

Smart Sutures

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Surgical sutures have been used for centuries to join two edges of a wound together to allow the body to heal faster. Originally, sutures were made from plant or animal materials such as silk, cotton, or catgut. Modern sutures are typically synthetic and made from polymer fibers. They can be resorbable, in that they dissolve over time and are absorbed into the tissue, or permanent, in which case they need to be removed after the wound has healed sufficiently to remain closed.

Technological advances have made diagnostic devices smaller and more wearable. With a reduction in size comes an abundance of new applications. Thread-based technology has miniaturized electronic systems to such a degree that they can be integrated into surgical sutures. This allows modern sutures to be replaced with smart sutures that are capable of so much more than just holding tissue together.

The development of thread-based technology has been studied by many professionals over several years. However, until recently, it has not been commercially feasible due to the high cost of the materials and equipment required for mass production. The thread has also been largely inflexible, making practical applications scarce. In contrast, the flexibility of smart threads allows them to be sewn in three dimensions, rather than the traditional two dimensional diagnostic devices. Recent developments make the possibility of smart sutures and intelligent bandages a conceivable reality within a year or two.

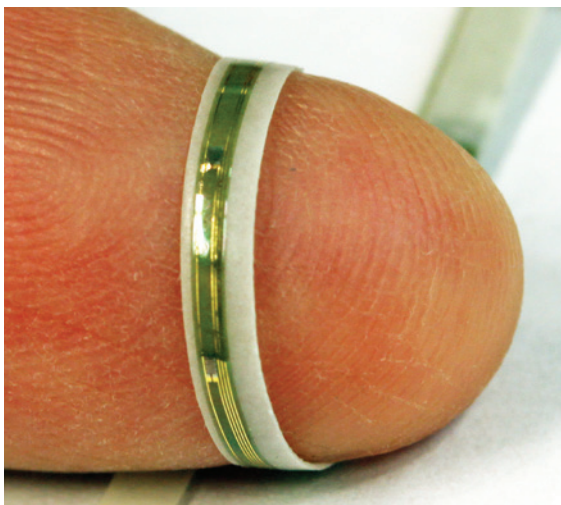


Optical image of a polymer-silicone suture strip after suturing. Credit: John Rogers, University of Illinois

Making Nanomaterials

Nanomaterials can be fashioned in a variety of ways, with the most effective technique for manufacturing synthetic materials being electrospinning.¹ The electrospinning process involves passing an electrical current through a polymeric solution contained within a syringe. A metallic board or plate acts as the electrode, drawing the electrically charged polymeric solution towards it. The solvent that is used can be either water or alcohol. This solvent evaporates en route to the metal board, leaving only the polymeric nanofibers to coat the metallic surface or the substrate that needs to be coated.

Electrospun nanofibers are quick to produce and are relatively low cost. The technique of electrospinning is simple and yet effective for a number of applica-



The flexibility of the polymer-silicone sutures allows it to be wrapped around a finger. Credit: John Rogers, University of Illinois

tions. The composition of the electrospun nanofibers can vary in size from only 10 nanometers (nm) to over 1000 nm in diameter. Electrospun nanofibers have been used in the medical field for wound dressings. Silver and silver alloys have been used extensively in wound dressings as well, due to the antimicrobial properties of silver. However, electrospun nanofibers remain largely two dimensional, which does not provide the range of applications that a thread-based technology would.

Paper has been found to be an ideal substrate for implantable or wearable devices as it is cost-effective to produce, environmentally friendly, widely available throughout the world, and easy to produce. However, the platform is inherently two dimensional and is thus not suitable for suturing.

Thread-Based Devices

The development of thread-based technology over the years has delved into a number of options for a base thread, often using polymer or silk threads. An example of one such study is that conducted by researchers from the University of Illinois.² This research focused on the ability of smart sutures to provide heating to a wound or monitor temperature.³

According to John Rogers, one of the researchers, there are various applications for these electronic sutures and he says, “We think that we’ll be able to do optical measurements and therapy as well. (e.g. blood oximetry and UV treatment)”

Temperature-Regulating and Sensor Sutures

For these particular sutures, a fine layer of crystal silicon nanomembrane was laid on top of the polymer

or silk thread. Following this, metal (such as gold) electrodes were placed on the top of the silicon layer in a serpentine pattern to allow for greater flexion within the thread. Finally, an epoxy was applied to coat the suture. Containing the inflexible elements, such as silicon and metal alloys, within the epoxy coating ensures that the strain of torsion applied to these components is reduced. The sutures can be sewn in much the same manner as conventional surgical sutures using corkscrew-like twists. The sutures are then attached to an external power supply. Rogers says, “In our latest devices of this type, we use wireless power delivery, in which metallic traces in the suture serve as the receiver antenna.” This allows the sutures to be less invasive and restrictive.

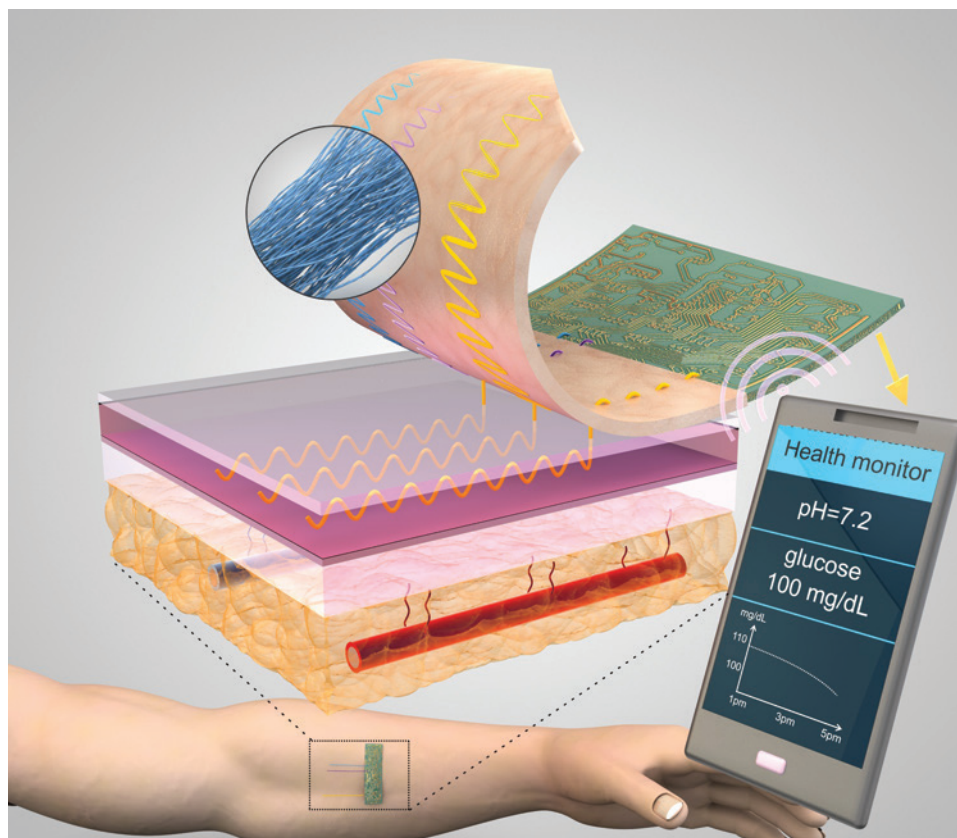
These sutures have been tested for the suturing of incisions on rat skin, proving that the tensile strength is sufficient to be drawn through animal tissue without breaking or damaging any of the mechanical components. However, the threads have not been subjected to live animal testing for heating capabilities or sensing temperature variations.

An additional function that can be applied to the sutures is that of drug delivery. The sutures can be coated in certain classes of thermally-activated polymer matrix, where thermal triggers change the permeability of the coating, thus releasing the drug as required. Rogers explains that this is “mostly relevant for small-molecule drugs.”

Resorbable Sutures

The same principles can be used to create resorbable sutures, using almost any resorbable polymer. This includes silk fibroin, poly(lactic-co-glycolic acid) or PLGA, polycaprolactone or PCL, and collagen. Rogers says, “We now have a set of electronic materials that are also resorbable, such that the entire system can resorb over time.” This eliminates the need to remove sutures after a wound has healed. Using resorbable smart sutures has the additional benefit of allowing the electronic sutures to be integrated into the organs or body cavity during a surgical procedure.

This technology can be applied to several platforms, such as stretchable catheters and medical “tattoos”



Coated cotton threads penetrate multiple layers of tissue to sample interstitial fluid and direct it to sensing threads that collect data, such as pH and glucose levels. Conductive threads then deliver the data to a flexible wireless transmitter sitting on top of the skin. Credit: Nano Lab, Tufts University

which are applied to the surface of the skin. Rogers adds, “We are pursuing broad classes of electronic device platforms that allow integration with the human body in new ways, ranging in form from balloons (for use in cardiac ablation therapy), to sheets (for integration with the cortex to allow high resolution stimulation and electrophysiology mapping), to sleeves (for wrapping the epicardial surface or the bladder), to injectable needles (for optogenetic studies of the deep brain).”

Coating Cotton

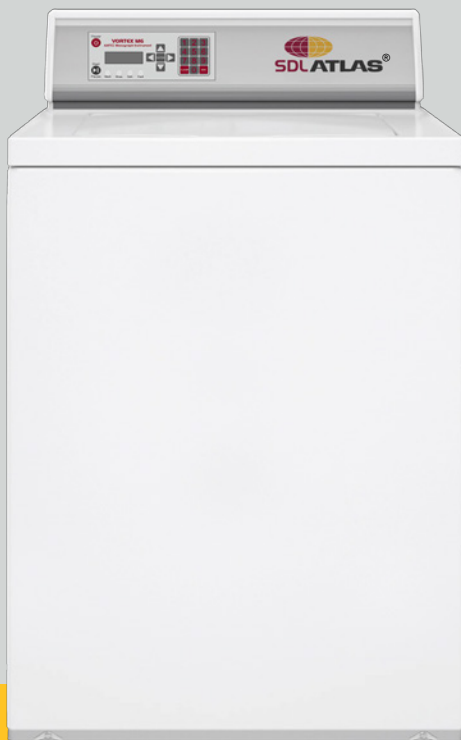
In a paper co-authored by Sameer Sonkusale, director of the interdisciplinary Nano Lab in the Department of Electrical and Computer Engineering at Tufts University, researchers used cotton as the base for their smart sutures.⁴ Rather than layering components onto the thread, the cotton is coated in different nanomaterials. This makes it possible for them to be sutured into wounds or surgical implants and provide information on the performance of the device or the health of the wound. The possibility

also exists that the sutures could be used for organ transplants, allowing doctors to monitor the transplanted organ for any signs of rejection or infection.

Sonkusale confirms that the smart sutures have already been tested in vitro (in a laboratory environment) and in vivo (in a live environment) in animals. However, long-term biocompatibility studies in animals and humans are still needed to ensure that patients will not suffer from any unforeseen side-effects of persistent exposure to the technology. These studies will also ensure that the technology remains efficacious and durable throughout the required observation period.

Since cotton threads have been used, the sutures are not only more flexible than plastic, they also have excellent wicking properties. Cottons typically used in the textile industry are coated with wax or a similar compound, which is designed to improve tensile strength. This wax coating can be removed through oxygen plasma cleaning. Not only does this increase the hydrophilic properties of the thread,

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Liquid flowing in cotton threads sutured into skin. Credit: Nano Lab, Tufts University

it also adds an –OH (hydroxyl group) bond to the surface of the thread to allow for effective bonding of the nanomaterials.

Sonkusale says, “Threads are plasma-treated so that nanomaterials bond to the threads through covalent interaction with functional groups on plasma-treated threads. In some cases, polymeric additives are used for stronger adhesion.”

The increased hydrophilic properties of the threads allow medication to be delivered directly into the suture, and thus wicked through the length of the stitching. Any medication delivered this way will effectively disperse the liquid directly into the wound, penetrating several layers of skin and tissue if necessary. Drug delivery through this method provides a simple and painless alternative to drips or injections as the sutures can be delivered to the intracellular space (the space within an organism’s cell).

Nanomaterials that are ideal for coating textiles to be used in thread-based diagnostic applications include silver, zinc oxide, and titanium. These nanomaterials are remarkably cost-effective, making mass production and commercialization very feasible. After being plasma treated, the threads are passed through a conductive ink to make them into functional electrodes. A number of conductive inks were experimented with, such as silver or silver chloride, carbon nanopowders, carbon nanotubes (CNTs), and polyaniline (PANI). The ink is cured onto the thread using a drier when necessary, and thread that was to be sutured into animals for study was sterilized using ultraviolet light.

The nanomaterials used to coat the thread are chosen to suit the required purpose. The threads used for these smart sutures are coated with different nanomaterials to detect different environmental conditions.

A suite of smart threads was created for different functions. “For example,” explains Sonkusale, “for smart threads used for sensing strain, we used carbon nanotubes. For smart threads for sensing pH, we used carbon nanotubes and polyaniline nanofibers.”

The ability of the sutures to conduct a current was demonstrated using a three-electrode system. In a three-electrode system there are two working electrodes (i.e. they both have current passing through them) and a reference electrode (which has no current passing through it). This system is used when voltammetry is required to measure the current in an electrochemical cell. The reference electrode of the smart suture, which has a known and stable electrode potential, was made from silver-silver chloride.

The data that can potentially be collected includes pH, strain, stress, pressure, temperature, and changes in glucose levels.⁵ Such data sets can then be used to determine whether a wound is becoming infected or how the body’s chemistry is changing. The results are transmitted wirelessly to a cell phone or a computer where they are analyzed. At this stage in the research and development of these smart sutures, individual threads are used for each distinct function. To achieve the monitoring of several conditions at the same time, the indi-



vidual threads would need to be combined to form composite threads.

The Future of Smart Sutures

So, what does the future of smart sutures look like? Sonkusale says, “These smart threads could serve as surgical sutures where they provide real-time information on whether the surgical site is healing or if there is inflammation. They could be used as part of the wound dressing to assess wound healing and monitor infection. They can be woven into tissues for real-time monitoring of biomarkers of overall health.” The possibilities are endless for practical applications of thread-based technology.

Rogers agrees, adding that smart sutures in the future will allow “multimodal sensing, wireless data transfer, and therapeutic functions such as electrical stimulation (e-stim), UV sterilization, drug release, thermal therapy, and more; all working in a closed feedback loop.” Diagnostics, monitoring, and treatment will become easier, quicker, more convenient, and less invasive. There will be no need for follow-up visits, or long waits in practitioners’ waiting rooms, as all information will be sent through the click of a button.



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Hydro responsive cotton thread to be used with a sensor and microfluidic circuit. Credit: Alonso Nichols, Tufts University.