would be to make the switching faster — for example, by toggling the polarization, phase or spatial distribution of the pump light, using photochromic dyes, or, in the case of a flexible substrate, one could play with mechanical stretching.

More complex array geometries and unit cell structures will provide more freedom in tuning the lasing frequencies. Interesting interplays between multiple lasing modes are expected — for example, in the strong light–matter coupling regime, which has been shown to arise even at room temperature[10] and to enhance nonlinearities. ❐

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WEARABLE ELECTRONICS

Nanomesh on-skin electronics

Hollow, nanoscale metal filaments in open-mesh architectures provide soft, shape-conformal electrical interfaces to the skin as the basis for high-precision, irritation-free sensing platforms.

John A. Rogers

In many clinical diagnostics, skin serves as a measurement window for quantitative assessments of physiological health. Prominent examples are in biopotential recordings that yield insights into cardiovascular activity, skeletal muscle behaviour and brain function through electrocardiograms, electromyograms and electroencephalograms, respectively. Signals in the latter two cases can also serve as the basis of systems for human–machine control interfaces. Standard skin electrodes for such recordings rely on bulky, paste-on conductive pads with hard-wired connections to separate data acquisition electronics. Although suitable for use in hospital and laboratory settings, such approaches are incompatible with continuous, long-term monitoring at home, in a way that does not disrupt routine daily activities. Now, writing in *Nature Nanotechnology*, Miyamoto *et al.*[1] describe a multilayered, open-mesh network of hollow metallic nanofilaments constructed in a manner that allows their direct integration with the soft surface of the skin. Ultrathin electrical interfaces formed in this manner enable nearly unimpeded transepidermal water loss and air permeation, without mechanical constraint or dermatological irritation, even for chronic operation in electrophysiological recordings and other forms of electronic sensing at the skin interface. The results represent valuable contributions to the broader field of skin-integrated electronic technologies[2,3], as next-generation wearables with capabilities that greatly exceed those of traditional wristband-mounted devices.

The authors fabricate their nanomesh constructs by first electrospinning a water-soluble polymer, polyvinylalcohol (PVA), to form a spaghetti-like, multilayer entanglement of fibres with diameters of 300–500 nm. Coating this nanostructure with a thin layer of gold, transferring the resulting film to the surface of the skin, and then removing the PVA by gently washing it away with water completes the process. The resulting conductive, skin-integrated gold nanomesh consists of an interconnected network of hollow, metallic half-cylinders with open spaces in between, where adhesion to the skin is hypothesized to involve an ultrathin (a few tens of nanometres) residual layer of PVA at the interface. The sparse area coverage and the thin geometry combine to yield exceptionally low bending stiffness, such that capillary effects associated with the drying of water following dissolution of the PVA are sufficient to pull the structure into perfect, conformal contact with the textured surface of the skin. Figure 1 shows micrographs associated with experiments on human skin and skin replicas. By comparison to previously reported microscale, two-dimensional metallic mesh structures deterministically formed by lithographic processes and transferred to the skin using elastomeric stamps[4], the nanoscale networks introduced here offer improved mechanics, enhanced air/water permeability and superior ability to conform to curved surfaces. Detailed dermatological studies reveal a complete absence of redness, irritation or other adverse reactions of the skin.

Certain aspects of skin compatibility follow from compliant mechanical properties associated with the nanomesh architectures and the hollow half-cylinder geometries of the constituent filaments, as demonstrated by measurements of conductivity in stretched and unstretched states. Data suggest optimal deformability for samples that are first transformed, by controlled buckling mechanics[5,6], into 'wavy' shapes. Here,

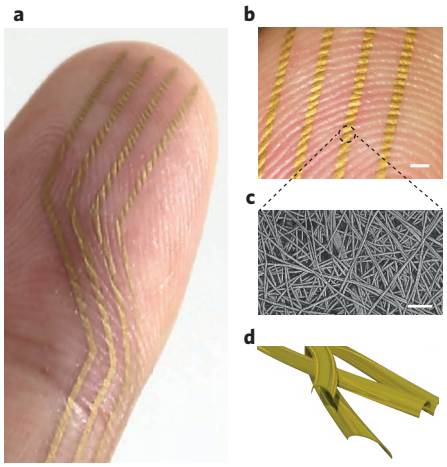

Figure 1 | Skin-interfaced nanomesh electronics. **a**, Image of patterned conductive traces formed from gold nanomesh structures and configured along the length of a finger, extending to its tip. **b**, Magnified image of similar traces on the fingertip, illustrating their ability to conform to the fingerprint ridge patterns. Scale bar, 1 mm. **c**, Scanning electron micrograph of the mesh architecture. Scale bar, 5 μm. **d**, A schematic illustrating the hollow, half-cylindrical gold nanofilament constituents of the mesh. Reproduced from ref. 1, Macmillan Publishers Ltd.

stretching to strains of ~15% results in no observable change in conductance; stretching beyond this level, to values up to 40% (larger than most requirements in skin-integrated applications) leads to modest, but predictable, reductions. Cyclical testing and careful investigations by high-resolution microscopy lead the authors to conclude that this favourable mechanics derives from the ability of the mesh to "repeatedly and reversibly undergo division and restoration" in a manner analogous to a collection of correlated mechanical switches distributed across a two-dimensional plane. The redundancy afforded by the multilayer, interconnected configuration of the metallic filaments is undoubtedly important in this context.

As skin-integrated conductive films, these systems can serve as the basis for a range of electrically active, body-worn sensors. Electromyograms captured using these platforms exhibit signal fidelity that compares well with clinical standards based on gel electrodes. Additional examples include sensors of touch, temperature and pressure. The first involves determination of contact with conductive objects through changes in resistance. The second and third rely on the addition of polymer composites that offer resistive responses to temperature and pressure, respectively. All demonstrations use externally connected wireless electronics for signal capture and transmission.

Beyond these device possibilities, it may be interesting to explore similar concepts involving semiconductors and dielectrics, with a goal of establishing a complete portfolio of nanomesh materials for active skin-integrated electronics. Charge transport characteristics and coupled mechanics of such systems might represent fruitful topics for fundamental work. Applications could focus on fully integrated systems that offer sensing functionality along with power supply, signal acquisition and wireless communication capabilities, without the need for any separate electronics. Here, one could envision interfaces not only with the surface of the skin, but perhaps with internal organs as well. In this context, the nanomesh construct could be valuable in allowing a minimally impeded flow of biofluids in a manner conceptually similar to recently reported macroperforated implantable electronic sheets[7]. In all cases, practical utility will require strategies for encapsulating the meshes to protect them from physical and chemical damage by contact with the surroundings, but without compromising the essential attractive features of the open architectures. Addressing these fundamental challenges and pursuing the associated technology opportunities will require a blend of interdisciplinary approaches in chemistry, materials science, mechanics, electrical engineering and biosensing. ❐

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CANCER IMMUNOTHERAPY

From local to global

Nanoparticles that capture antigens produced *in situ* by tumours induce the 'abscopal' effect, improving the treatment of distant cancer lesions.

Willem J. M. Mulder and Sacha Gnjatic

Nanoparticle drugs are heralded as the next frontier in tumour treatment, although enthusiasm has been tempered after a meta-analysis found their delivery to tumours not to be very effective[1]. Nevertheless, nanocarriers are now applied not only as delivery systems for drugs, but also as active vehicles to enhance current treatment modalities, in particular through their interactions with immune cells. One such application is reported in the current issue of *Nature Nanotechnology*, in which Yuanzeng Min and colleagues[2] use nanoparticles in tumour mouse models to enhance the immune response to local radiation treatment and help to control distant disease through antigen capture and immune enhancement.

In patients with metastases, clinical or radiation oncologists measure each separate tumour lesion as its own entity, and an outgrowth at a single tumour site indicates development of intrinsic tumour resistance and therapy failure. In contrast, immuno-oncologists score the overall burden of metastatic tumours through the modulation of coordinated innate and adaptive immunity, ultimately targeting tumour antigens. The promise of immunotherapy is that it may overcome limitations caused by tumour heterogeneity, thanks to neoantigens (new, unique antigens produced by gene mutations in the tumour) and shared tumour antigens (such as cancer/testis antigens found in many tumour types), both of which distinguish tumours from self, arise in various clonal growths, and can be adaptively targeted by immune responses. Because selecting antigens to target with vaccines or cell therapies has proven challenging, the idea of using tumour sites *in vivo* as natural antigen sources to help prime or boost immunity has generated a lot of interest. In particular, treatments aiming to trigger immunity *in situ*[3], such as local irradiation or injection of immunostimulants (CpG, poly-ICLC or other TLR ligands) or immunomodulators (local anti-CTLA-4) may be a great way to sensitize the immune system for systemic responses through a cascade reaction involving tumour antigen capture and presentation, in addition to the expected local cytostatic effects.

The concept that local tumour tissue irradiation may help to improve untreated distant tumour sites is known as the abscopal effect, a term initially coined by R. H. Mole in 1953 to describe adverse events in non-irradiated sites. Although mechanisms were linked early on to lymphoid organs, the role of systemic antitumour immunity in this process was only formally proposed in the 1980s by Japanese researchers and further elucidated more recently[4]. Today, an abscopal effect