Bioelectronic Monitoring Systems for Dialysis

1) Background, Technology Foundations
2) Applications in the NICU and PICU
3) Applications in Shunted Hydrocephalus
4) Applications in Kidney Transplant Rejection

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Electronics for the Human Body
‘Epidermal’ Electronics

Multimodal, Clinical Quality Data

Science 344, 70 (2014).
Quantitative Correlation to Clinical Gold Standards

**Electrocardiography**

**Hydration**

- 6 mm
- ΔT at 1.5 s (°C)

**Tonometry (pressure)**

- 2 cm
- IDS (µA)
- Time (s)
- ECG (mV)
- QP
- R
- T
- S

- k (W·m⁻¹·K⁻¹)
- Moisture level (AU)

- 20 40 60 80 100
- 0.2 0.3 0.4

- 1 2 3

- 19 19.2 19.4 19.6 19.8 20
- 0 0.5 1

- 0 0.5 1

- 136 133 130

- 0 1 2 3 4 5

- Radial artery
- Epicondyle vessel
Thermal Conductivity -- Microvascular Blood Flow

Trauma induced perfusion changes

Thermal Actuators/Sensors for Blood Flow Measurement

Occlusion and Reperfusion
Measurement Capabilities in Epidermal Electronics

**Thermal:** Thermography, Thermal Transport, Hydration

**Electrical:** Biopotential (ECG, EMG, EEG), Hydration

**Fluidic:** Sweat (loss and chemistry), blood flow

**Mechanical:** Strain, motion, modulus, pressure

**Optical:** UVA/UVB, oximetry, PPG, vein mapping

**Mechano-acoustic** – cardiac auscultation, etc.
Neonatal Intensive Care

Current  Future
Wireless, Epidermal Vital Signs Monitoring Systems

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Interdisciplinary Research
Engineering & Medicine

45 co-authors!!

Materials Science
Mechanical Engineering
Electrical Engineering
Biomedical Engineering
Computer Science
Science
Dermatology
Neonatology
Pediatrics

Graduate students
Undergraduates
Postdocs
Nurses
Doctors
Faculty

RESEARCH

ARTICLE SUMMARY

Biomedical Engineering

Binodal, wireless epidermal electronic systems with in-sensor analytics for neonatal intensive care


INTRODUCTION: In neonatal intensive care units (NICUs), continuous monitoring of vital signs is essential, particularly in cases of severe prematurity. Current monitoring platforms require multiple hard-wired, rigid interfaces to a neonate's fragile, underdeveloped skin, and, in some cases, invasive lines inserted into their delicate arteries. These platforms and their wired interfaces pose risks for long-term tissue injury, create physical barriers for skin-to-skin contact between neonate and bonding, and frustrate even basic clinical tasks. Technologies that bypass these limitations and provide additional, advanced physiologic data that could enable direct access to an unmet clinical need for a highly vulnerable population.

RATIONALE: It is now possible to fabricate wireless, battery-free vital signs monitoring systems based on ultrathin, “skin-like” measurement modules. These devices can gently and non-invasively interface with the skin of neonates with gestational ages down to the edge of viability. Four essential advances in engineering science serve as the foundations for this technology: (i) schemes for wireless power transfer, (ii) new materials and processes for integrated electronics and circuitry; (iii) strategies for time-synchronized streaming of wireless data from two separate devices; and (iv) designs that enable visual inspection of the skin interface while also allowing magnetic resonance imaging and x-ray imaging of the neonate. The resulting systems can be much smaller in size, lighter in weight, and less traumatic to the skin than any existing alternative.

RESULTS: We report the realization of this class of NICU monitoring technology, embodied as a pair of devices that, when used in a time-synchronized fashion, can reconstruct full vital signs information with clinical-grade precision. One device mounts on the chest to capture electrocardiogram (ECG) data, while the other rests on the base of the foot to simultaneously record photoplethysmogram (PPG) data. This binodal system captures and continuously transmits ECG, PPG, and (from each device) skin temperature data, yielding measurements of heart rate, heart rate variability, respiration rate, blood oxygenation, and pulse arrival time as a surrogate of systolic blood pressure. Successful tests on neonates with gestational ages ranging from 28 weeks to full term demonstrate the full range of functions in two level III NICUs. The thin, lightweight, low-modulus characteristics of these wireless devices allow for integration into the neonatal environment without compromising safety or function. These platforms also facilitate therapeutic skin-to-skin contact between neonates and parents, which is known to stabilize vital signs, reduce morbidity, and promote parental bonding. Beyond use in advanced hospital settings, these systems also offer cost-effective capabilities with potential relevance to global health.

CONCLUSION: The advances outlined here serve as the basis for a skin-like technology that not only reproduces capabilities currently provided by invasive, wired systems as the standard of care, but also offers multipoint sensing of temperature and continuous tracking of blood pressure, all with substantially safer device-skin interfaces and compatibility with medical imaging. By eliminating wired connections, these platforms also facilitate therapeutic skin-to-skin contact between neonates and parents, which is known to stabilize vital signs, reduce morbidity, and promote parental bonding. Beyond use in advanced hospital settings, these systems also offer cost-effective capabilities with potential relevance to global health.

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A. ECG

B. PPG

C. 1 cm

D. PPG device on the chest (C) and on the back (D).
Hydrocephalus and Shunts

Ventricle

shunt

Obstruction

Ventricle

shunt
Hydrocephalus and Shunts

1. Congenital

2. Traumatic Brain Injury

Standard of Care: Ventricular Shunts

- Kinking
- Obstruction
- Rupture
- Nonspecific Symptoms

“Our son has undergone 189 surgical procedures related to his shunt. He has had 100s of CT scans, X-rays. He has missed birthdays, school events and virtually every holiday.”
Pilot Studies on Patients (n=11)

Simple Skin Interface

No Flow vs. Confirmed Flow

\[ \Delta T_{\text{sensors}} / T_{\text{actuator}} \]

\[ \text{On Shunt} \quad \text{Off Shunt} \]

\[ N = 5 \quad P^* = 0.012 \]

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Northwestern Medicine

Willie Meyer
Hydrocephalus patient

Interdisciplinary Research
Engineering & Medicine

23 co-authors

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Mechanical Engineering
Electrical Engineering
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Computer Science
Neurological Surgery

Graduate students
Undergraduates
Postdocs
Clinical coordinators
Surgeons
Faculty

**Biosensors**

**Epidermal electronics for noninvasive, wireless, quantitative assessment of ventricular shunt function in patients with hydrocephalus**

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Hydrocephalus is a common and costly neurological condition caused by the overproduction and/or impaired resorption of cerebrospinal fluid (CSF). The current standard of care, ventricular catheters (shunts), is prone to failure, which can result in neurological symptoms such as headaches, dizziness, and nausea. Shunt failure can be identified using imaging such as computed tomography (CT), magnetic resonance imaging (MRI), radioisotope shunt patency studies (RSPSs), and more recently, Doppler ultrasound. Critical to patient diagnosis and care, each of these methods has inherent limitations, including high cost, poor accuracy, and limited accessibility.

**INTRODUCTION**

Ventricular shunts represent an essential component of clinical treatment for hydrocephalus, a common and debilitating neurological disorder that results from an imbalance in the production and/or impaired resorption of cerebrospinal fluid (CSF), leading to an intracranial pressure (ICP) imbalance. Ventricular shunts involve the placement of a valve, typically silicon catheters, connected upstream and downstream of a regulating valve, to drain CSF from the ventricles to a distal absorptive site. In this study, "ventricular shunt" refers to a shunt system consisting of a proximal catheter draining CSF from the ventricular system, a flow regulator, and a distal catheter draining fluid from the valve to the recipient site, such as the peritoneum, pleural cavity, or right atrium. Although effective in CSF diversion and prevention of the sequelae of hydrocephalus, shunts are highly prone to failure (1). Clinical symptoms of shunt malfunction tend to vary, thus eliminating specific symptoms such as headache, nausea, and somnolence, thereby creating challenges in clinical diagnosis (1, 2). Because of the wide variety of malfunction types, a simple, easy-to-use, and accessible diagnostic tool is required.

At the University of Illinois at Urbana-Champaign, a joint collaboration between the Querrey Simpson Institute for Bioelectronics and the National Institute of Neurological Disorders and Stroke has developed an overcoat technology that provides a versatile and effective platform for on-demand desorption of CSF, thus facilitating targeted drug delivery and on-demand modulation of shunt function. This technology is 100% drug-free and cost-effective, and it can be easily integrated into existing shunt systems, providing a noninvasive, patient-friendly solution for shunt malfunction monitoring.

**METHODS**

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Bio-Integrated Electronics

Brain

Heart


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Soft Electronics for Monitoring Kidney Transplants

**Thermal Sensor Probe**
- silicone
- polyimide
- gold
- polyimide
- silicone

**Wireless Module**
- silicone
- flex PCB
- stiffener
- silicone

**Renal Capsule**
- thermal sensor

**Kidney**
- wireless module
- thermal sensor
Measurement Modalities – Temp + Conductivity

**Temperature Mode:**
- ~ 10 mK resolution
- ~ 20 °C range
- 1 Hz Sampling Rate

**Thermal k Mode:**
Healthy Tissue —> Low thermal $k$
Diseased Tissue (Increased Blood Flow) —> High thermal $k$

$\Delta T (°C)$

- $k = 0.2 \text{ W/m-K}$
- $k = 0.4 \text{ W/m-K}$

**Graph:**
- Temperature vs. time (min)
- Sensor vs. IR Camera

**Diagram:**
- Thermal Sensor
- Low Current
- High Current
- Software Control
- Temperature
- Thermal $k$
Applications in Limb Transplant

Surgical Placement

Continuous Data Recording

Back (Transplanted vs. Native)

Limb (Transplanted vs. Native)
Senior Collaborators

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Prof. Y. Zhang (Tsinghua) -- mechanics

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Prof. L. Gallon – kidney transplants
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