Soft Electronics for the Human Body

1) Epidermal Electronics

2) Biodegradable Electronics

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The Dominant Future for Electronics:

**Smaller, Faster, Cheaper**

**Past**

**Present**

**Future**

**Industrial**

**Personal**

**Smaller, Faster Cheaper**
An Alternative Future for Electronics:

**Stretchy, Curvy, Bio-Integrated**

**Past**

**Industrial**

**Present**

**Personal**

**Future**

**Bio-Integrated**

New Concept: ‘Epidermal’ Electronics

1) Ultra-thin (~5 µm), ultra-light (~1 mg/cm²)
2) Ultra-low modulus (~5 kPa), stretchable (30%)
3) Air/water permeable; waterproof

‘electronic temporary tattoo’
Stretchable Silicon

(1): Thin -- **Flexible**  \[\rightarrow\]  (2): Wavy -- **Stretchable**

Si nanoribbons

Si wafer

--- 50 µm

--- 10 µm

Epidermal Electronics on Skin, and Free-Standing

Skin Mounted, Deformed

Free Standing

Fractals are a class of geometries defined by self-similarity.
Clinical Standard Measurements Through The Skin

**Electrocardiography**

**Hydration**

**Tonometry (pressure)**
Measuring EKG, Forearm EMG via EES (w/ Coleman)

Epidermal Electronics for the Auricle -- EEG

Persistent EEG for BMI

Precision Skin Temperature via Epidermal Electr.

Delivery of Heat -- Meas of Thermal Conductivity

Nat. Mater. 12, 938 (2013).
Thermal Actuators/Sensors for Blood Flow Measurement

Occlusion and Reperfusion

Characterization of Dermatographic Urticaria

**Figure a:** Image of skin with a trauma mark.

**Figure b:** Graph showing temperature (°C) over time (min) with a vertical line indicating trauma.

**Figure c:** Graph showing change in temperature (ΔT) over time after heater turns on (s), with lines for 'Before' and 'After' conditions.

**Figure d:** Heat map showing temperature distribution with color scale.

**Figure e:** Another image of skin with a trauma mark.

**Figure f:** Graph showing temperature (°C) over time (min) with a vertical line indicating trauma.

**Figure g:** Graph showing change in temperature (ΔT) over time after heater turns on (s), with lines for 'Before' and 'After' conditions.

**Figure h:** Heat map showing temperature distribution with color scale.
Clinical Studies With Loreal

a. Cheek

b. Dorsal forearm

C. Volar Forearm

d. Wrist
Measurement of Arterial Blood Pressure Waves

Nat. Comm. DOI: 10.1038/ncomms5496 (2014).
Epidermal PZT Actuators/Sensors for Modulus Measurement

Clinical Study Involving 32 Volunteers
Wireless, Electronic Data Tattoo

Small 11, 906 (2015).
Multiphysics Modeling: Mechanics and EM

Small 11, 906 (2015).
Wireless, Electronic Data Tattoo

Small 11, 906 (2015).
NFC System Architecture

Sensor (Transducer)

- CPU
- Memory
- A/D conv.
- Regulator

NFC Interface

Wireless Reader 13.56MHz

Data

Magnetic Field

Energy

unpublished
Wireless ECG Data, Comparison to Clinical Standards

Clinical Standard

Epidermal

unpublished
Long Range (~1 m) Operation, On-Board Data Analytics

unpublished
Arrays of Chip Scale Batteries

unpubl.
Mounting, Deformation on Skin

Bending, Twisting, Pinching, Stretching

unpubl.
Compact Integration by Folding

LM Sil 
Device
LM Sil
Silicone

Solar cell
Folding line
Battery

Wrap
Align
Press

Top
Bottom
Top
Bottom

ε_{max}(%) 0.13

Silicone
LM Sil
Cu

unpubl.
Stretchable NFC Temperature Sensor w/ Battery

unpubl.
Temperature Data-Logging + Wireless Readout

Temperature (°C)

Time (s)

0 100 200 300 400 500 600

Ready Exercise Rest

26.5 27.0 27.5 28.0 28.5

TI NFC AMS NFC

unpubl.
Real time ECG and heart rate logging in ultra-thin sticker form factor for clinical monitoring, neuromarketing and sports applications.
Commercial Activities – MC10, Reebok, L’Oreal

**CheckLight (Reebok/MC10)**

**Biostamp (MC10)**

**UVSense (L’Oreal/MC10)**
Epidermal Microfluidics, and Sweat Analytics

In revision, Science Translational Medicine
Epidermal Microfluidics, and Sweat Analytics

In revision, Science Translational Medicine
Epidermal Sweat Analytics
Bio-Integrated Electronics

Brain

Heart


Nature Comm. 10.1038/ncomms4329 (2014)
An Alternative Future for Electronics: Bio / Eco Resorbable, Transient

Past  Current  Future

Industrial  Personal  Bio / Eco Resorbable

Science 337, 1640 (2012).
Potential Applications

1) Zero/Reduced E-Waste Consumer Electronics
2) Implantable Therapeutics / Diagnostics
3) Environmental Monitors / Sensors
4) …

Silicon is Water Soluble!

\[ Si + 4 \text{H}_2\text{O} \rightarrow \text{Si(OH)}_4 + 2 \text{H}_2 \]

Transient Electronics – Test Platform

Si, SiO₂, Mg, MgO and silk

Science 337, 1640 (2012).
Intracranial Monitors for TBI

**Current**

Non-degradable → Secondary surgery
Wired operation → Restricted movement
External interface → Infection / hemorrhage

**Future**

Bioresorbable → Eliminate extraction
Wireless operation → Free movement
Fully sutured → Safe, minimal risk

http://violetsjourney.blogspot.com/2012/02/icp-monitoring.html
Bioresorbable Intracranial Pressure Sensors for TBI

Nature (2016)
**Performance in Water and aCSF**

*In-vitro* Operation in DI

![Graph showing pressure and resistance over time for commercial versus transient sensors.](image)

*In-vitro* Operation, With PLGA Encapsulation in aCSF @ 37 C

![Graph showing pressure and resistance over time for commercial versus transient sensors over multiple days.](image)

*Nature (2016)*
In-vivo Wireless Monitoring – Pressure and Temperature

Schematic

In-vivo Results Using A Rat Model

Tercekik response

Breathing pressure

Increase of blood circulation recovering from anesthesia

ice sauna for release fever

Nature (2016)
The Future of Electronics is
*Stretchy and Bioresorbable*

**Epidermal Electronics**

**Transient Electronics**
Senior Collaborators

**Engineering Science**

Prof. Y. Huang (NU) – mechanics modeling

Prof. P. Ferreira (UIUC) – manufact.

Prof. R. Nuzzo (UIUC) – surf. chem.

Prof. X. Li (UIUC) – MOCVD

T. Lyszczarz (LL) – CMOS proc.

**Clinical Medicine**

Dr. B. Litt (Penn) – epilepsy

Dr. M. Kliot (NU) – neurosurgery

Dr. M. Slepijan (Sarver) – cardiology

Dr. A. Paller (NU) – NICU