

MEMS Sensors for the Body: From Wireless Implants to Transdermal Diagnostics

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Abstract:

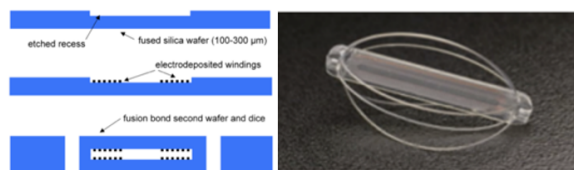
Microsystems are now being used to interface with the human body for sensing relevant parameters that impact the diagnosis and treatment of multiple diseases. As this technology continues to mature, many examples of both research and regulator-approved products are expected to become available. This paper highlights several such microsystem-based interfaces associated with our laboratory, including wireless endovascular permanent implants for detection of pulmonary artery pressure utilized in managing medication of patients with heart failure; wireless fingertip implants intended for sensing of normal and shear forces for restoration of sensation in diabetic patients; microneedle-based devices for transdermal detection of cytokines used in assessment of inflammation; and transdermal intramuscular oxygen sensors for replacement of muscle biopsies in the detection of mitochondrial-based metabolic dysfunction.

Keywords: Implant, biosensor, endovascular, tactile, cytokine

Introduction

Microsystems for medicine, including implants and transdermal devices, have been envisioned for decades. Nearly 70 years ago the 'endoradiosonde', a swallowable device reporting gastro-intestinal pressure, was published. The recent convergence of microfabrication, wireless communication, and low-power electronics has expanded this field tremendously, resulting in devices that measure physiological parameters from the body and transmit data, either wired or wirelessly, to guide treatment.

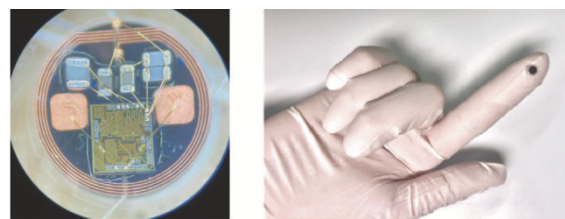
Endovascular pressure sensors



Wireless endovascular pressure sensors for catheter-based implantation within the pulmonary artery can guide titration of medication used to manage patients with congestive heart failure. These devices are realized using fused silica micromachining. The sensor comprises a passive LC resonator; pressure-induced deflection of the fused silica plates shifts its resonant frequency. An external reader detects this frequency shift and converts it to a pressure waveform.

Clinically, this sensor was validated in the CHAMPION trial, where 550 patients received implants. The device enabled clinicians to titrate therapy based on daily pulmonary artery pressure data. Patients whose treatment incorporated sensor data experienced a 30% reduction in heart-failure-related hospitalizations at six months and a 38% annualized reduction over the full follow-up period. These devices are now commercially available.

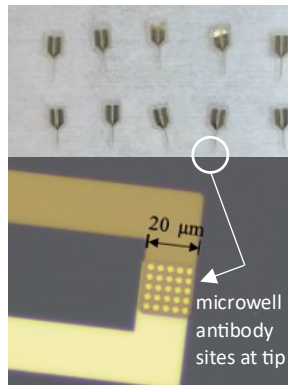
Implantable tactile sensors



Building on this fabrication technology, wireless, battery-free tactile sensing systems designed to restore touch sensation in individuals with paralysis have been fabricated. Unlike wearable tactile sensors that such patients may struggle to don, a subdermal capacitive pressure sensor encapsulated in a hermetic fused-silica package, paired with a custom ASIC that enables wireless power transfer and data communication, is investigated. Ex vivo implantation in a macaque fingertip showed that the sensor could detect

physiologically relevant light-touch forces (<1 N) with a sensitivity of 0.8 pF/N, force resolution of 4.3 mN (comparable to natural mechanoreceptor thresholds), and reconstruction of dynamic forces with high fidelity ($R^2 = 0.94$).

Microneedle cytokine sensors



These devices are needle-shaped impedance sensors designed for rapid, label-free, and real-time detection of cytokines *in vivo*. The device integrates a $20\ \mu\text{m} \times 20\ \mu\text{m}$ microwell array onto a fused-silica microneedle, enabling localized electro-

chemical sensing through impedance changes generated by specific antibody-antigen interactions within the microwells. This needle form factor supports minimally invasive transcutaneous or intramuscular deployment. Antibody immobilization and antigen binding produce reproducible impedance signatures. To validate *in vivo* functionality, the microneedle sensor was inserted into transgenic mice expressing human IL-8. Real-time impedance measurements correlated closely with ELISA-derived serum cytokine levels, enabling detection across four orders of magnitude with picomolar sensitivity, enabling a robust, minimally invasive tool for continuous cytokine monitoring, with potential applications in point-of-care diagnostics and real-time immune profiling.

Transdermal Oxygen Sensors

Monitoring oxygen levels in living tissues is essential for understanding metabolic function, disease progression, and physiological stress. A microfabricated electrochemical oxygen sensor that integrates a three-electrode gold system, a polyvinyl-alcohol (PVA) hydrogel electrolyte, and a dip-coated PDMS oxygen-permeable membrane on a flexible polyimide substrate is implemented. The resulting device is compact (2.4 mm diameter sensing region) and ultrathin ($\sim 100\ \mu\text{m}$), enabling insertion into soft tissues while maintaining structural robustness. The hydrogel electrolyte simplifies fabrication by eliminating the need for liquid reservoirs and leak-prone microfluidic chambers.



Electrochemical impedance spectroscopy confirmed comparable ionic conductivity between hydrogel- and saline-based devices, and chronoamperometry revealed effective oxygen diffusion through the PDMS-hydrogel stack, confirming the efficacy of the hydrogel electrolyte as stable, biocompatible medium that does not compromise selectivity or sensitivity.

Sensor functionality was validated *in vivo* using adult zebrafish, where it reliably measured intramuscular oxygen levels within the physiological range of 20 – 50 Torr. Measurements across multiple animals demonstrated reproducibility and agreement with expected tissue oxygenation. These findings establish such hydrogel-electrolyte oxygen sensors as a platform for minimally invasive, real-time monitoring of tissue oxygen levels, with strong potential for biomedical research and future clinical applications.

Acknowledgements

These selected examples of MEMS sensors for the body also represent the work of many students, postdocs, and collaborators over the years, which are detailed in the references below. Funding from DARPA, NIH, NSF, CDMRP, and private industry are gratefully acknowledged.

References

- Mackay, RS and Jacobson, B. "Endoradiosonde," *Nature* 179 (1957).
- Allen MG. "Microfabricated implantable wireless microsystems: Permanent and biodegradable implementations," *Proc. IEEE MEMS Conf* (2014).
- Du L, Hao H, Ding Y, Gabros A, Mier TC, Van der Spiegel J, Lucas TH, Aflatouni F, Richardson AG, Allen MG. "An implantable, wireless, battery-free system for tactile pressure sensing," *Microsystems & Nanoengineering*, 9(1):130 (2023).
- Song N, Xie P, Shen W, Oh H, Zhang Y, Vitale F, Javanmard M, Allen MG. "A microwell-based impedance sensor on an insertable microneedle for real-time *in vivo* cytokine detection," *Microsystems & Nanoengineering*, 7(1):96 (2021).
- Venkatesh V, Burg L, Anderson VE, Zolkipli-Cunningham Z, Falk MJ, Allen MG. "Microfabricated electrochemical oxygen sensors with hydrogel electrolytes for *in vivo* applications," *J. Micromechanics and Microengineering*, 35(12):125013 (2025).