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Nature-Inspired Orthopedic Implant Coating Kills Bacteria, Monitors Strain

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By Deb Borfitz

June 5, 2023| Researchers at the University of Illinois Urbana-Champaign believe they have come up with an attractive approach to the battle against bacteria that can infect orthopedic implants—as well as the surfaces people encounter in everyday life, including smartphone screens and kitchen countertops. The smart surgical implant coating contains no chemicals but was instead inspired by the wings of cicadas and dragonflies that are naturally antibacterial through physical interactions, according to Qing Cao, associate professor of materials science and engineering.

These "antimicrobial nanopillar arrays" do a good job of killing bacteria, including those resistant to antibiotics, he adds. They also exhibit long-term stability in vivo without causing toxic side effects, inducing acute inflammatory responses, or experiencing functional degradation during at least eight weeks after implantation, as reported in a study that published recently in Science Advances (DOI: 10.1126/sciadv.adg7397 (https://doi.org/10.1126/sciadv.adg7397)).

Besides preventing infection, the dual-purpose coating maps the strain distribution along the implant—as demonstrated on a rod used for spinal fusion surgery. The integrated strain sensor continuously monitors the biomechanics to provide a "warning of instrument failure," says Cao.

As envisioned, physicians will one day be able to rely on these highly sensitive, flexible electronic sensors to monitor strain, he says. They could thereby watch the healing progress of individual patients, guide their rehabilitation to shorten the recovery time and minimize risks of failed fusions, and repair or replace devices

before they hit the point of failure.
Periprosthetic infections affect up to 10% of patients fitted with orthopedic implants, and device failures occur at least that often, notes Cao. Both are clinically problematic, not to mention painful for patients.

Bacteria on implants form a biofilm that spreads to nearby tissue and antibiotics alone typically aren't helpful, so the device needs to be surgically replaced, continues Cao. Device failure commonly involves loosening caused by mechanical shielding or implant breakage, which also requires revision surgery.

Efforts by various groups over the years to address these risks have been stymied by significant clinical and technological barriers. Loading the surface of implants with a slow-release antibiotic may kill the bacteria, but only for a limited time, and creates the "perfect environment for development of drug resistance," Cao says. Moreover, individuals may have allergic or toxic side effects from chemicals in the drug.

Others have attempted to integrate mechanical gauges with orthopedic implants and surrounding tissues, but these have required the creation of special cavities to house the sensors that are hard and expensive to build and jeopardize the mechanical reliability of the device, he adds. They also don't accommodate differences between individuals and surgical procedures due to their limited surface coverage and spatial resolution.

Two-Pronged Approach

The insects that kickstarted development of the novel antimicrobial approach have naturally occurring structures on the surface of their wings, notably arrays of high-density and high–aspect ratio nanopillars with precisely controlled and optimized geometries, the Illinois team reports. Pulling from their expertise in microelectronics, they created a large-area thin foil patterned with nanoscale pillars to mimic these features. When a bacteria cell attempts to bind to the foil, the pillars puncture the cell wall, killing it. Meanwhile, the nanostructure was similarly found to have no detrimental effects on mammalian (including human) cells.

Separately, for the device failure issue, they then integrated sensor arrays built on single-crystalline silicon nanomembranes on the flat side of the nanopillars, Cao explains. This enables both sensitive strain gauges and high-performance multiplexing circuits.

The ability of the smart-coating foils equipped with the multiplexed silicon strain sensor arrays to determine the progress of spinal fusion and detect implant loosening was validated in an ex vivo sheep model under various physiological conditions. Rodent models authenticated in vitro results, demonstrating the implant coating is functional, stable, and well tolerated in vivo.

Financial support for the work is coming from both the National Science Foundation (NSF) and the Department of Defense (DOD), reports Cao. The NSF is particularly interested in how the nanostructures are generated and the best shape for bacteria-killing power. The DOD has a critical need for better implants due to the many veterans suffering from orthopedic problems.

Overall demand for lumbar spinal fusion is increasingly rapidly in the U.S. due to an aging population, Cao says. Between 2004 and 2015, surgical volume grew by 62.3% with total cases climbing from 122,679 to 199,140.

Cao and his graduate student Yi Zhang have patent protection on the nanostructured bactericidal polymer foil, he reports. They are considering the launch of a small startup.

Product Build

Fabrication of the nanostructures begins by generating a template with an array of nanowells of a certain diameter and depth, and with uniform interstitial spacing, says Cao. Polyamic acid liquid precursors are then put on top, turning into a solid polyimide film featuring the high-density nanopillar arrays that can be peeled off and attached to the surface of an implant.

The team endeavored to come up with a better shaped nanostructure than what they witnessed on the wings of cicadas, but it turned out to be the top performer as measured by both the ability to kill bacteria and withstand normal-use conditions, Cao says. This includes exposure to liquid washing and drying cycles, simulating the typical sterilization of devices prior to implantation.

The application process involves covering the surface of the titanium spinal rods with medical grade, double-sided tape and then laminating on the polyimide film. "I'm not saying this is the best way to do it, but it works so far," he says.

Ultimately, the coating may come pre-applied on the implants. Cao and his colleagues are currently investigating the behavior of the adhesive layer in the in vivo environment.

High-Potential Technology

Within the next six months, the research team expects to begin testing the device in sheep and goats, which in many respects are anatomically like humans, says Cao. They will simultaneously monitor the strain-mapping functionalities of the smart implant coating (daily basis) and the progress of healing with biomedical CT imaging (every few weeks) and then check to see if the two sets of data agree with each other.

In the interim, they'll be working to make the electronics wireless through Bluetooth or near-field communication with interfaces to their coatings, as will be required for clinical application, Cao says. Results of trials with the large animal models will determine the fate and pace of translational development and use in humans.

A coating for the spinal rods used for lumbar fusion is just the beginning, says Cao. Among the reasons for this starting point is that one of the collaborators on the project is an orthopedic physician who specializes in this type of surgery. It is also relatively easy to wrap the foil around the surface of the implants, including both the spinal rods and blade plates used to fuse bones together.

In the future, the development team hopes to expand its applicability to other types of orthopedic implants with more complicated structures as well as other types of biomedical implants, including simple catheters, Cao says. Infection is a common problem with all types of biomedical implants because it is natural for bacteria to attach to the surface of devices introduced into the human body.

Exciting technology is emerging from the convergence of biomimetic design, nanotechnology, and electronics to solve serious and critical biomedical problems, says Cao, noting that for him this sort of project is a career first. The Illinois team is now working with the NSF to prepare a podcast and video clip about the smart surgical implant coating that will soon be featured on The Discovery Files (https://www.nsf.gov/news/mmg/mmg_disp.jsp?med_id=188575&from=) series, which airs on radio stations across the country and distributed to 177 countries worldwide.

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