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Nanomedicine: Gold nanowires to mend a heart

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whose spin encodes a qubit — from one quantum dot to another. In a conventional wire this electron would quickly be lost in a sea of other electrons.

With this motivation, two research groups — Christopher Bäuerle and Tristan Meunier of the Institut Néel in Grenoble and co-workers at laboratories in France, Japan and Germany¹, and independently, Chris Ford and co-workers at Cambridge University and the National Physical Laboratory² — have demonstrated an alternative means of transportation for electrons. They still use a nanowire but dry up its electron sea, and then to help the electrons over the peaks in the potential, they employ an applied electrical potential as a nanoscale ‘conveyor belt’. This applied potential has many minima, and each of these is able to trap electrons. By changing the position of these minima it is possible to remove a single electron from a quantum dot, drag it along the nanowire (and over all the peaks in the potential inside the nanowire), and deposit it in a second quantum dot. In many ways the minima in the applied potential are like mobile quantum dots.

This mechanism is already remarkably reliable, working for approximately 95% of attempted transfers^{1,2}. This allowed Ford and co-workers² to shuttle an electron back and forth between two quantum dots up to 60 times, which means that the cumulative distance travelled by the electron was about 0.25 mm — a distance that is almost macroscopic.

The speed of the electron shuttle is remarkable: moving at $2,870 \text{ m s}^{-1}$, it would be classified as ‘hypersonic’ if it were an airplane. Of course, most electrons in the electron sea move about a hundred times faster owing to the exclusion principle, so taking the shuttle must feel more like riding a camel than a jet. Nevertheless, the shuttle can move electrons between quantum dots separated by a few micrometres in about a nanosecond. Moreover, Bäuerle, Meunier and co-workers have shown that loading an electron onto the shuttle and unloading it again also only takes about a nanosecond. This suggests that an electron could be transferred from one quantum dot to another well before it loses its spin coherence. Indeed, in an earlier experiment⁴ it was shown that electrons in a similar shuttle kept their spin coherence for approximately 25 ns. However, these electrons were not picked up from and delivered to quantum dots. The next challenge, therefore, is to measure if spin coherence can indeed be maintained during transfer between quantum dots, which is essential for applications in quantum computing.

The new single-electron shuttle has two main ingredients: the piezoelectric effect and surface acoustic waves. When a piezoelectric material such as gallium arsenide (GaAs) is strained, electric charge accumulates and an electric potential is created. Both groups use surface acoustic waves (sound waves concentrated at the surface of a solid) to strain GaAs nanowires. This produces an

oscillating electric potential that travels along the nanowire with the acoustic wave, with the minima of this potential dragging single electrons along the nanowire (Fig. 1).

If the single-electron shuttle does preserve spin coherence, it will open the door to a host of exciting applications. Ways of manipulating and using quantum information that have so far been the domain of quantum optics may soon become feasible with electrons in solids. For instance, it may become possible to test Bell inequalities with electrons or to teleport the quantum state of an electron. The electronic versions of such experiments will have certain advantages over their quantum optics counterparts; for example, unlike photons, electrons in solids naturally interact and readily exchange information with each other. Most notably a coherent single-electron shuttle will open an array of new possibilities for the design of an electronic quantum computer. □

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NANOMEDICINE

Gold nanowires to mend a heart

Incorporating gold nanowires into porous alginate scaffolds can improve the conductivity of engineered heart patches made from these materials.

Marisa E. Jaconi

The heart is one of the most complex organs in our body. The *de novo* construction of even a tiny piece of heart tissue with suitable mechanical stiffness and appropriate electrical conduction characteristics has not yet been achieved. Cardiac tissues become irreversibly damaged after a heart attack because the heart cannot repair itself. Therefore, there is a great need for novel tissue-engineering approaches to repair diseased heart tissues¹. Simple injections to engraft single cells onto the heart may offer some hope, but this approach

remains inefficient because cardiac cells cannot easily self-organize and survive in the hostile damaged environment.

Writing in *Nature Nanotechnology*, Daniel Kohane and colleagues² at Massachusetts Institute of Technology and Harvard Medical School show that incorporating gold nanowires within a three-dimensional alginate scaffold can improve the conductivity of the scaffold and allow cardiac cells that grow on this scaffold to contract synchronously. The gold nanowires connect the pore walls of the scaffold together

and improve the electrical communication between the cardiac cells (Fig. 1).

To generate a bioengineered cell patch composed of heart cells that are organized in space and can contract synchronously requires the cells to express high amounts of the gap junction protein, connexin 43. This protein functions as a plug-in between adjacent heart cells to enable electrical impulses to propagate from one cell to another. Cells that are connected should be closely aligned to optimize the directional propagation of the impulse and to produce

synchronous contractions. Because gold nanowires have useful mechanical and electrical properties, Kohane and co-workers embedded gold nanowires about 1 μm long and 30 nm in diameter within an alginate scaffold — a porous biological polymer commonly used in the regeneration of different tissues.

As the nanowires were longer than the average thickness of the alginate pore wall of 500 nm, the non-conducting pore walls of the scaffolds were electrically connected together by the nanowires. This enhanced the conductivity of the scaffold and allowed cells to bind in greater numbers and form thicker and better-aligned tissues. This was confirmed by higher expression of connexin 43 in the composite scaffold; a previous study has also shown that electrical stimulation of cardiac cells cultured on scaffolds can enhance connexin 43 expression³. Cellular calcium transients that were recorded at sites remote from the point of electrical stimulation showed that the cells contracted synchronously throughout the composite scaffold.

Writing in *Nano Letters*, Debra Auguste and co-workers⁴ from Harvard University report similar results for gold nanoparticles homogeneously distributed in an electrically conductive hydrogel. This conductive 'golden' gel displays elastic features similar to the heart tissue, and heart cells that grew on this conductive hydrogel also expressed higher levels of connexin 43.



Figure 1 | Symbolic drawing of a gold-wired cage representing a heart containing gold nanowires. Kohane and co-workers² incorporated gold nanowires into porous alginate scaffolds to create cardiac patches that allow heart cells to communicate electrically and contract as a unit.

Using gold nanoparticles or nanowires within biomaterials that can be further functionalized with chemical cues⁵ may have a tremendous impact when applied in medicine. For instance, such composite biomaterials may be used to engineer a multitude of other types of tissues, including neuronal and bone, or to improve the surface electrical properties and

biocompatibility of many materials, such as implants. Moreover, these materials may also direct stem cell differentiation⁶.

However, several questions remain to be explored. For example, how do the cells attach to the nanowires? Can cells 'digest' the gold particles? Would the incorporation of additional cell types such as fibroblasts and/or endothelial cells affect the properties and function of the scaffolds? It is expected that, when sutured onto a damaged heart, the biomaterial will degrade and leave the gold nanowires in the regenerated area where cells have self-organized and become functional. However, such *in vivo* experiments need to be demonstrated. In particular, proving electrical coupling between single cells or cell clusters or within the damaged heart tissue in preclinical small-animal models would be a worthwhile challenge. □

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NANOPARTICLE DEVICES

Going with the electron flow

Electric currents can be steered by coupling the flow of electrons and ions in films of gold nanoparticles coated with ionic ligands.

Xi Yu and Vincent M. Rotello

Charges flow in response to external electrical fields in a way that is similar to the flow of liquids in response to mechanical forces. In conducting materials, electron transport and ion migration are the two basic forms of charge flow that result in electric currents. Although the flow of ions and the flow of electrons can both be described by classical fluid transport equations, the charge transport mechanisms involved are fundamentally different. Moreover, ionic transport usually occurs in electrolytes, whereas electron transport normally takes place in metals

and semiconductors^{1,2}. What happens when ion and electron flows merge, and what new properties can be created by integrating these two carriers in a single material? Writing in *Nature Nanotechnology*, Bartosz Grzybowski and colleagues³ at Northwestern University now report that internal charge gradients created by coupling the flows of electrons and ions can be used to steer electric currents in nanostructured films.

The co-existence of ionic flow and electron flow has been observed before in mixed ionic–electronic conductors (MIEC) such as metal oxides, metal sulphides and

ceramics⁴. However, charge mobility in these materials is low at regular temperatures, and the complex steady-state behaviour arising from the coupling of the two charge carriers is difficult to describe theoretically and difficult to control in practice. Grzybowski and co-workers instead used gold nanoparticles functionalized with charged ligands to assemble MIEC materials.

Monolayer-protected metallic nanoparticles have been employed extensively as granular conducting materials in which electron transport occurs by tunnelling between metal