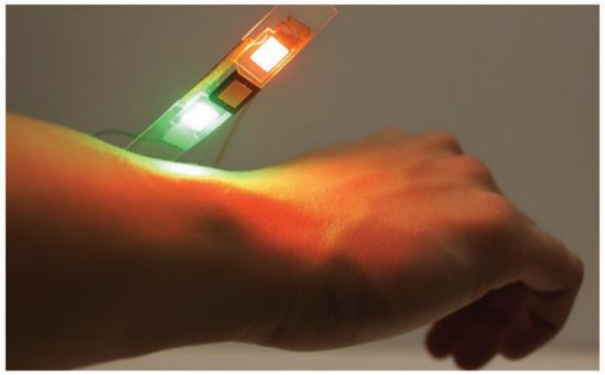
USC University of Southern California

ECE 105: Introduction to Electrical Engineering



Lecture 14

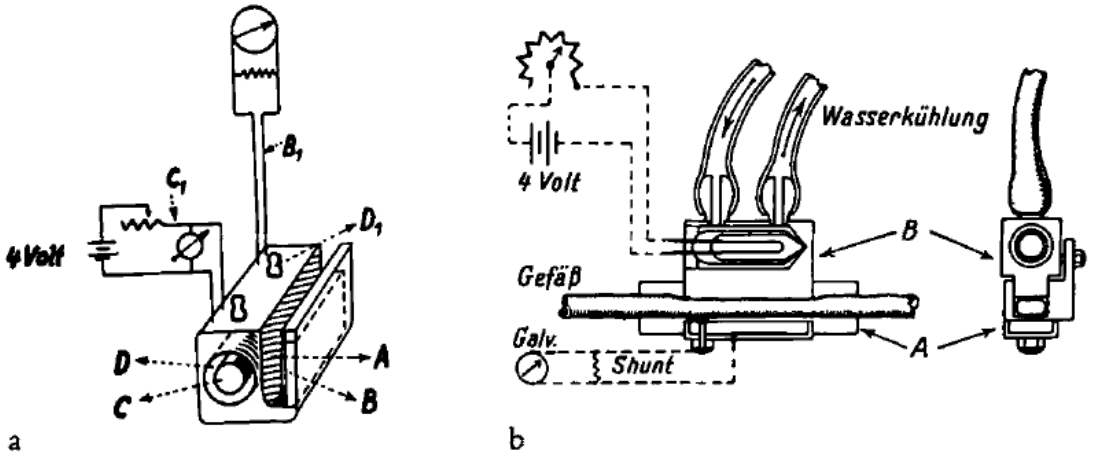
Bio sensing 4

Yasser Khan

Rehan Kapadia

Oximetry - History

- 1864, The discovery that the colored substance in blood was the carrier of oxygen was made by George Gabriel Stokes (1819-1903)



- 1935, Kurt Kramer (1906-1985) showed that the Lambert-Beer law applied to hemoglobin solutions and approximately to whole blood, and measured saturation by the transmission of red light through unopened arteries.

- 1942, Glenn Allan Millikan (1906-1947) built a light-weight ear "oximeter" during World War II to train pilots for military aviation using a mercury vapor light, yellow and purple filters, and a copper oxide photocell.

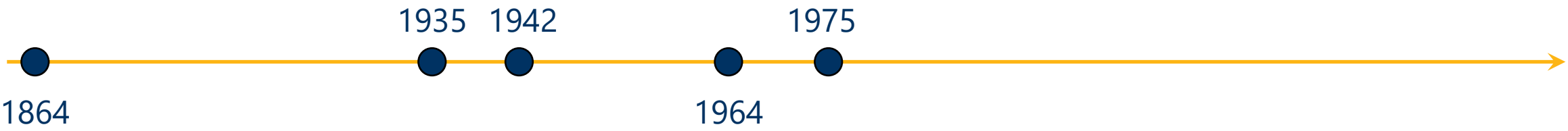
1864 1935 1942

Oximetry - History

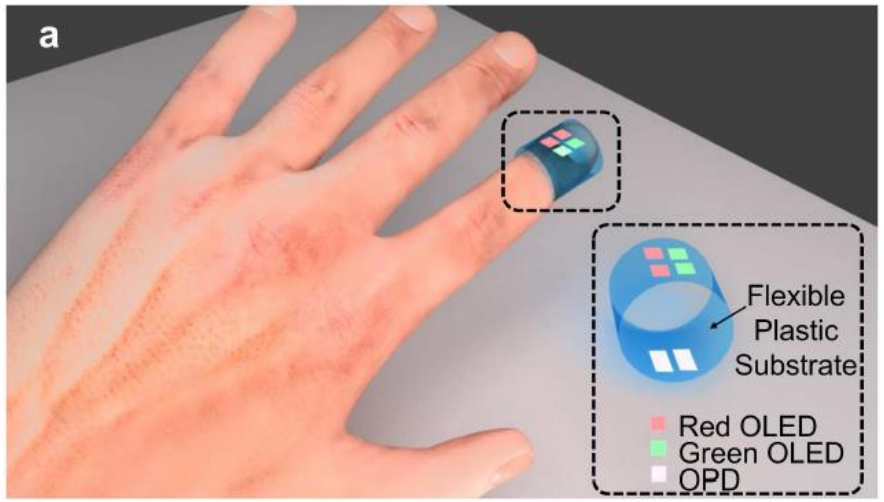
- Around 1964, Robert Shaw, a surgeon and inventor in San Francisco, began design and construction of a self-calibrating, eight-wavelength ear oximeter. His concept was to uniquely solve the simultaneous equations by using one more wavelength than the number of separate forms of hemoglobin needing identification.

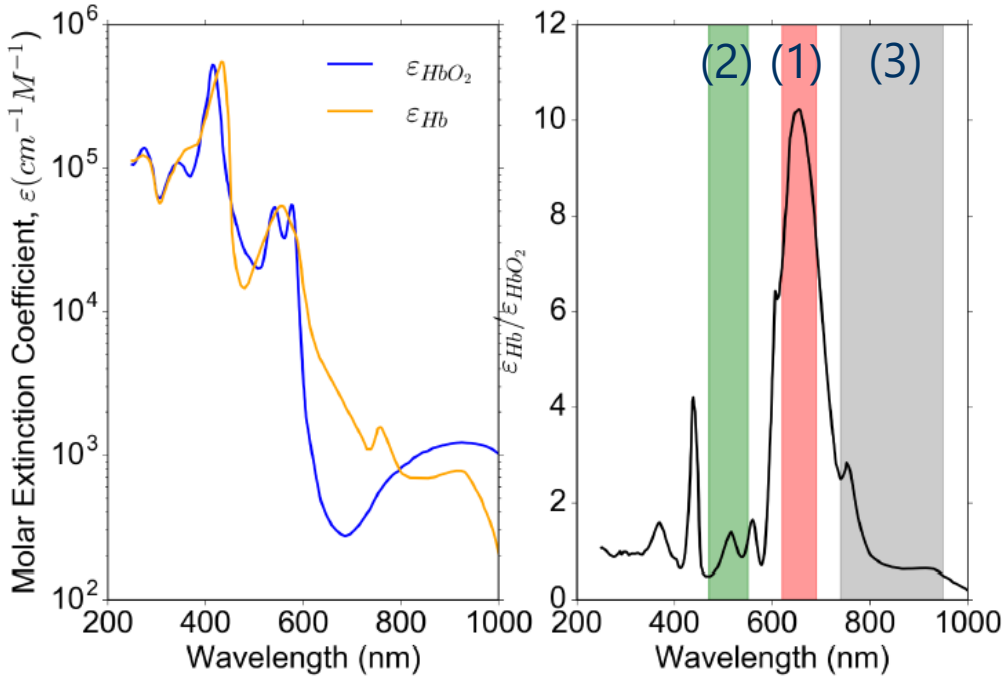
- 1975, Pulse oximetry was reported by Nakajima, Hirai, Takase, Kuse, Aoyagi, Kishi, and Yamaguchi of the Minoha Corporation. They used fiberoptic bundles to conduct light to and from a finger. Initially the main problem was extreme sensitivity to motion.

Solid state pulse oximeter "probes" on typical locations. Ohmeda Company, Boulder, CO.



Motivation for flexible oximeters

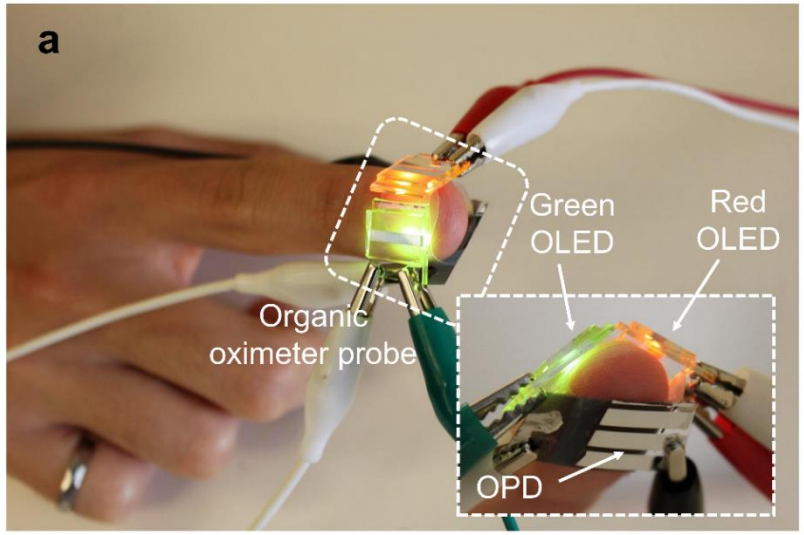




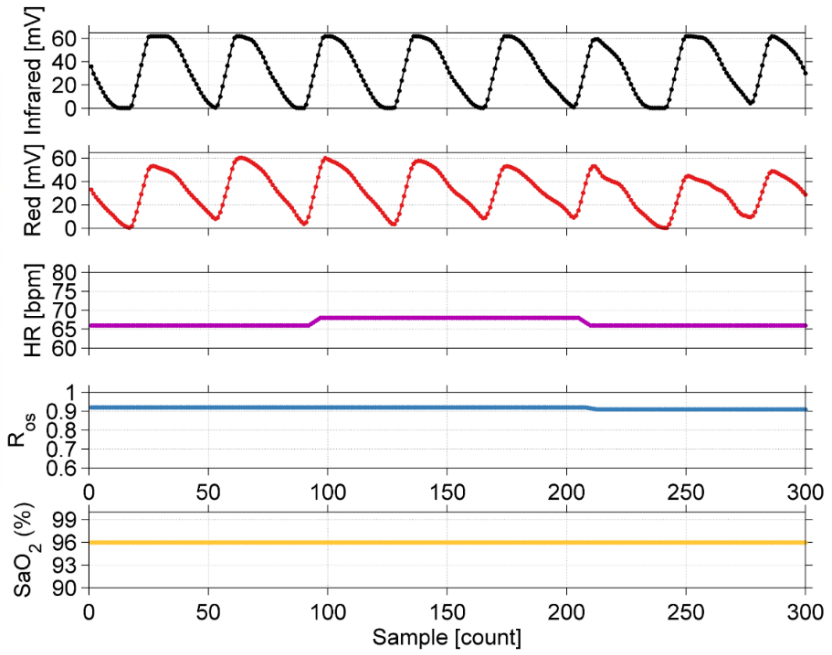
Ratio of the
molar extinction coefficients
(1) red (ε_{Hb} / ε_{HbO_2} > 6)
(2) green ε_{Hb} / ε_{HbO_2} < 2)
(3) NIR (ε_{Hb} / ε_{HbO_2} < 3)

- Flexible and printed oximeter sensor to replace conventional rigid finger probe.
- The difference in the molar extinction coefficient of oxygenated and deoxygenated hemoglobin at green is comparable to the difference at NIR wavelengths.
- Either of the combinations of “red and green” or “red and NIR” can be used for oximetry.

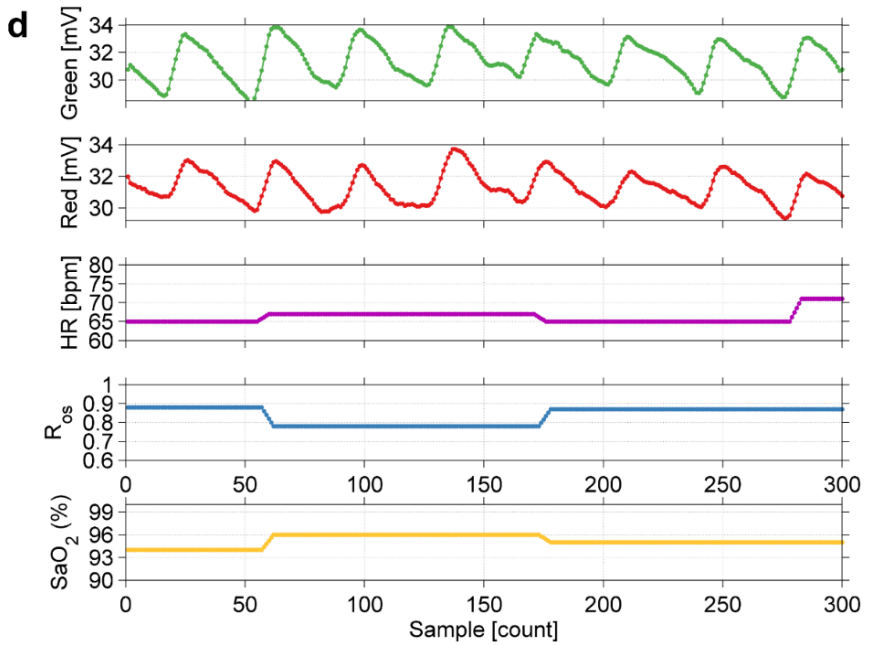
Organic optoelectronic pulse oximetry system



Oximeter probe



The PPG signal obtained using red and infrared light of commercially available probe

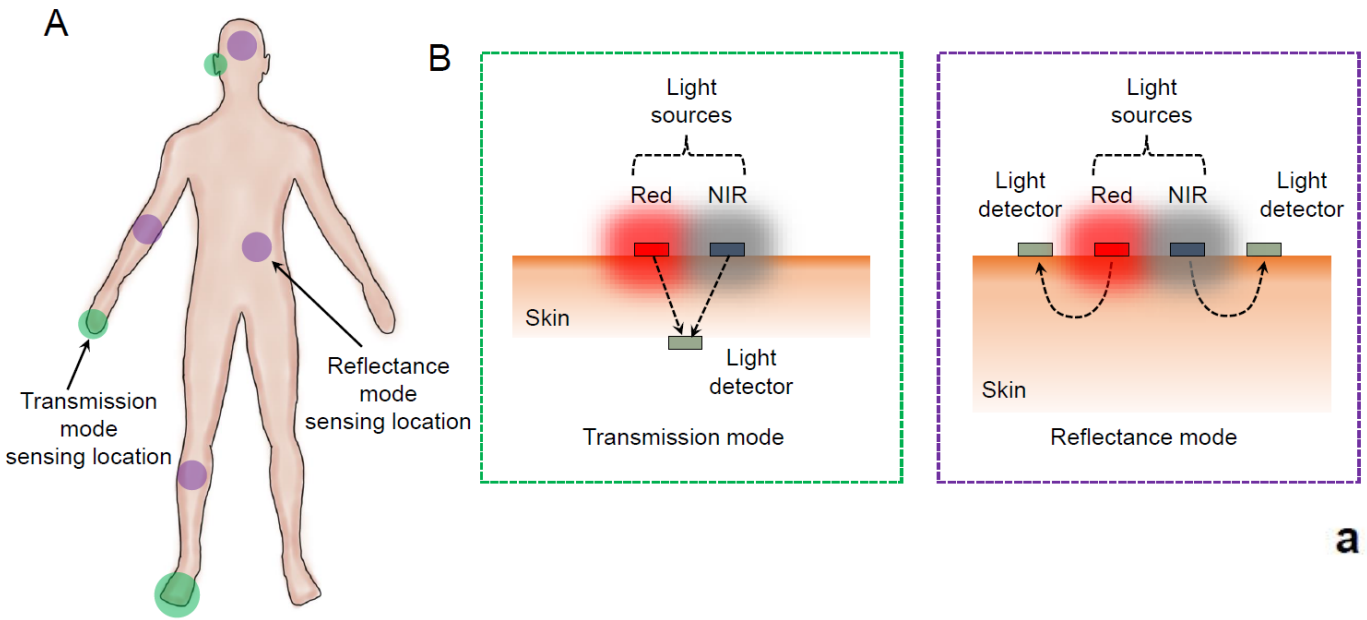


The PPG signal obtained using red and green light of the organic probe

- Heart rate (HR) was obtained by timing the systolic peaks in the PPG signals.
- The ratio of the transmitted light at two wavelengths (R_{os}) is converted to arterial blood oxygen saturation (S_aO_2) using Beer-Lambert's Law in conjunction with an empirical correction.

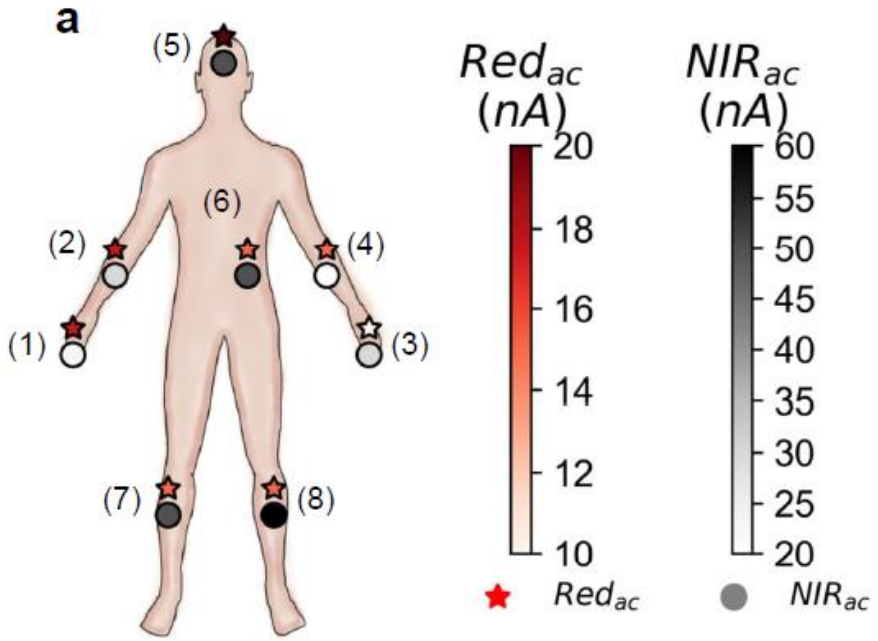
The organic sensor accurately measures pulse rate and oxygenation with errors of 1% and 2%, respectively.

Transmission vs. reflectance oximetry

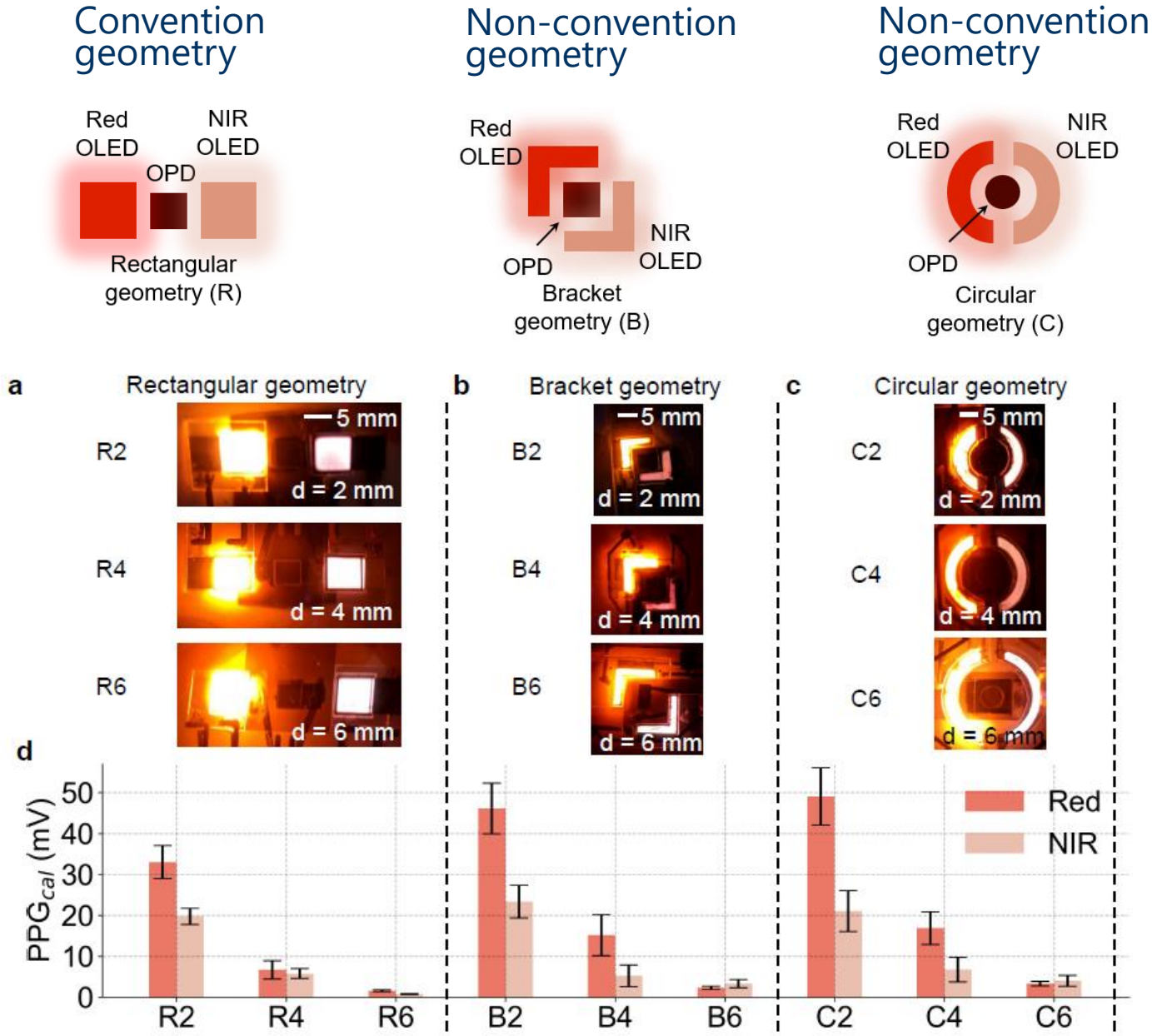


- Transmission-mode pulse oximetry is limited only to tissues that can be transilluminated, such as the earlobes and the fingers.
- If reflected light is used as the signal, the sensor can be used beyond the conventional sensing locations.

- AC signal is the highest at the forehead for both Red and NIR channels.
- Arms provide mid-range AC amplitude, while signal strength is low in the legs and chest area.
- Forehead is the best location for reflectance pulse oximetry.



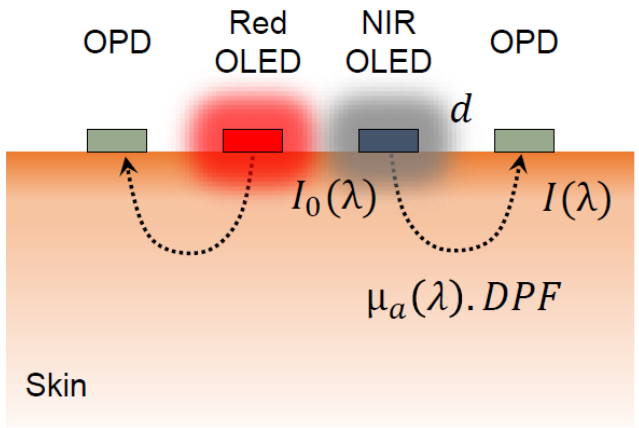
Effect of different sensor geometries



- Use perimeter lighting to increase the incident light.
- Use large-area light sources to improve PPG signal magnitude by spreading the flux over an area, rather than a single spot.

- Due to perimeter lighting and better light collection by the OPD, both bracket and circular geometries outperform the rectangular design in both pulsatile PPG signal magnitude and sensor efficiency.
- The bracket and circular design provide a negligible difference of PPG_{ac}.

Reflectance pulse oximetry

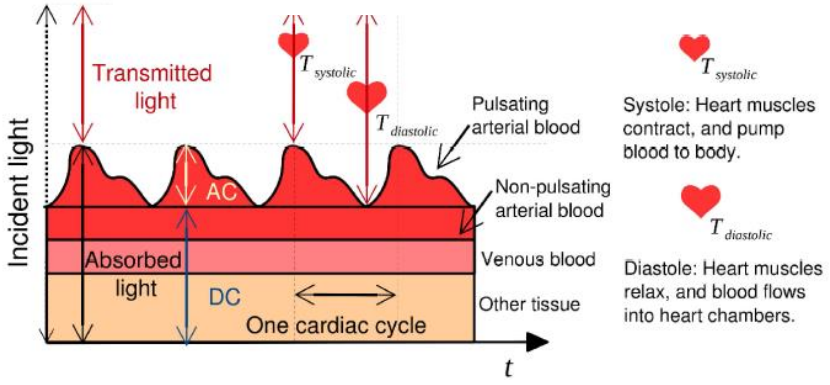


$$I = I_0 \exp(-\varepsilon C \cdot d \cdot DPF)$$

Here, I_0 is the incident light intensity,
ε is the molar extinction coefficient with unit of $mM^{-1}cm^{-1}$,
C is the concentration of the absorbent substance, and
d is the optical path length through the medium.

The absorbance, A, is now defined as,

$$A = -\ln \frac{I}{I_0} = \varepsilon C \cdot d \cdot DPF$$



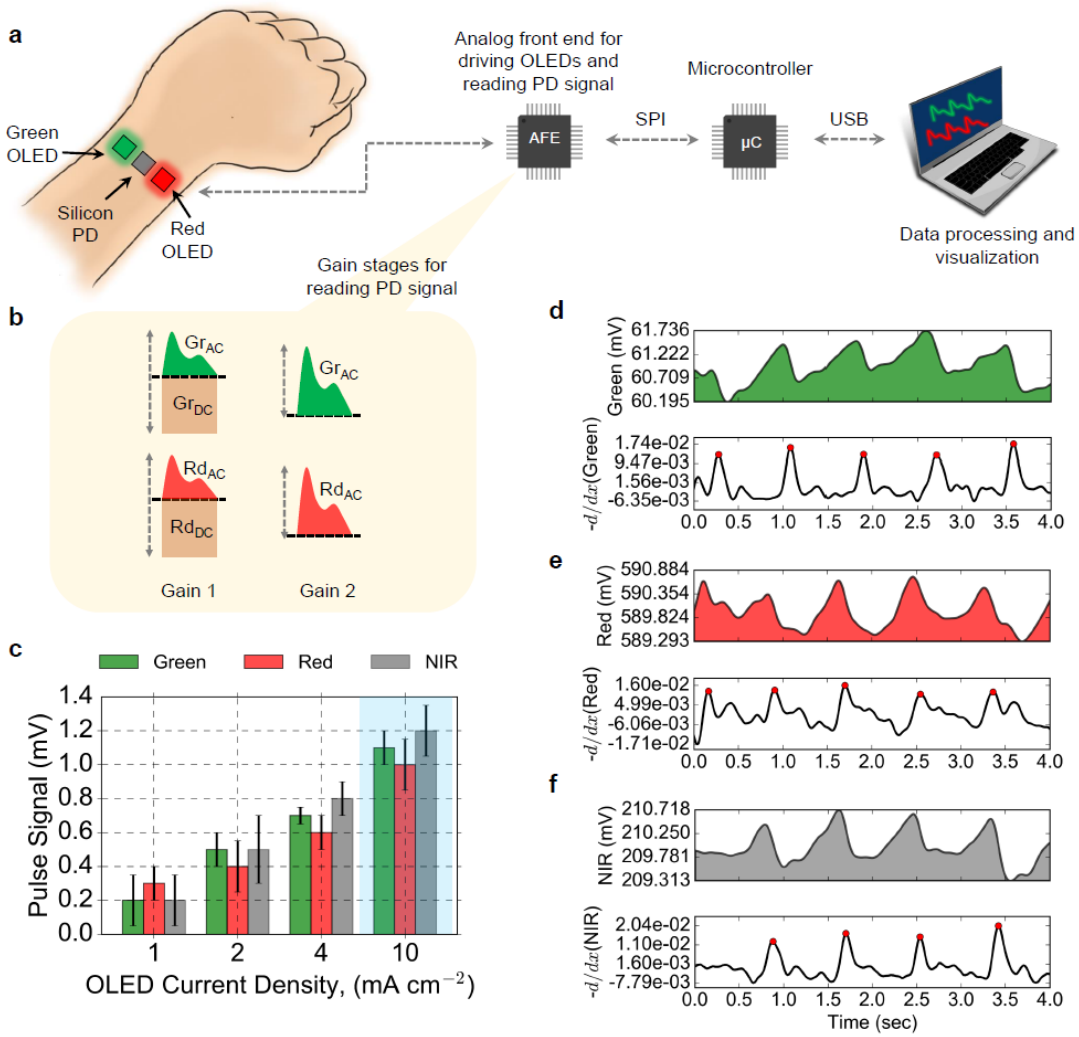
$$I_{high,dia} = I_0 \exp(-\varepsilon_{dc} C_{dc} \cdot d_{dc} \cdot DPF) \exp(-(\varepsilon_{HbO_2} C_{HbO_2} + \varepsilon_{Hb} C_{Hb}) \cdot d_{dia} \cdot DPF)$$
$$I_{low,sys} = I_0 \exp(-\varepsilon_{dc} C_{dc} \cdot d_{dc} \cdot DPF) \exp(-(\varepsilon_{HbO_2} C_{HbO_2} + \varepsilon_{Hb} C_{Hb}) \cdot d_{sys} \cdot DPF)$$

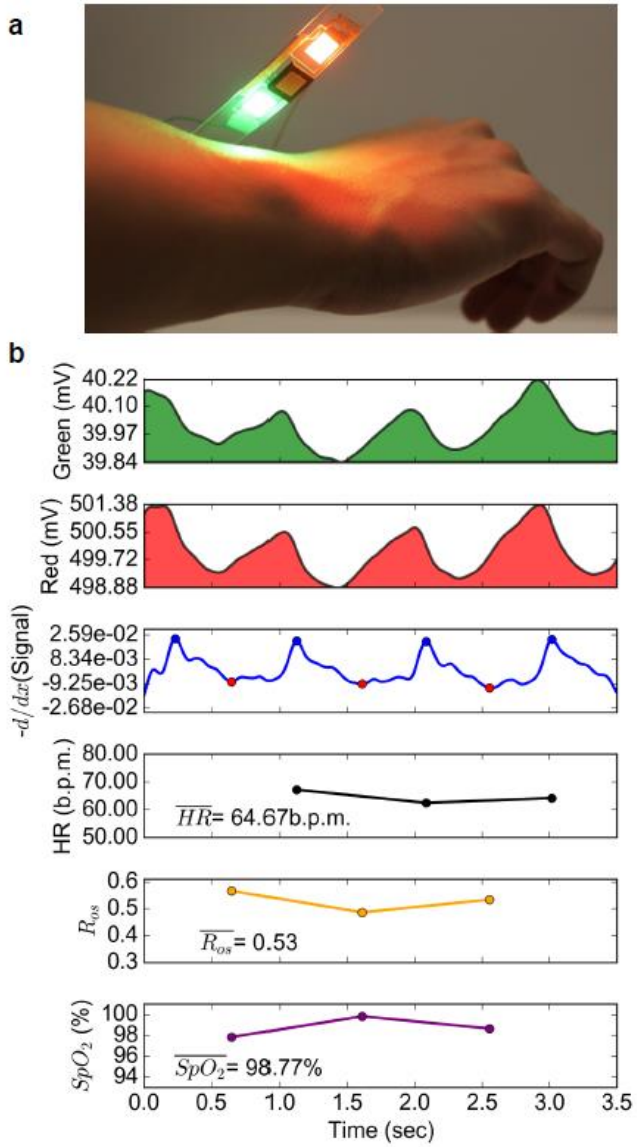
Skin, tissue, and bones — Oxy-hemoglobin — Deoxy-hemoglobin

Ratio, $$R'_{os} = \frac{R_{os}}{\frac{DPF_{\lambda_1}}{DPF_{\lambda_2}}}$$

Oxygen Saturation, $$S_aO_2(R'_{os}) = \frac{\varepsilon_{\lambda_1,Hb} - \varepsilon_{\lambda_2,Hb} R'_{os}}{(\varepsilon_{\lambda_1,Hb} - \varepsilon_{\lambda_1,HbO_2}) + (\varepsilon_{\lambda_2,HbO_2} - \varepsilon_{\lambda_2,Hb}) R'_{os}}$$

Reflection-mode PPG

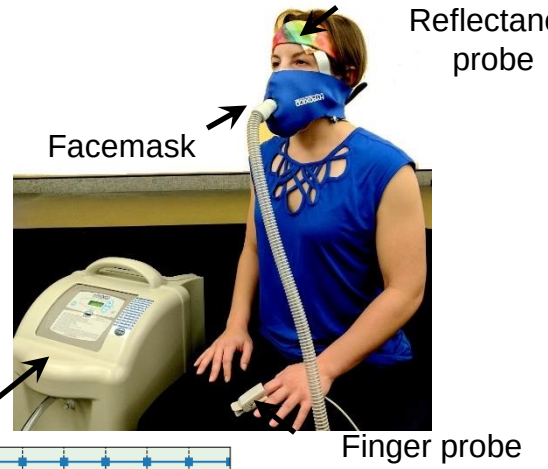




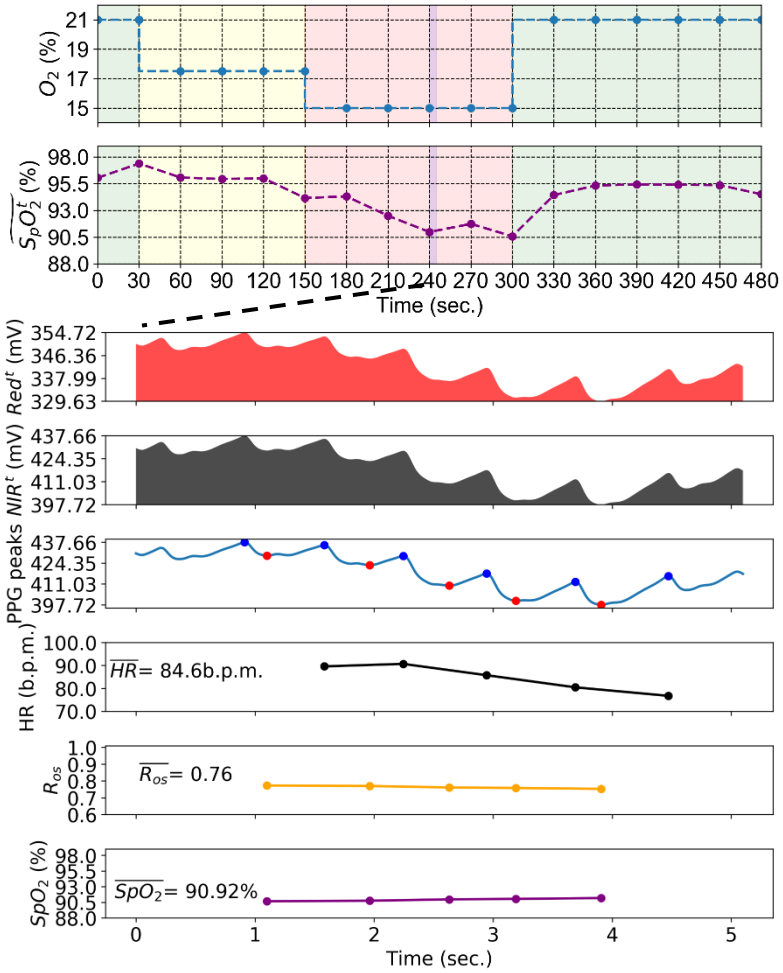
- Light absorption in the tissue depends on the wavelength of the light and, as a result, PPG signal attenuation of visible light is much more pronounced than that of NIR light.

Simultaneous transmission and reflection oximetry

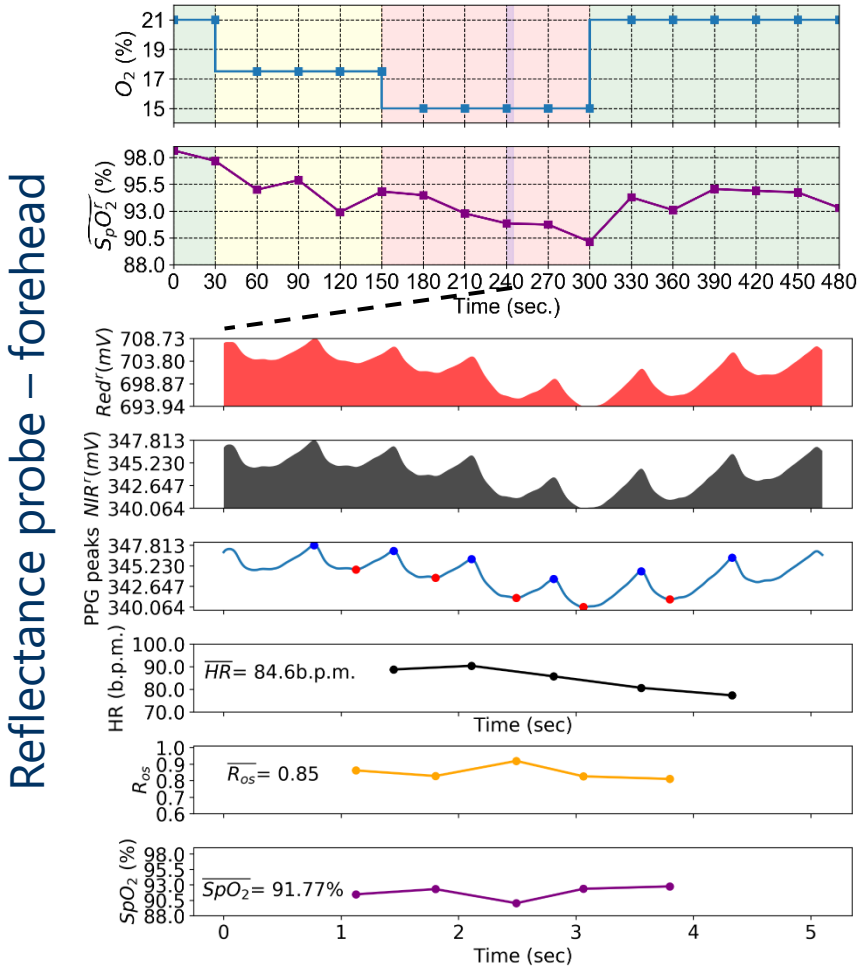
- Oxygen intake of a volunteer was controlled using an altitude generator. Both transmission and reflection-mode data was collected using a commercial and the printed probe, respectively.



Commercial finger probe – transmission

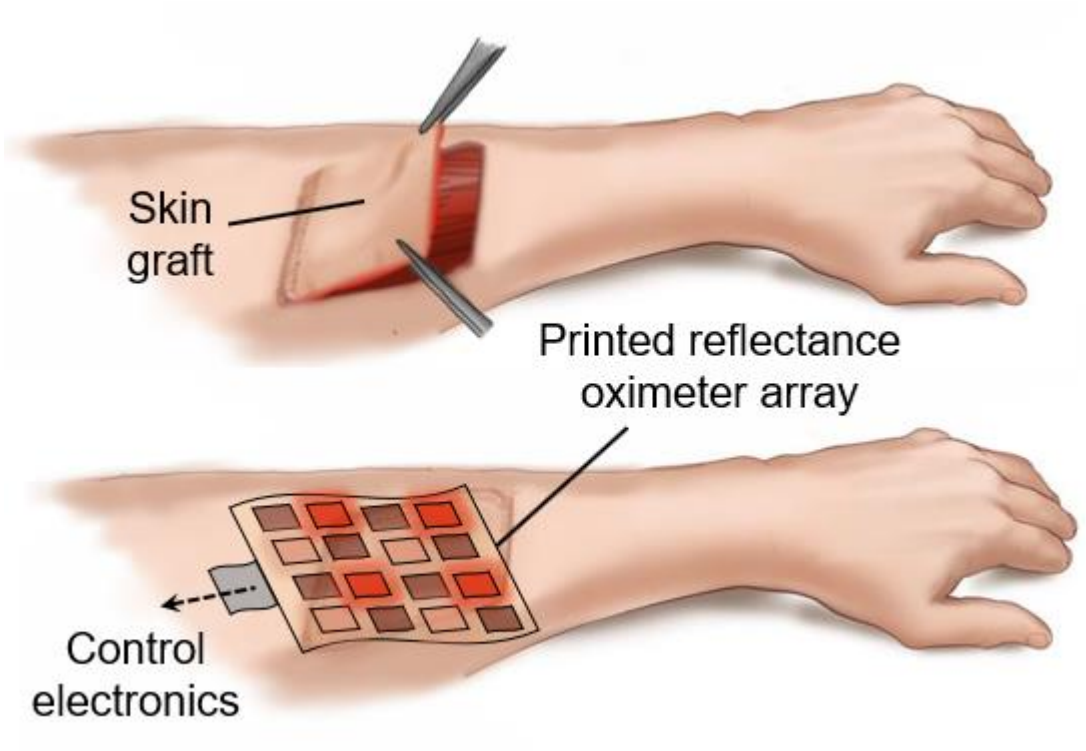


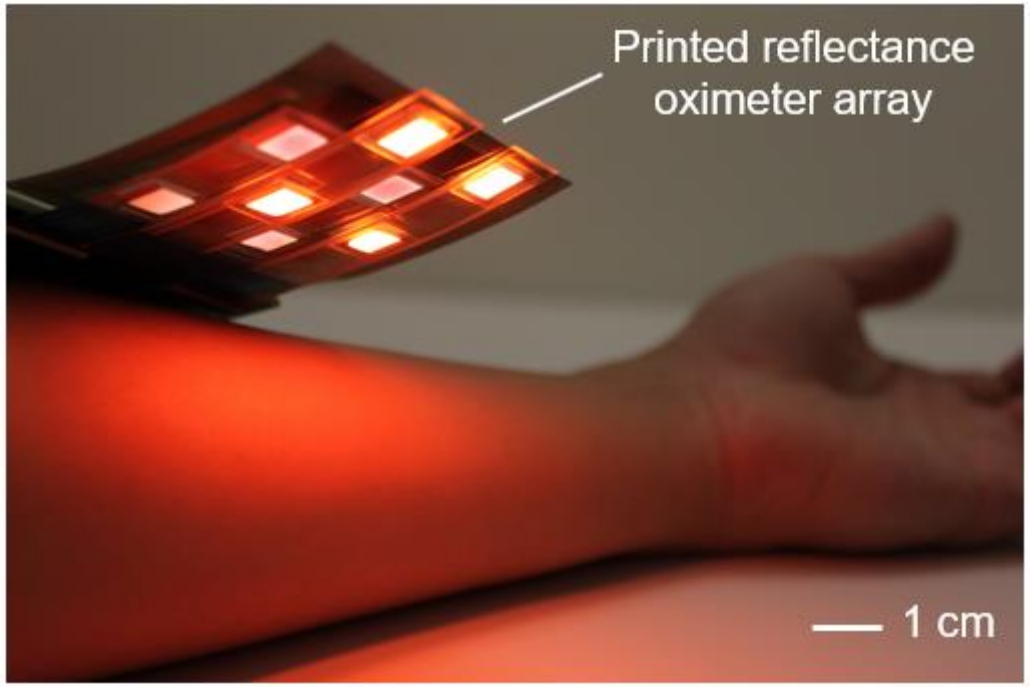
Reflectance probe – forehead



The reflectance oximeter measures SpO2 on the forehead with 1.1 % mean error compared to commercial transmission-mode pulse oximeters, which falls within the 1-2 % error margin that is inherent to pulse oximetry.

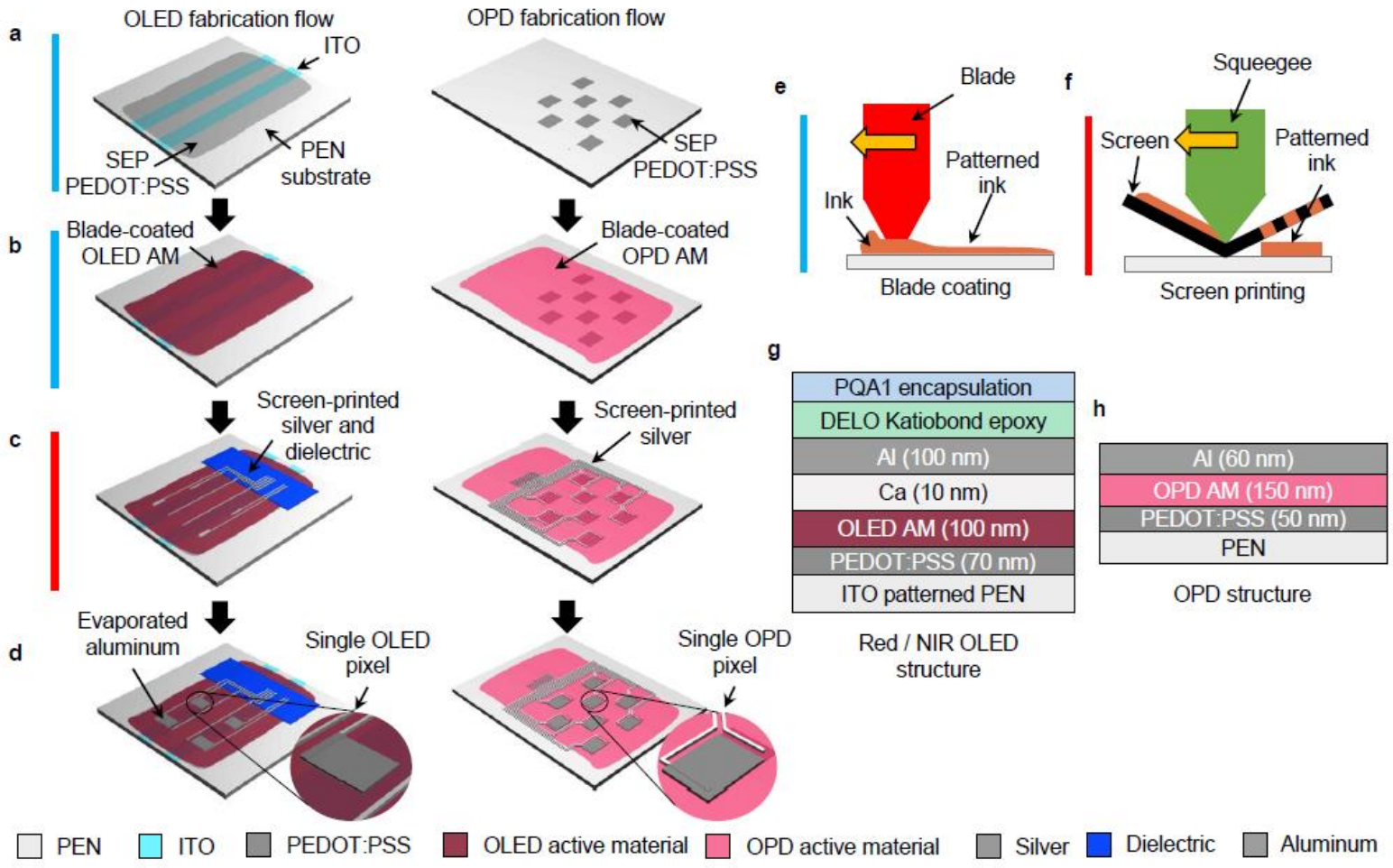
Printed oximeter array

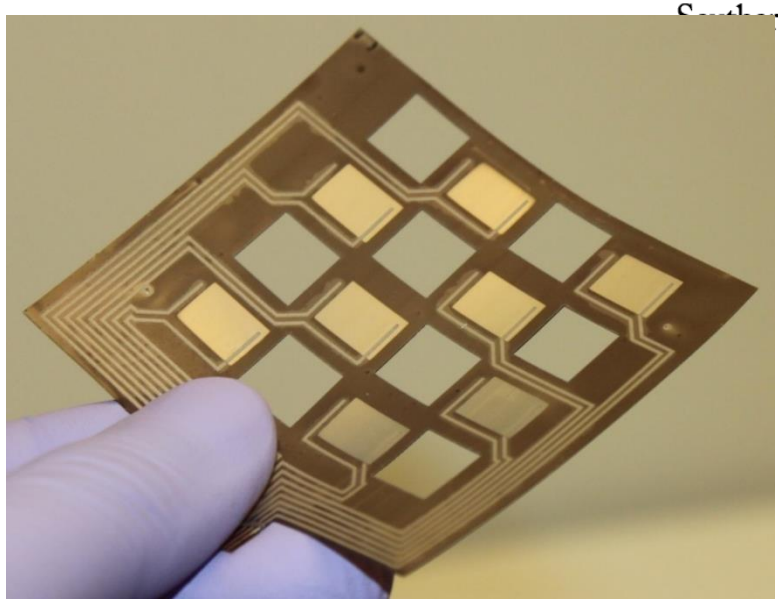




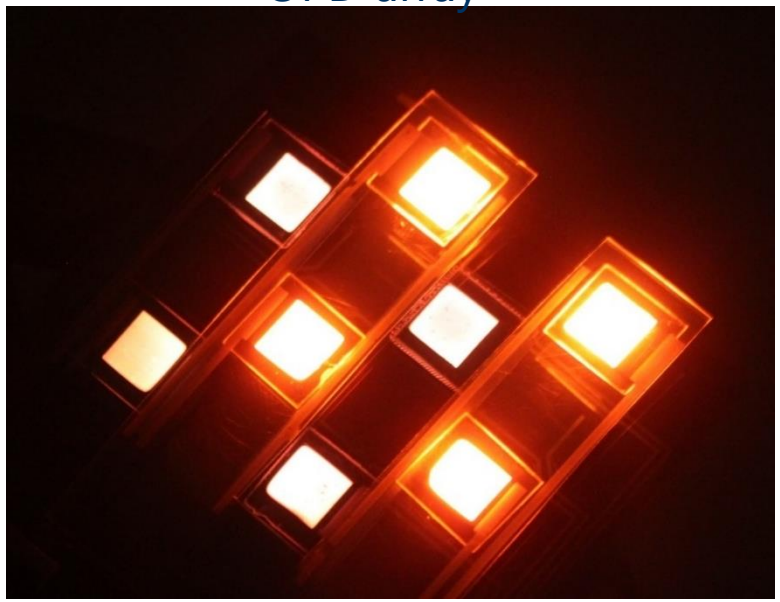
- Surgeons use skin flaps and grafts to reconstruct damaged skin.
- If blood supply to the flap or graft is compromised an oxygenation mapping device can be used to detect the insufficient oxygen supply.
- An array of oximeters provide 2D oxygenation mapping capability, and is promising for mapping oxygenation in tissues, wounds, pressure ulcers, or transplanted organs.

Oximeter array fabrication





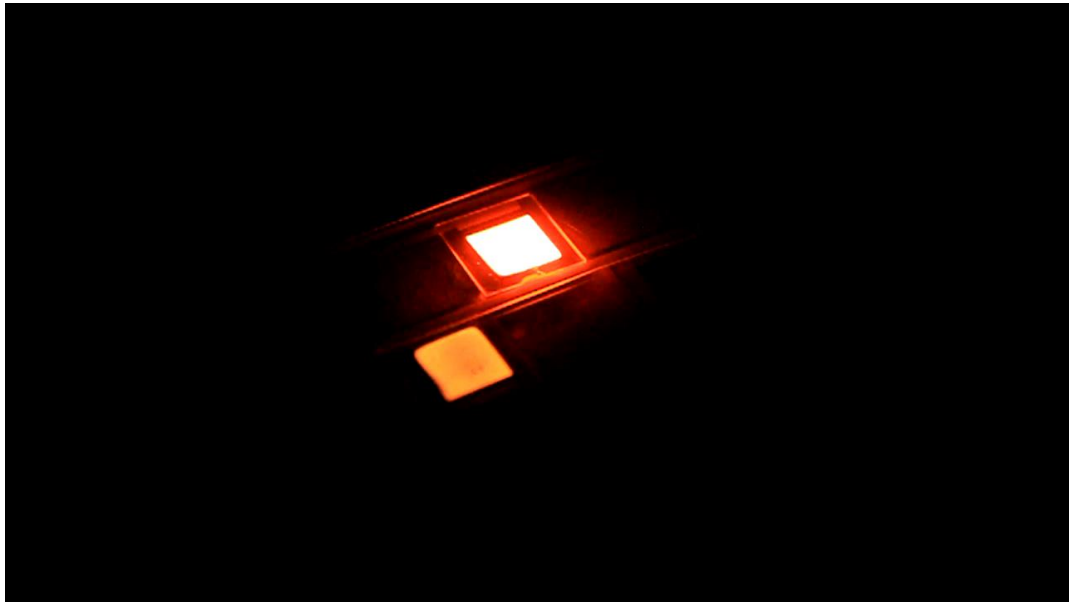
OPD array



Red and NIR OLED array

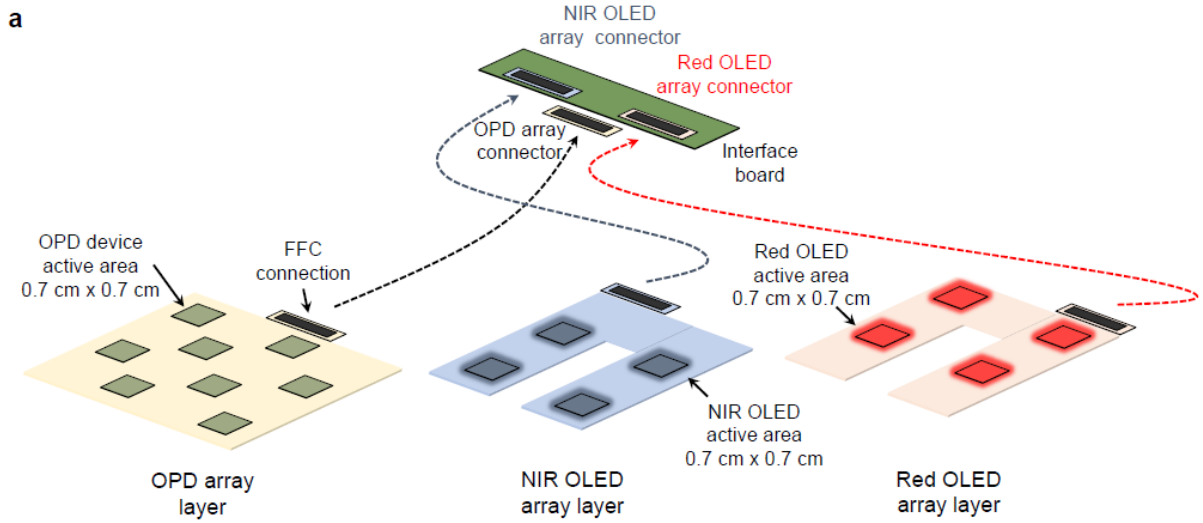
- A series of surface energy pattering, blade coating, and screen printing steps are utilized to fabricate the array.

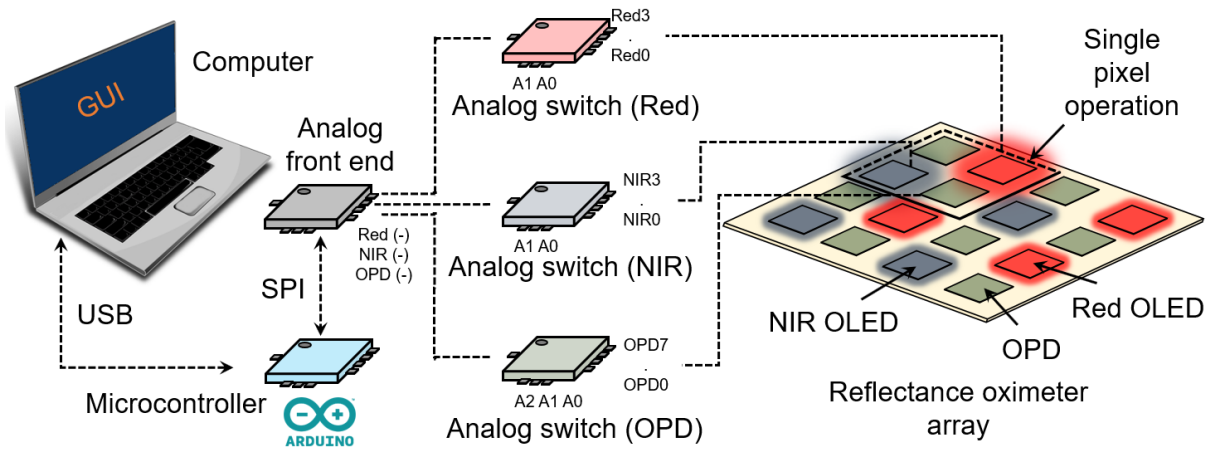
Printed Oximeter Array



OLED array – switching pixels

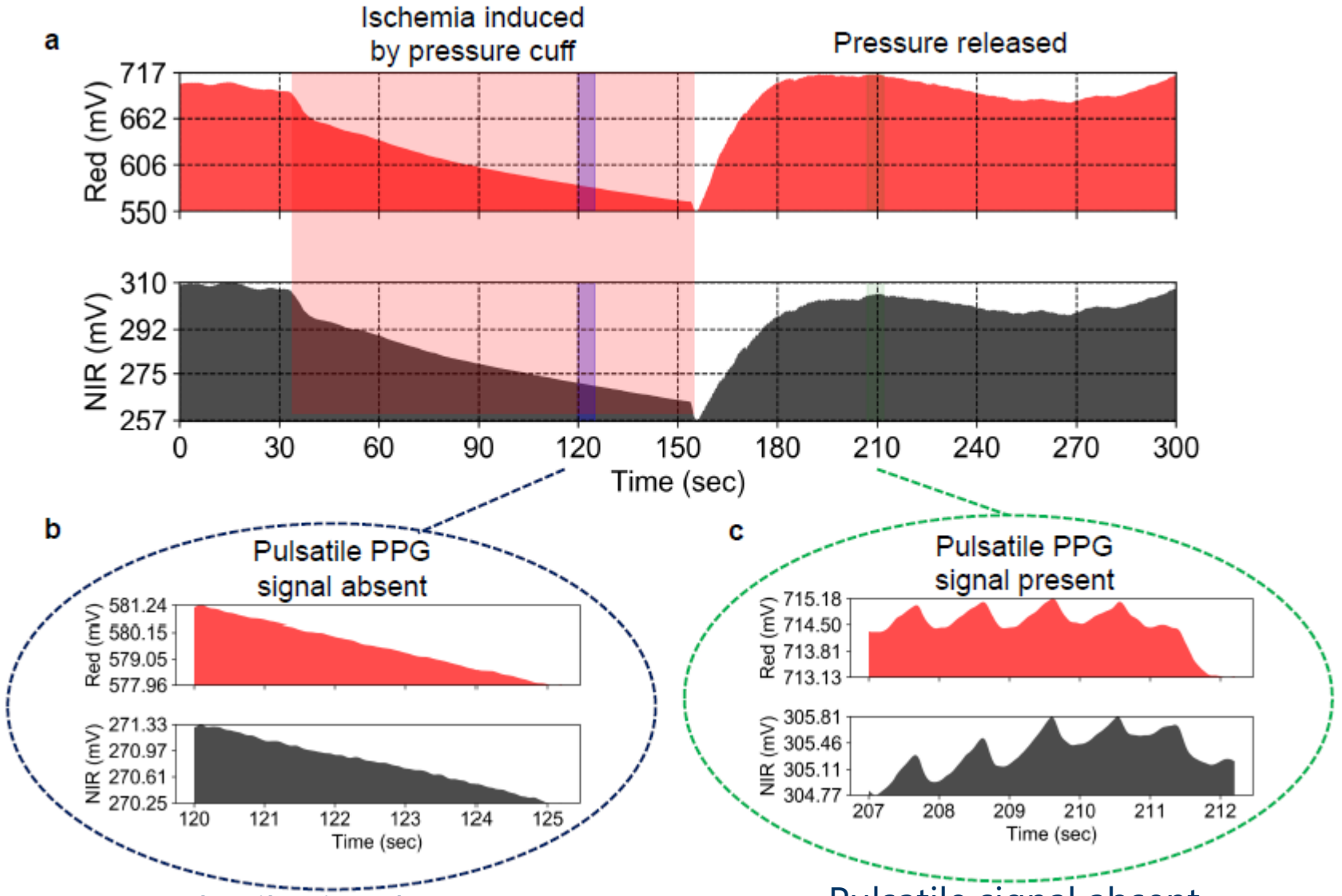
- Each pixel of the array (one red and one NIR OLED, and two OPDs) is connected to an analog front end (AFE) using multiplexers (MUXs), for both single pixel and array operation using the control electronics. The AFE drives the OLEDs and reads out the OPD signal.





Oximetry under pressure cuff induced ischemia

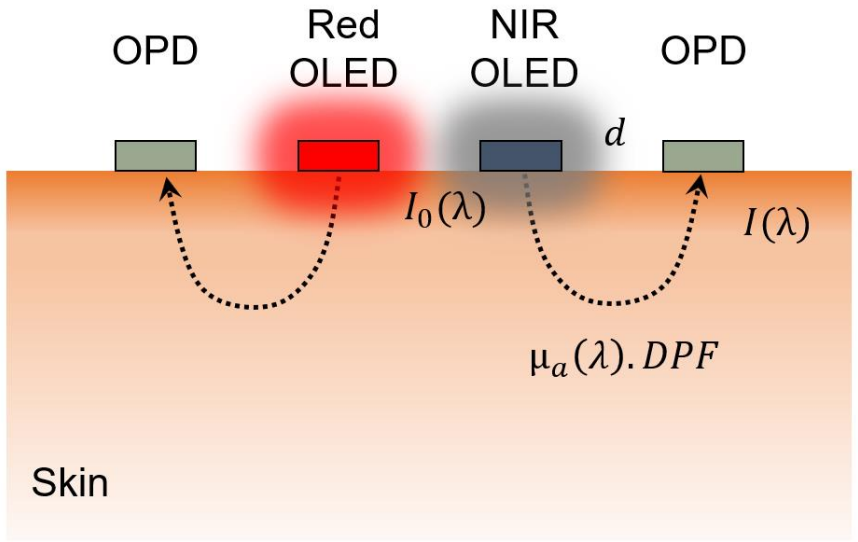
Due to low perfusion, or places on the body that have a low pulsatile signal, or to monitor oxygenation for tissue damage and injury susceptibility, a modified oximetry model is required.



Pulsatile signal present – pulse oximetry viable

Pulsatile signal absent – pulse oximetry not viable

Reflection oximetry in the absence of pulsatile signal



$$\Delta I(\lambda) = I_0(\lambda) e^{-\Delta\mu_a \cdot (\lambda) \cdot d \cdot DPF(\lambda)}$$

Where I(λ) is the measured diffuse reflected light intensity, $I_0(\lambda)$ is the incident light intensity, $\mu_a(\lambda)$ is the absorption coefficient of the probed tissue, d is the distance between the positions of incident and measured light, i.e., the source–detector separation, DPF(λ) the differential pathlength factor (DPF).

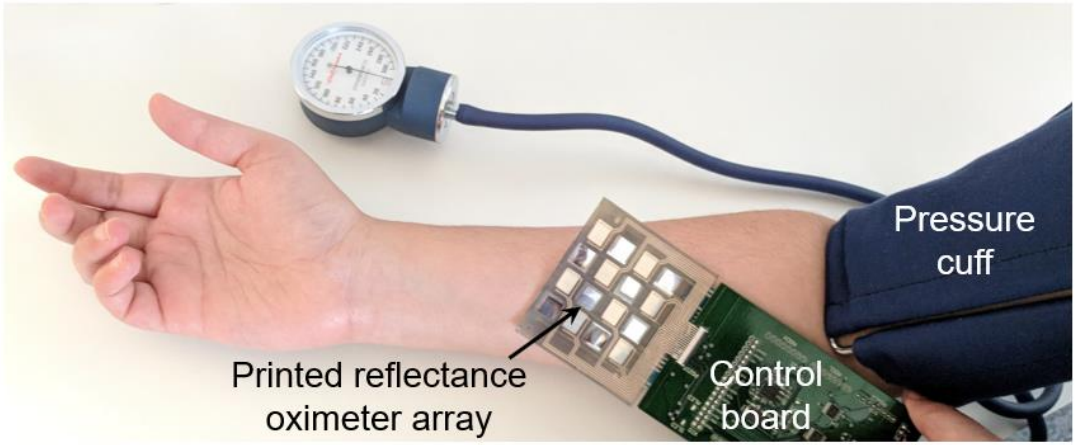
$$\Delta\mu_a(\lambda) = \varepsilon_{HbO_2}(\lambda) \cdot \Delta C_{HbO_2} + \varepsilon_{Hb}(\lambda) \cdot \Delta C_{Hb}$$

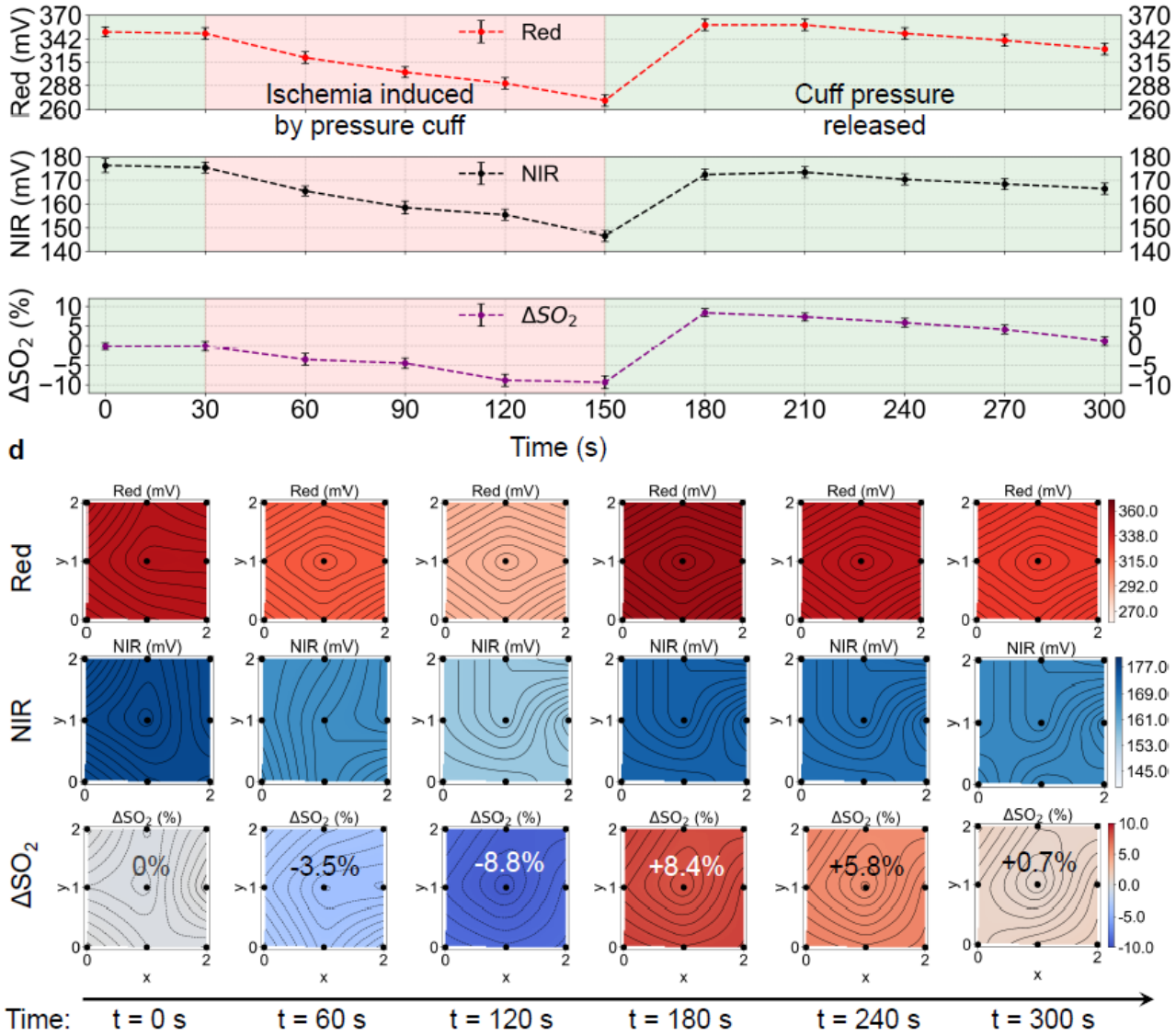
$\mu_a(\lambda)$ is given as the sum of the specific absorption coefficients α (λ), of HbO_2 and Hb, times the concentration.

$$\begin{bmatrix} \varepsilon_{HbO_2}(\lambda_1) & \varepsilon_{Hb}(\lambda_1) \\ \varepsilon_{HbO_2}(\lambda_2) & \varepsilon_{Hb}(\lambda_2) \end{bmatrix} \cdot \begin{bmatrix} \Delta C_{HbO_2} \\ \Delta C_{Hb} \end{bmatrix} = \begin{bmatrix} \frac{\ln \frac{I_0(\lambda_1)}{\Delta I(\lambda_1)}}{d \cdot DPF(\lambda_1)} \\ \frac{\ln \frac{I_0(\lambda_2)}{\Delta I(\lambda_2)}}{d \cdot DPF(\lambda_2)} \end{bmatrix}$$

Change in concentration of HbO_2 and Hb can be used to calculate the change in SO_2.

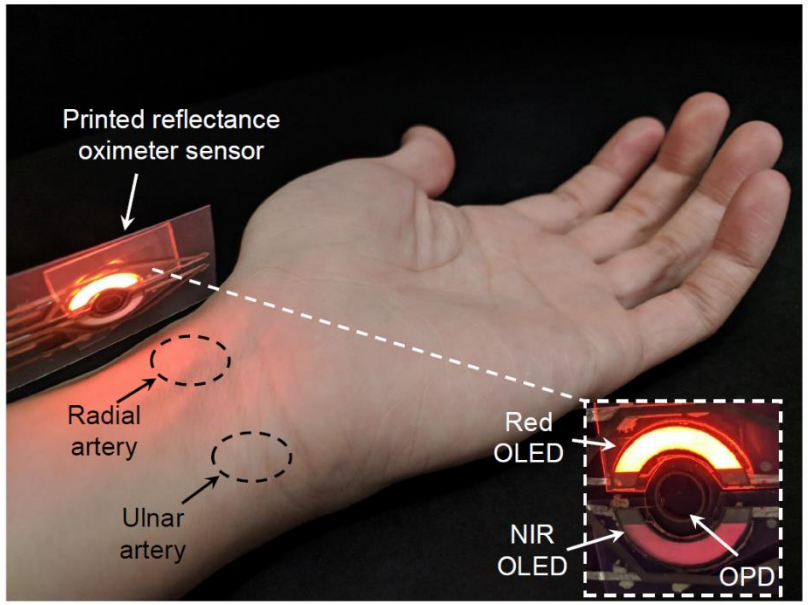
2D oxygen saturation monitoring in-vivo

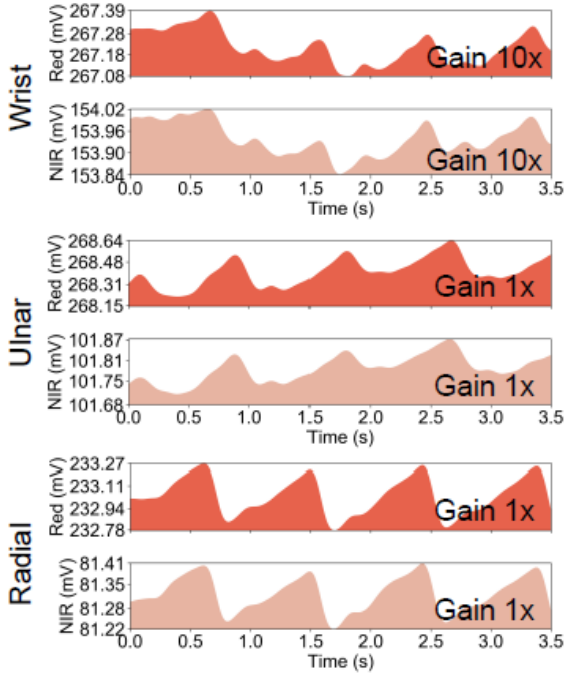


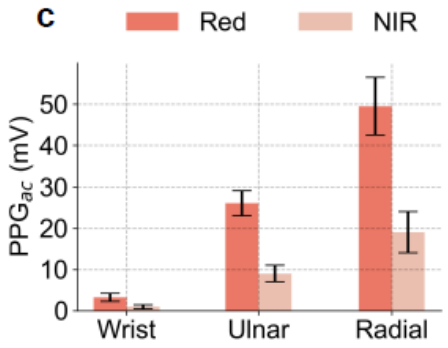


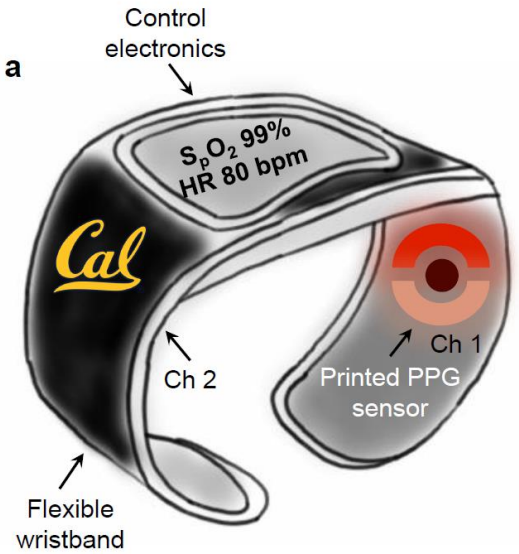
- Blood supply to the forearm is controlled by a pressure cuff.
- ΔSO2 varies from 0 % under normal condition to - 9 % under ischemia, and rises to 10 % when the pressure is released.

Organic smart wristbands



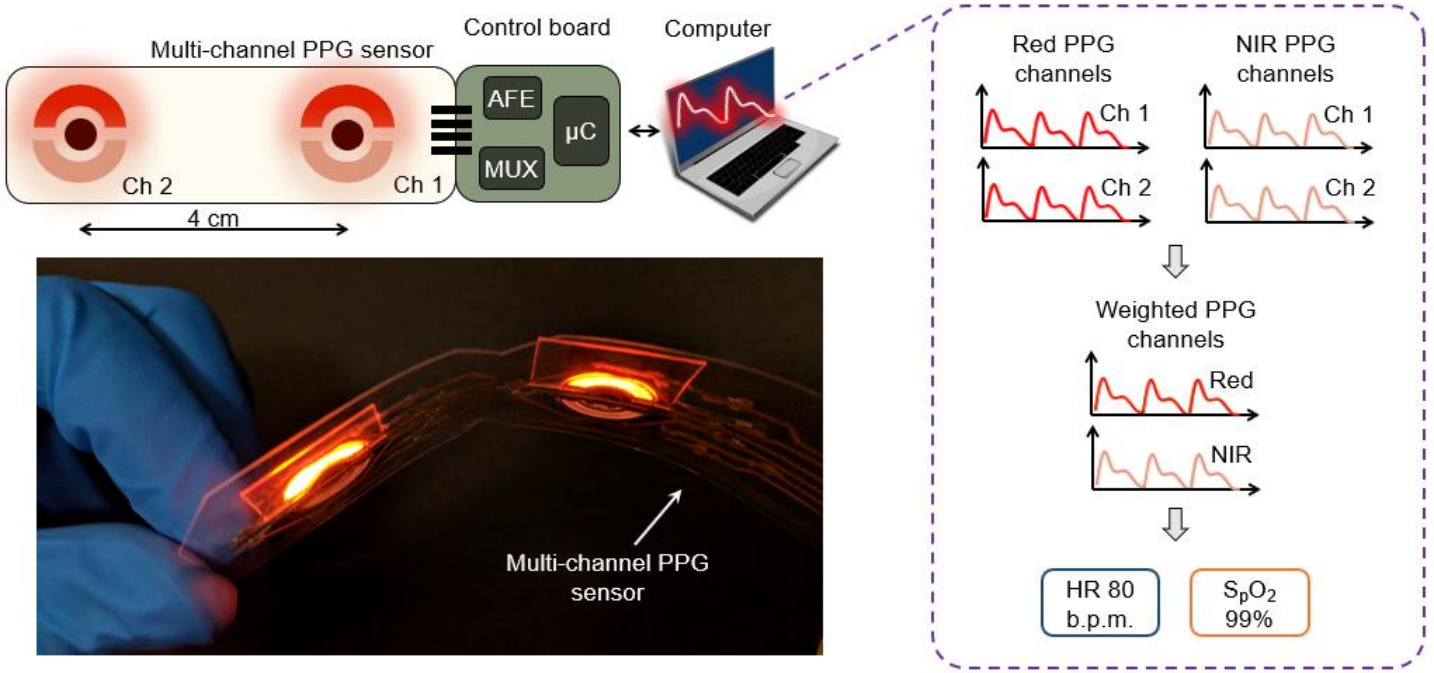


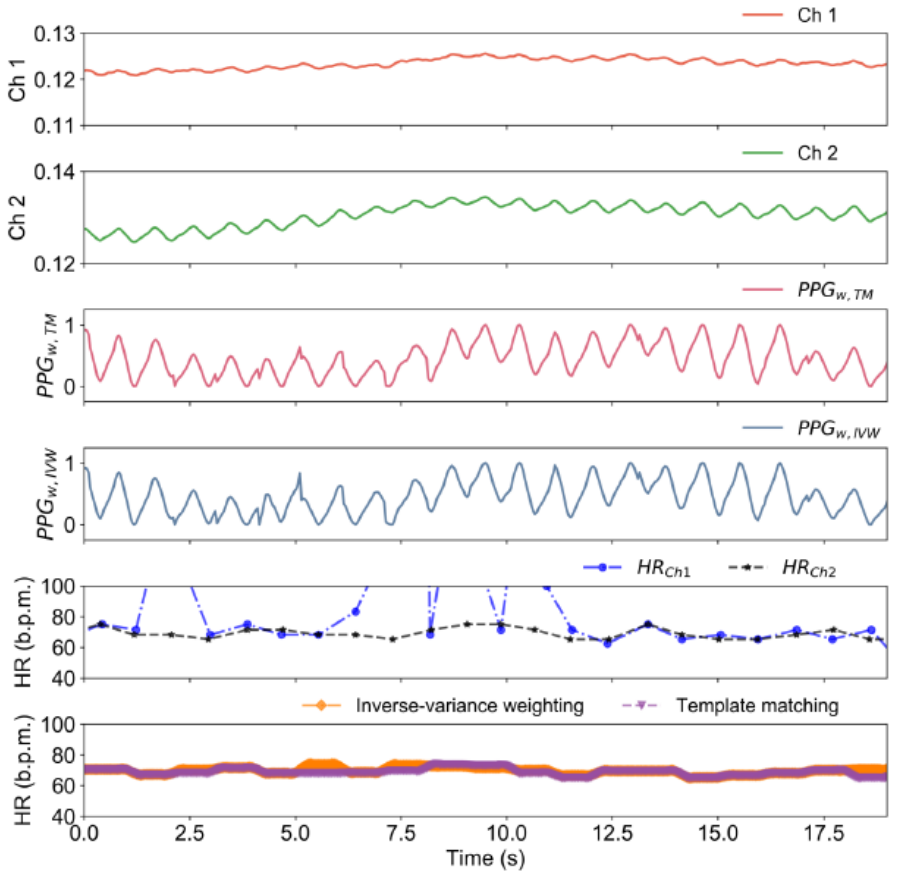




- The PPG signal on the underside of the wrist is much stronger.
- The watch band is used as a sensor.
- Multiple PPG channels are used to add redundancy to the measurement.
- Intelligent channel selection and use of a weighting algorithm increase accuracy to the data.

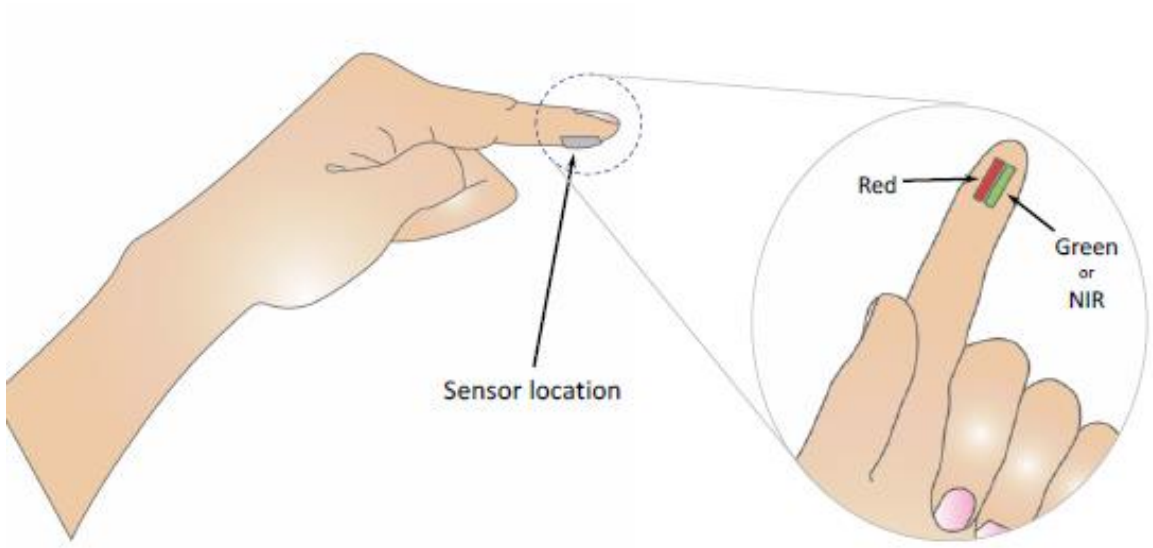
Smart wristband with intelligent channel selection

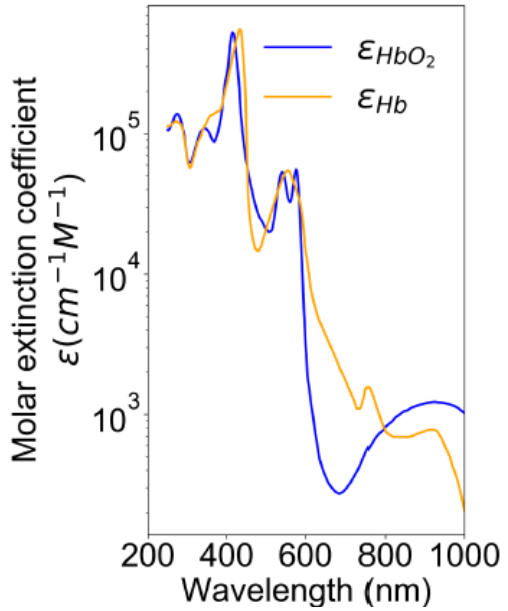


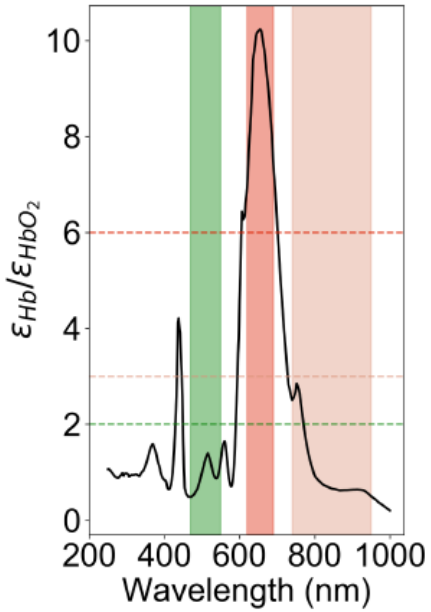


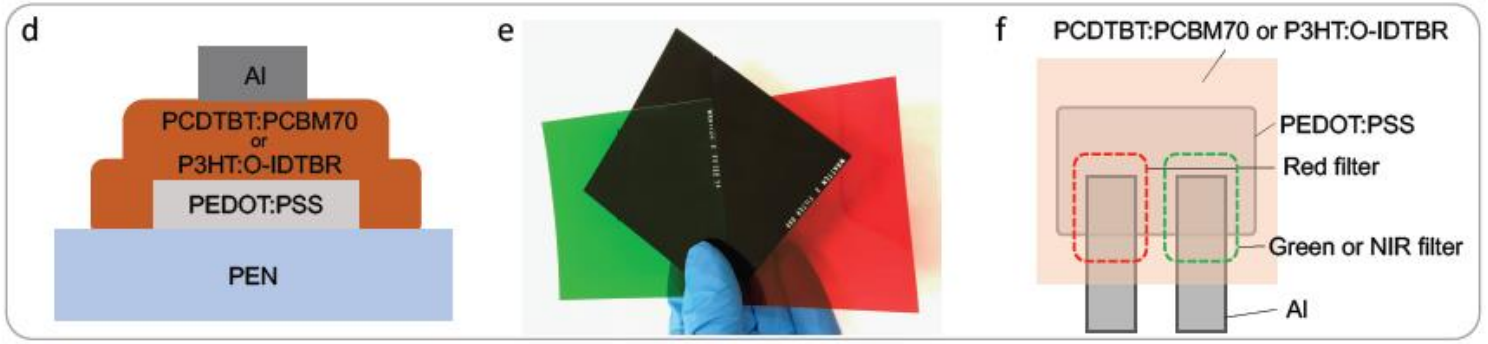
- The sensor is placed on the underside of the wrist, where Ch 1 collects data from the ulnar artery and Ch 2 collects data from the radial artery.
- After implementing template matching and inverse-variance weighting algorithms, accurate detection of HR is observed for both the algorithms compared to using only using Ch 1.

Ambient light sources for oximetry



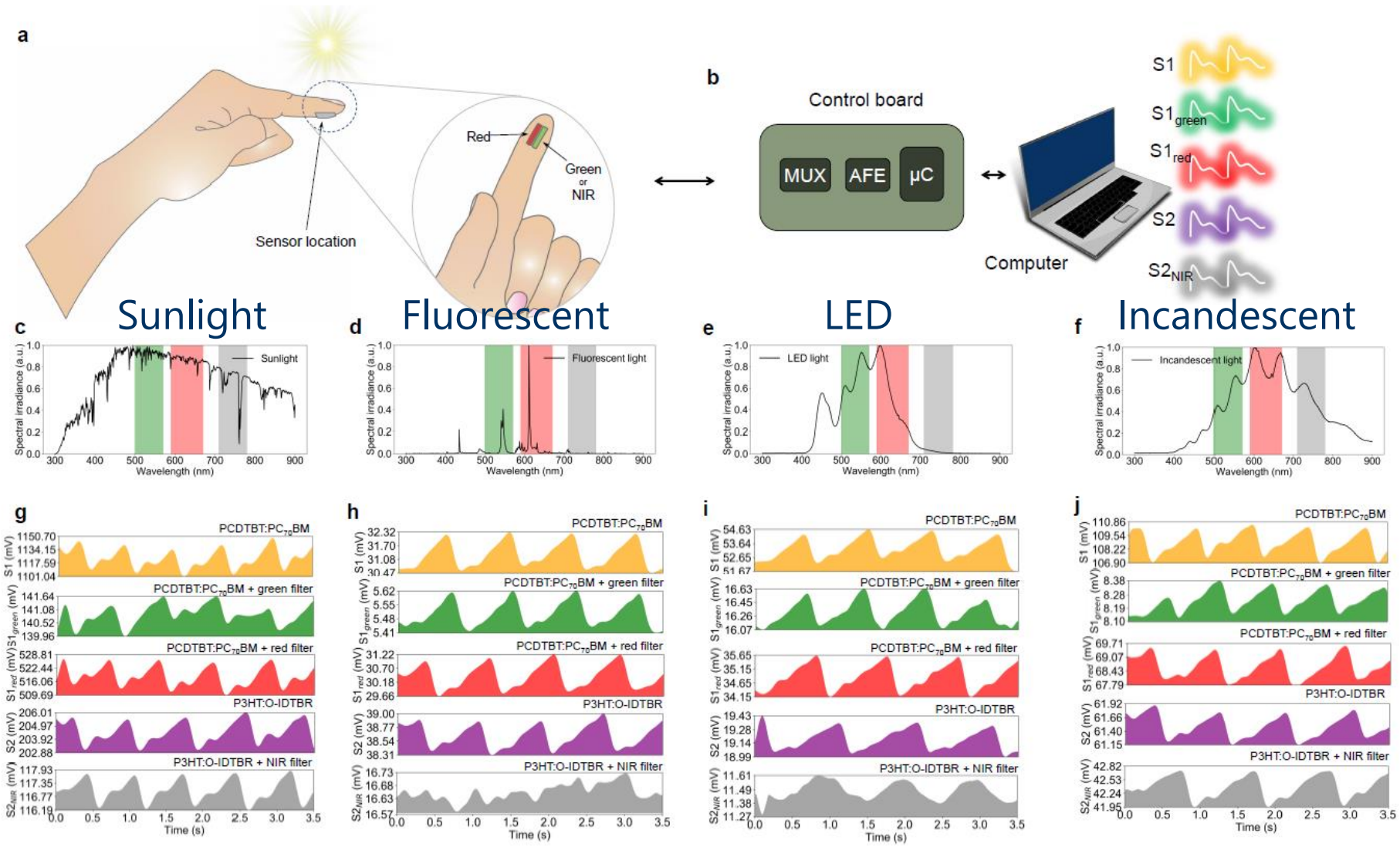






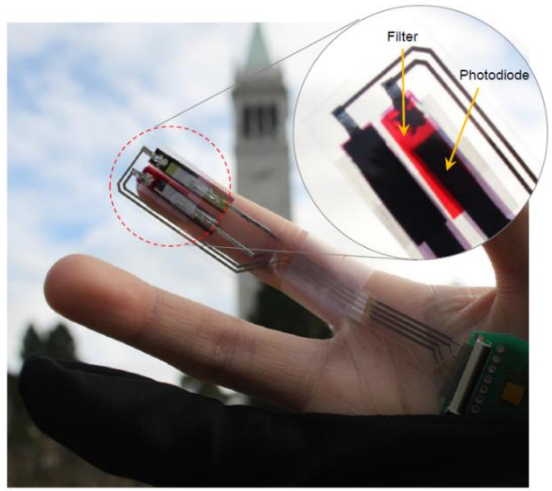
- Use ambient light as the light source for pulse oximetry.
- Develop photodiodes that are sensitive at green, red, and near-infrared light.
- Significantly reduce power consumptions of pulse oximeters.

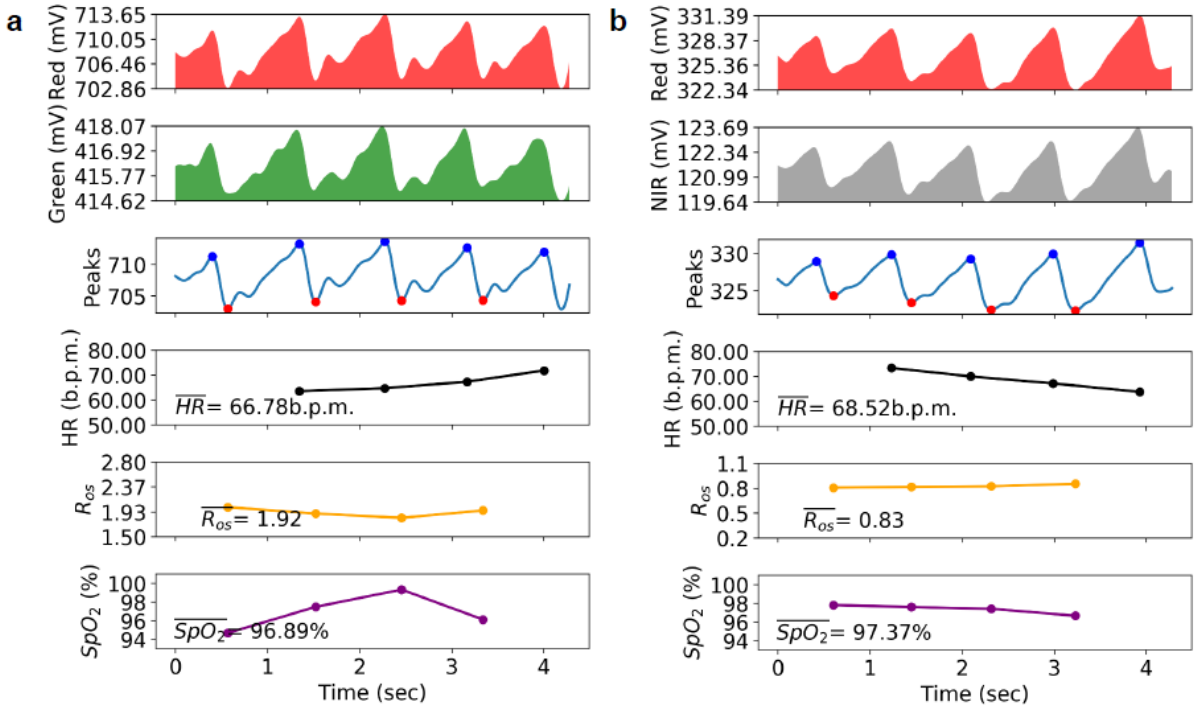
PPG with various ambient light sources

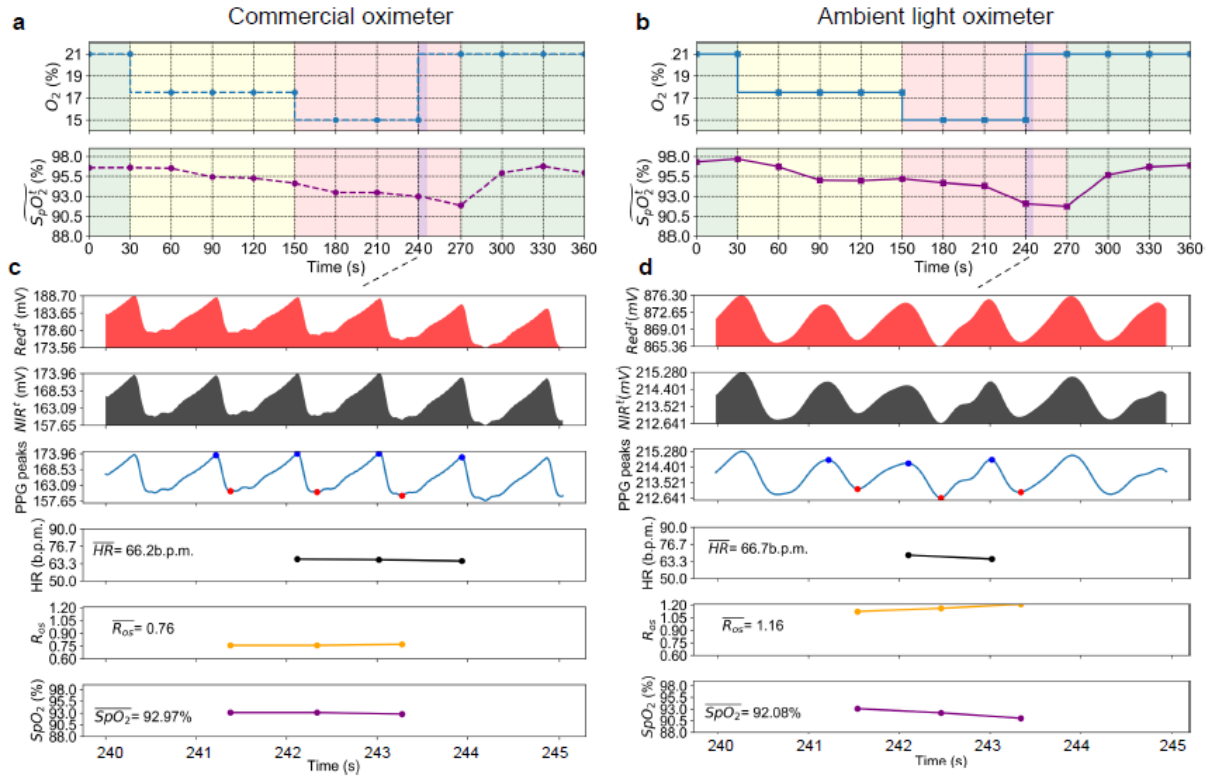


- Green, red, and NIR light sensors are designed with OPDs and filters
- Most ambient light sources include red and green light combinations for oximetry
- Sunlight and incandescent light has both red + green and red + NIR combinations for oximetry

Sun as the light source for oximetry



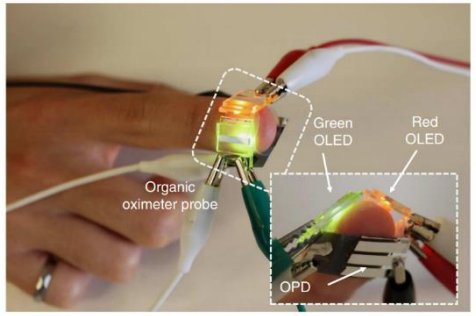




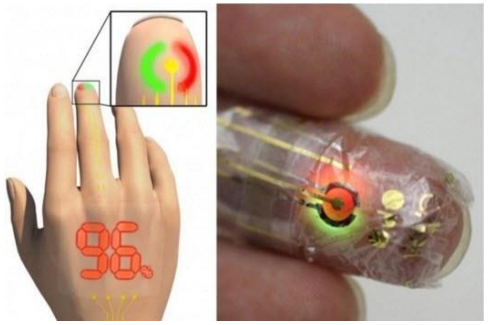
- Pulse oximetry can be done using sunlight with red + green and red + NIR light combinations
- Results are validated with commercial oximeters, and by varying oxygenation levels
- Lowest power oximeter!

Flexible oximeters over the years

Red and green OLEDs interfaced with OPD for transmission-mode oximetry, ***Nat. Commun.*** **2014 - Berkeley**

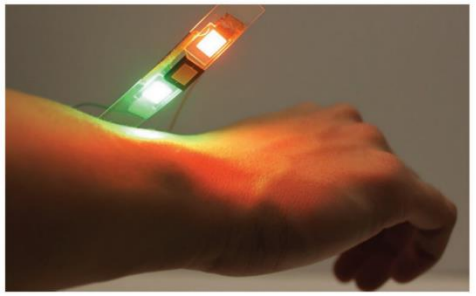


Ultraflexible organic photonic skin, ***Sci. Adv.*** **2016 – U of Tokyo**

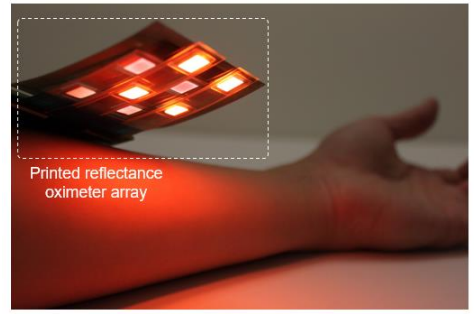


Thin, Battery-free, Skin-like Devices for Blood Oximetry, ***Sci. Adv.*** **2016 – Illinois**

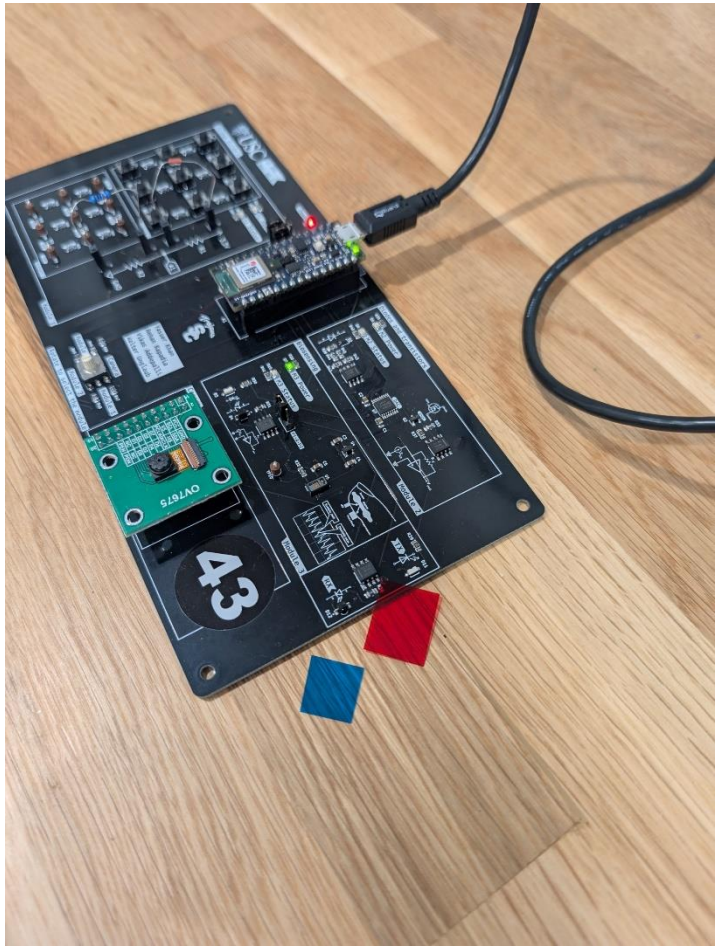
Printed flexible PLEDs interfaced for reflectance-mode oximetry, ***Adv. Mater.*** **2017 - Berkeley**

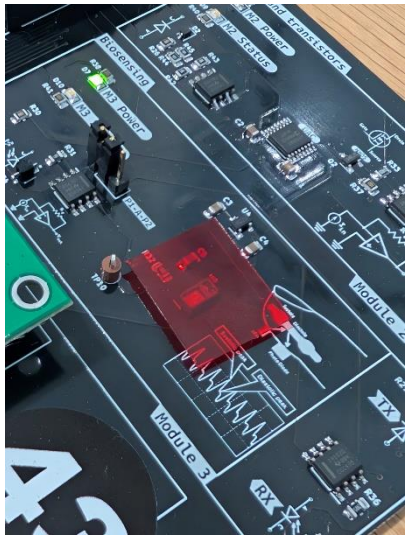


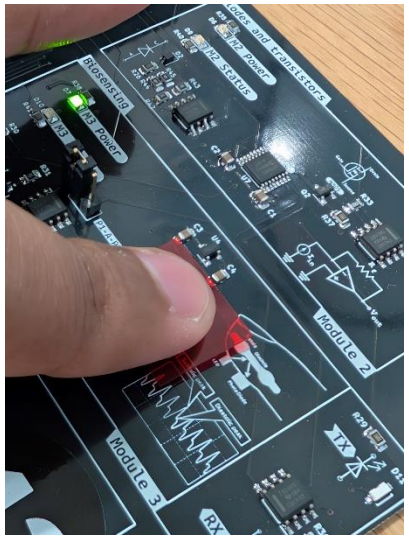
Printed PLED and OPD arrays for reflectance-mode oximetry, ***PNAS*** **2018 - Berkeley**

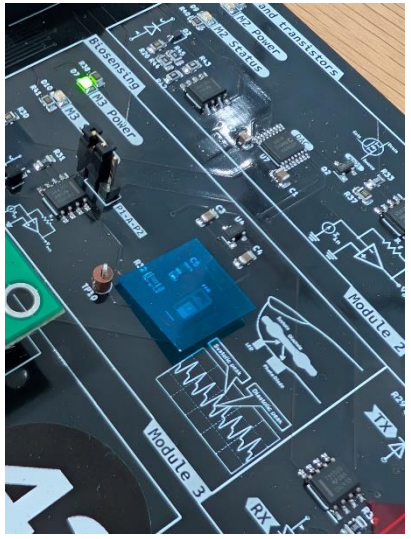


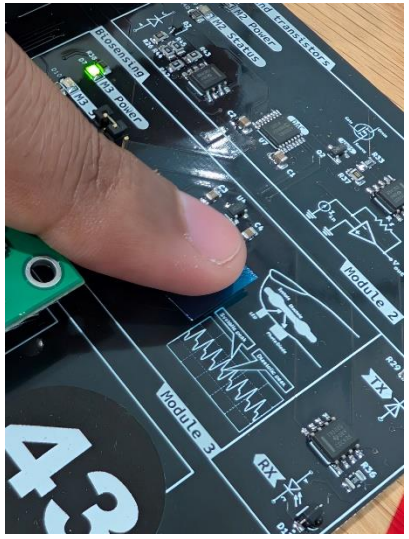
Challenge project – what's what











data-1.csv, data-2.csv, and data-3.csv are taken with red, blue, and no filters. You will have to detect which data uses which filter with code written in the python notebook.

Rules

1. Teams of two students.
2. Raise your arm when your code is ready to identify the data files automatically.
3. You'll get one chance for giving the correct answer.
4. You'll have to explain why the signals are different in different data files.