OPEN

NPG Asia Materials (2015) 7, e214; doi:10.1038/am.2015.104

www.nature.com/am

RESEARCH HIGHLIGHT

Injectable electronics as a modern day 'ship in a bottle'

John F Zimmerman[1] and Bozhi Tian[1,2,3]

NPG Asia Materials (2015) **7,** e214; doi:10.1038/am.2015.104; published online 11 September 2015

Although the first wearable pacemakers were introduced in the late 1950s, bio-integrated electronics are as relevant today as they were 50 years ago, with modern devices offering the potential for either recording or modulating cellular behavior in three dimensions (3D).[1] Such devices hold the promise for opening up exciting new avenues of treatment in a variety of ailments, from neurodegenerative disorders to traumatic spinal injuries.[2] However, one key challenge in this field is designing devices that are minimally invasive, with researchers constantly pushing to overcome the challenges associated with incorporating hard planar semiconductors with soft pliable biological tissues.[3] Among these concerns, flexibility, size and cytotoxicity all play a crucial role in determining how successful a device is.

In their recent work 'Syringe-injectable electronics' Charles Lieber and his colleges at Harvard University have taken significant strides in confronting these challenges, exhibiting meshed electronic polymers that can be injected into silicone gels and directly into a live rodent's brain.[4] This injectable approach offers several distinct benefits: First, it enables a precise positioning of these probes at a desirable target location. Second, it limits the device's surgical profile, allowing it to be introduced in a minimally invasive fashion, helps promote long-term bio-integration and reduces glial cell response. Additionally, once injected, these structures are seen to unfurl, expanding into a mesh network with final lateral dimensions up to 30 times the diameter of the insertion needle. This emergent structure included an array of protruding metal nanowire electrodes, connected by polymer ribbons bisecting at 45°. This expansion allows the probes to form intimate contact with the surrounding tissue, enabling multiplexed mechanical strain and neural signaling recordings.

We liken this style of design to a modern 'ship in a bottle', where a complex object emerges after passing through a narrow channel (Figure 1), enabling an expanded device design while remaining minimally disruptive to the native material. We believe that this approach offers substantial promise and suggests a variety of intriguing device designs. For instance, it should be possible to incorporate an origami/kirigami style folding element into the existing mesh design, allowing the controllable formation of 3D structures. Additionally, recent work has shown that silicon nanowires can be internalized by cellular systems.[5] Such constructs could also be incorporated with the current design, acting as possible electronic/force probes and stimulators, enabling studies in previously difficult-to-access intracellular domains. Finally, one important next step is introducing wireless functionality to avoid intrusive electrical contacts. Taken together, this technology offers a promising new approach to bio-integration and helps enable a new generation of minimally invasive devices.

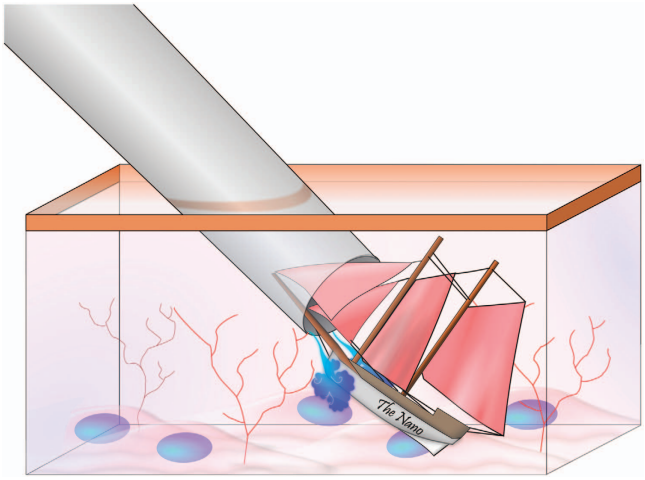

Figure 1 Schematic diagram of an injectable nanoscale 'ship in a bottle'.

CONFLICT OF INTEREST

The author declares no conflict of interest.

[1]Department of Chemistry, University of Chicago, Chicago, IL, USA; [2]The Institute for Biophysical Dynamics, University of Chicago, Chicago, IL, USA and [3]The James Franck Institute, The University of Chicago, Chicago, IL, USA
E-mail: btian@uchicago.edu

1 Tian, B., Liu, J., Dvir, T., Jin, L., Tsui, J. H., Qing, Q., Suo, Z., Langer, R., Kohane, D. S. & Lieber, C. M. Macroporous nanowire nanoelectronic scaffolds for synthetic tissues. *Nat. Mater.* **11**, 986–994 (2012).
2 Minev, I. R., Musienko, P., Hirsch, A., Barraud, Q., Wenger, N., Moraud, E. M., Gandar, J., Capogrosso, M., Milekovic, T., Asboth, L., Torres, R. F., Vachicouras, N., Liu, Q., Pavlova, N., Duis, S., Larmagnac, A., Voros, J., Micera, S., Suo, Z., Courtine, G. & Lacour, S. P. Electronic dura mater for long-term multimodal neural interfaces. *Science* **347**, 159–163 (2015).
3 Viventi, J., Kim, D.-H., Moss, J. D., Kim, Y.-S., Blanco, J. A., Annetta, N., Hicks, A., Xiao, J., Huang, Y., Callans, D. J., Rogers, J. A. & Litt, B. A conformal, bio-interfaced class of silicon electronics for mapping cardiac electrophysiology. *Sci. Transl. Med.* **2**, 24ra22 (2010).
4 Liu, J., Fu, T.-M., Cheng, Z., Hong, G., Zhou, T., Jin, L., Duvvuri, M., Jiang, Z., Kruskal, P., Xie, C., Suo, Z., Fang, Y. & Lieber, C. M. Syringe-injectable electronics. *Nat. Nanotechnol.* **10**, 629–636 (2015).
5 Zimmerman, J. F., Murray, G. F., Wang, Y. C., Jumper, J. M., Austin, J. R. & Tian, B. Z. Free-standing kinked silicon nanowires for probing inter- and intracellular force dynamics. *Nano Lett.* **15**, 5492–5498 (2015).