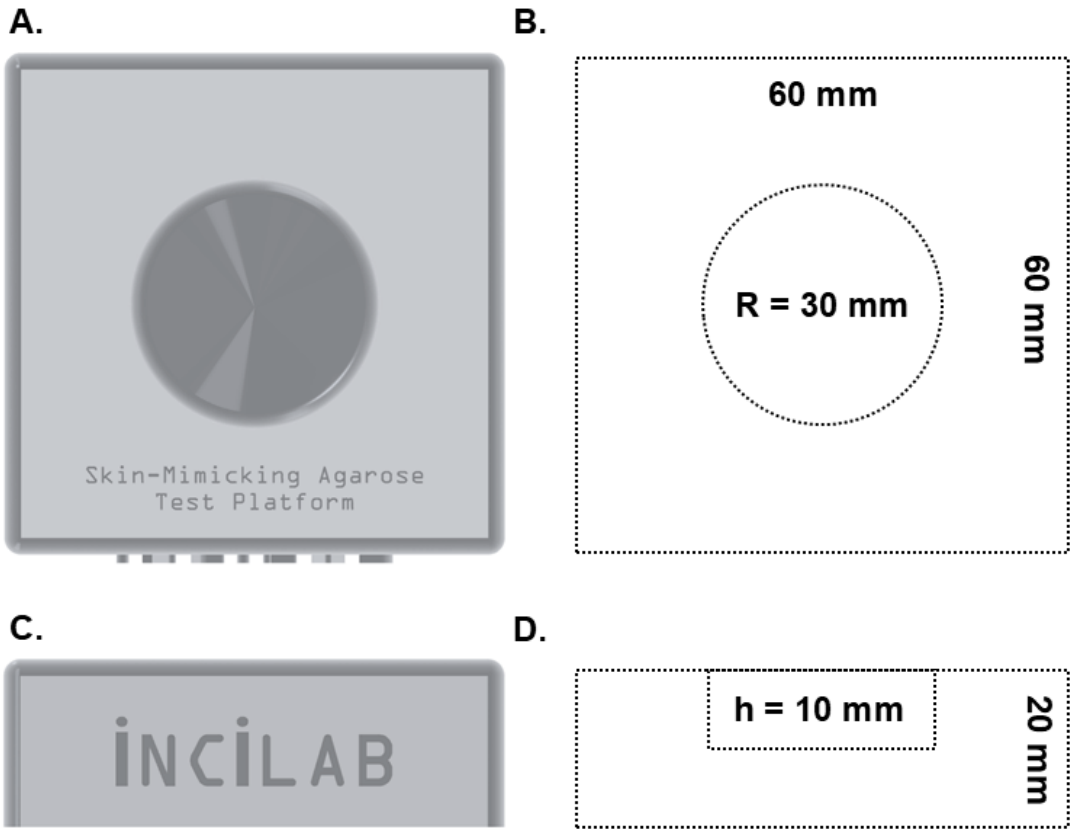

Fig. S2 Dimensions of skin-mimicking agarose test platform, (A) 3D design (top), (B) Dimensions (top), (C) 3D design (side), and (D) Dimensions (side).

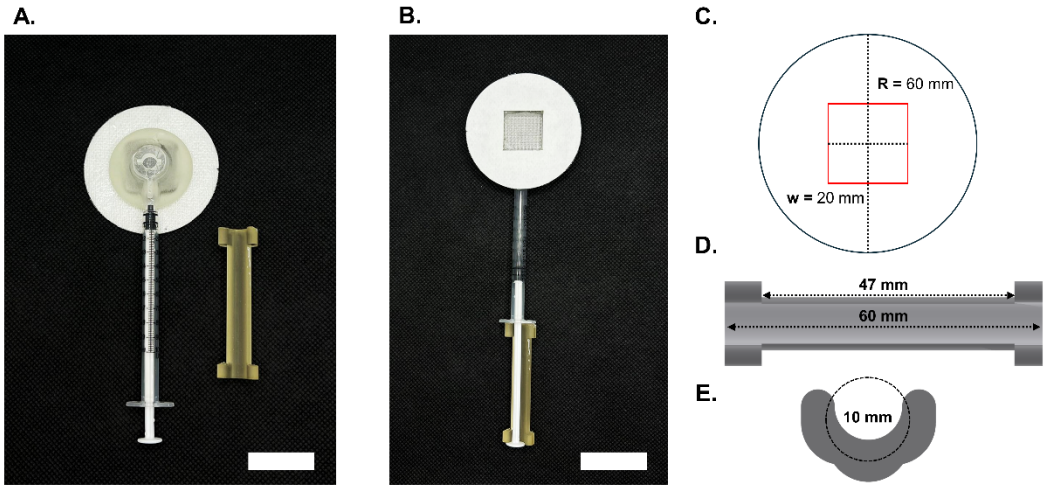

Fig. S3 Assembled µHolloSense and accessory parts, (A) device without stopper (back), (B) device with stopper (front), (C) dimensions for bandage cutting, (D) stopper dimensions (front), and (E) device dimensions (top). All scale bars represent 1 cm.

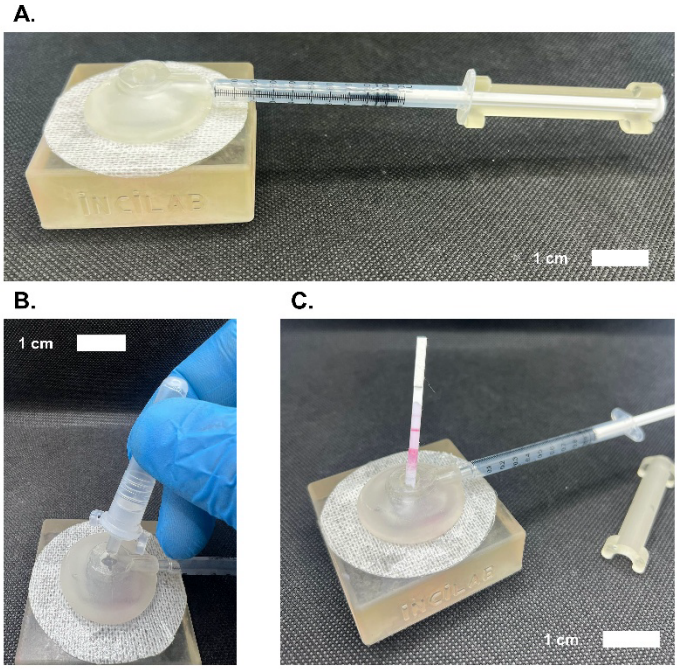

Fig. S4. Operation of µHolloSense and model antigen test, (A) device in suction mode, (B) buffer addition from the buffer port, and (C) LFA strip insertion.

Table S1: Cost /Component analysis for bench scale production of a single µHolloSense excluding overhead costs.

Component	Cost
Resin (*11.2 g – 10.2 mL, 1 µHolloSense and 1 stopper as set***)**	$0.34 per set
Printing and Curing Cost (*Electricity and device cost***)**	$0.10 per set
Post Processing (*Isopropil alcohol, gloves, etc.***)**	$0.05 per set
Consumables (*Wipes, tissues, etc.)*	$0.06 per set
Labor (*$6/h, 15 device per batch***)**	$0.25 per set
Medical Tape	$0.10 per device
Syringe	$0.10 per device
Total (single device): $1	

Table S2: Comparison of the recent studies and our platform.

Reference	Pressure Mechanism	Estimated Cost	Extracted Volume	Time	Production Method	Pros and Cons
Jiang et al. (2024) [1]	-50 kPa (Hand pump)	High	20.8 µL	25 min	Stainless steel MN + rigid patch + hand pump	PROS: High volume collected, over 100 puncture sites CONS: Lengthy extraction time (25 min), requires external hand pump, complex assembly
Ribet et al. (2023) [2]	Positive (Compression)	Medium-High	1.1 µL	~3 min	Single Stainless Steel MN + Microfluidic paper chip	PROS: Precise volume metering (0.1-1 µL), dry storage capable CONS: Single needle only, very small extraction volume (1.1 µL), stainless steel fabrication
Xie et al. (2024) [3]	75 Pa (Vacuum tube)	Medium-High	18.4 µL	5 min	3D-printed MN (10×10) + vacuum tube system	PROS: Rapid extraction (5 min), very low pressure (75 Pa), integrated sensing papers CONS: Requires vacuum tube system
Miller et al. (2018) [4]	Positive (Compression)	High	Up to 16 µL	Several hours	Stainless Steel MN + Concentric holder + compression system	PROS: High volume extraction (up to 16 µL) CONS: Lengthy assay time (hours), complex holder design
Samant and Prausnitz (2020) [5]	-50 kPa (Vacuum)	High	1–6 µL	20 min	Solid metal MN array + vacuum system	PROS: Clinically tested CONS: Requires multiple insertions, solid metal fabrication, external vacuum
Wang et al. (2021) [6]	Vacuum pressure	High	1–10 µL	2–10 min	Solid glass MN (700-1500 µm) + vacuum	PROS: Ultrasensitive protein quantification down to pg/mL levels CONS: Glass microfabrication, requires a vacuum equipment
Wilkirson and Lillehoj (2024) [7]	Vacuum-assisted	Medium	Not specified	<20 min	MN array + Patch LFA	PROS: Direct on-patch testing CONS: Volume not quantified, multi-step fabrication, external vacuum
Sharkey et al. (2025) [8]	Osmotic Pump	Low-Medium	Not quantified	15–45 min	Hydrogel MN + Paper microfluidics + osmotic pump	PROS: Zero-power passive extraction CONS: Slow extraction (up to 45 min)

Guentner et al. (2025) [9]	50 kPa (Positive pressure ring)	Medium-High	~15.5 µL	5 min	3D-printed polymer HMN (Two-photon polymerization) + pressure device	PROS: Near-zero failure rate, optimized pressure gradient (10 kPa increment), high precision printing, rapid extraction CONS: Requires specialized two-photon equipment, complex fabrication, an external pressure device needed
Abbasiasl et al. (2025) [10]	Capillary flow + passive hydrophilicity	Medium	Not specified	Several minutes	High-precision projection 3D printing + coating	PROS: Continuous ISF sampling, integrated biomarker detection on-patch down to mM level, polymeric biocompatible MNs CONS: Requires advanced 3D printing and thin oxide coating fabrication
µHolloSense	**Negative (Syringe vacuum)**	**Low**	**Sufficient for LFA**	**5-20 min**	**One-step SLA 3D Printing**	**PROS: Low cost ($1), integrated LFA port, one-step fabrication, all-in-one wearable** **CONS: In vitro validation only**

REFERENCES

[1] X. Jiang, E. C. Wilkirson, A. O. Bailey, W. K. Russell, and P. B. Lillehoj, "Microneedle-based sampling of dermal interstitial fluid using a vacuum-assisted skin patch," *Cell Reports. Phys. Sci.*, vol. 5, no. 6, p. 101975, Jun. 2024.

[2] F. Ribet, A. Bendes, C. Fredolini, M. Dobielewski, M. Böttcher, O. Beck, J. M. Schwenk, G. Stemme, and N. Roxhed, "Microneedle Patch for Painless Intradermal Collection of Interstitial Fluid Enabling Multianalyte Measurement of Small Molecules, SARS-CoV-2 Antibodies, and Protein Profiling," *Adv. Healthc. Mater.*, vol. 12, no. 13, May 2023.

[3] Y. Xie, J. He, W. He, T. Iftikhar, C. Zhang, L. Su, and X. Zhang, "Enhanced Interstitial Fluid Extraction and Rapid Analysis via Vacuum Tube-Integrated Microneedle Array Device," *Adv. Sci.*, vol. 11, no. 21, p. 2308716, 2024.

[4] P. R. Miller, R. M. Taylor, B. Q. Tran, G. Boyd, T. Glaros, V. H. Chavez, R. Krishnakumar, A. Sinha, K. Poorey, K. P. Williams, S. S. Branda, J. T. Baca, and R. Polsky, "Extraction and Biomolecular Analysis of Dermal Interstitial Fluid Collected with Hollow Microneedles," *Commun. Biol.*, vol. 1, p. 173, 2018.

[5] P. P. Samant, M. M. Niedzwiecki, N. Raviele, V. Tran, J. Mena-Lapaix, D. I. Walker, E. I. Felner, D. P. Jones, G. W. Miller, and M. R. Prausnitz, "Sampling interstitial fluid from human skin using a microneedle patch," *Sci. Transl. Med.*, vol. 12, no. 571, p. eaaw0285, Nov. 2020.

[6] Z. Wang, J. Luan, A. Seth, L. Liu, M. You, P. Gupta, P. Rathi, Y. Wang, S. Cao, Q. Jiang, X. Zhang, R. Gupta, Q. Zhou, J. J. Morrissey, E. L. Scheller, J. S. Rudra, and S. Singamaneni, "Microneedle patch for the ultrasensitive quantification of protein biomarkers in interstitial fluid," *Nat. Biomed. Eng. 2021 51*, vol. 5, no. 1, pp. 64–76, Jan. 2021.

[7] E. C. Wilkirson, D. Li, and P. B. Lillehoj, "Lateral Flow-Based Skin Patch for Rapid Detection of Protein Biomarkers in Human Dermal Interstitial Fluid," *ACS Sensors*, Nov. 2024.

[8] C. T. Sharkey, A. F. Aroche, I. G. Agusta, H. Nissan, T. Saha, S. Mukherjee, J. S. Twiddy, M. D. Dickey, O. Velev, and M. A. Daniele, "Design and Characterization of a Self-Powered Microneedle Microfluidic System for Interstitial Fluid Sampling," *Lab Chip*, vol. 25, pp. 4577–4587, 2025.

[9] A. Guentner, J. Barreiros, Y. Temiz, P. Glatzel, N. Shamsudhin, N. Bellini, M. Zenobi-Wong, and E. Delamarche, "3D-Printed Polymer Hollow Microneedles on Microfluidic Platforms for

Minimally Invasive Interstitial Fluid Extraction," *Adv. Mater. Technol.*, 2025.

[10] T. Abbasiasl, S. Sarıca, U. C. Yener, E. Yilgor, I. Yilgor, H. Ceylan Koydemir, E. Öztürk, and L. Beker, "A Hydrophilic Hollow Microneedle Platform for Sampling Interstitial Fluid and On-Site Biomarker Detection," *Adv. Mater. Technol.*, vol. 10, no. 22, 2025.