Université de Toulouse

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SmartPhOx: Smartphone-Based Pulse Oximetry Using a Meta-Region Of Interest

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Spo2 and your health

- 95 – 100% => healthy
< 92% => Dangerous, sign of cardiovascular or respiratory problem

- SpO2 monitoring :
  - To avoid the consequences of prolonged poor oxygenation (Hypoxia)
  - To detect and treat the underlying issue

SpO2 monitoring and the fight against COVID-19

- Some cases of covid expressed silent hypoxia : SpO2 drops to 50% without feeling short of breath !


IEW

The New York Times

OPINION

The Infection That's Silently Killing Coronavirus Patients

This is what I learned during 10 days of treating Covid pneumonia at Bellevue Hospital.

April 20, 2020

Special offer. Subscribe for ~~€2~~ €0.50 a week.

SpO2 monitoring solutions based on custom hardware

Arterial Blood Gas Analyzer	Bulky machine		Requires blood sample
Pulse oxymeter	Light sensor Photoreceptor		Lightweight, accessible, widely used in hospitals Not widely used out of hospitals

The spark for SmartPhOx

The New York Times

SUNDAY REVIEW | The Infection That's Silently Killing Coronavirus Patients

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however, most patients requiring emergency intubation are in shock, have altered mental status or are grunting to breathe. Patients requiring intubation because of acute hypoxia are often unconscious or using every muscle they can to take a breath. They are in extreme duress. Covid pneumonia cases are very different.

A vast majority of Covid pneumonia patients I met had remarkably low oxygen saturations at triage — seemingly incompatible with life — but they were using their cellphones as we put them on monitors. Although breathing fast, they had relatively minimal apparent distress, despite dangerously low oxygen levels and terrible pneumonia on chest X-rays.

We are only just beginning to understand why this is so. The coronavirus attacks lung cells that make surfactant. This substance helps the air sacs in the lungs stay open between breaths and is critical to normal lung function. As the inflammation from Covid pneumonia starts, it causes the air sacs to collapse, and oxygen levels fall. Yet the lungs initially remain "compliant," not

Smartphone based solution

- Smartphone flashlight and camera based solution : not accurate enough

- Smartphone-based and hardware-assisted solution : PHO2 [1]

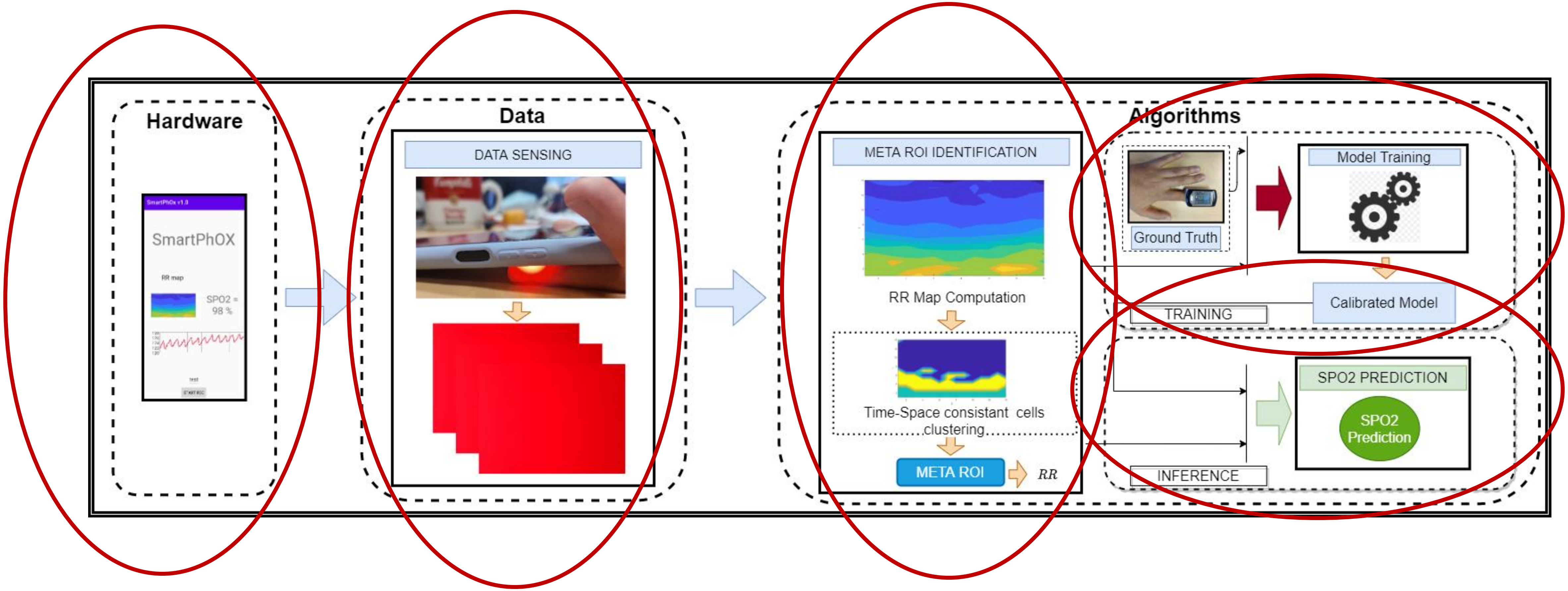
- Some high-end smartphone that incorporate dedicated light sensors for SpO2 sensing

[1]Nam Bui, Anh Nguyen, Phuc Nguyen, Hoang Truong, Ashwin Ashok, Thang Dinh, Robin Deterding, and Tam Vu. 2017. PhO2: Smartphone based Blood Oxygen Level Measurement Systems using Near-IR and RED Wave-guided Light. In Proceedings of the 15th ***ACM Conference on Embedded Network Sensor Systems (SenSys '17)***

We propose SmartPhox

- Can be used on any standard smartphone no add-ons required.
- Uses the camera and flashlight available in every off the shielf devices
- Results from 37 users : RMSE spo2 prediction error of within the FDA's accuracy threshold

SmartPhOx architecture

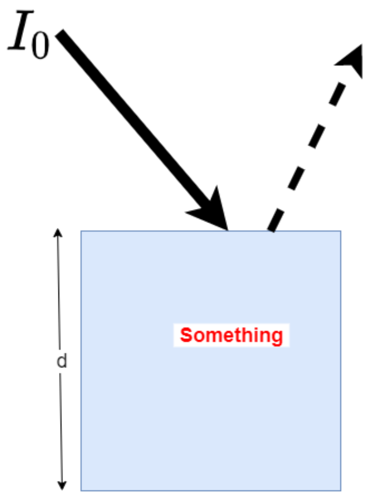


Outline

- Principle of SpO2 measurement with a smartphone
- SmartPhOx system
- Performance evaluation
- Conclusion

Principle of SpO2 measurement with a smartphone

Once upon a time, the Beer-Lambert law ...



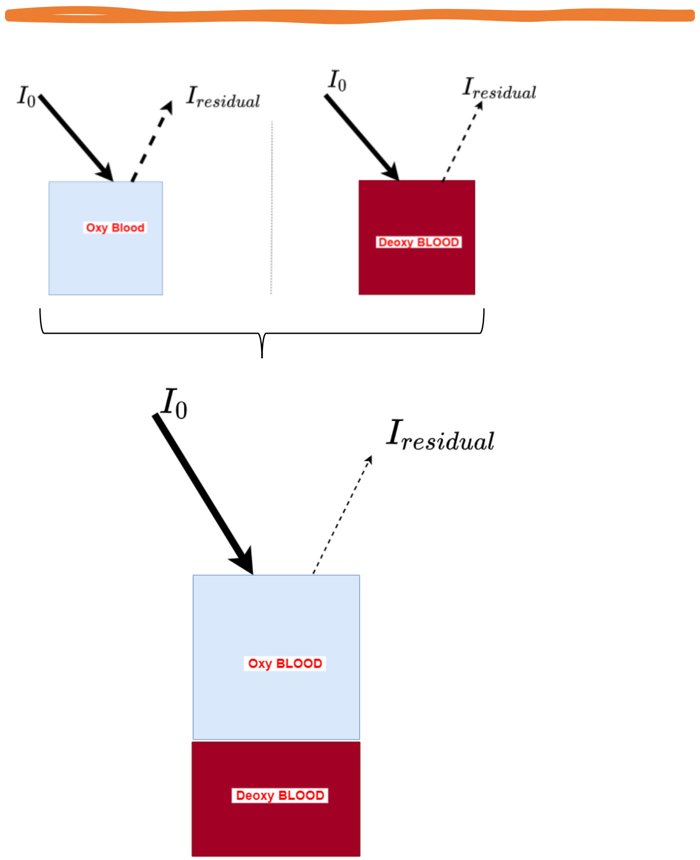
$$I_{residual} = I_0 \exp^{-d\rho\epsilon}$$

d is the path length

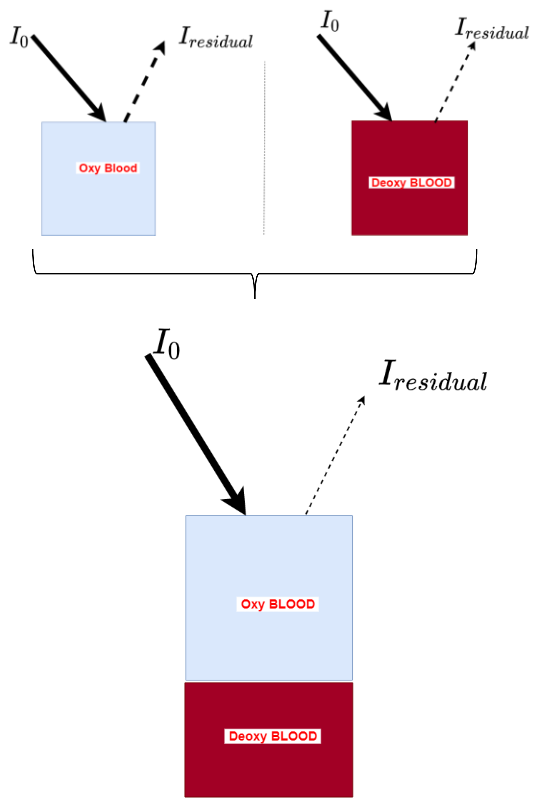
ρ the middle concentration

ϵ The middle extinction coefficient

Oxygenated and Deoxygenated blood absorb light differently

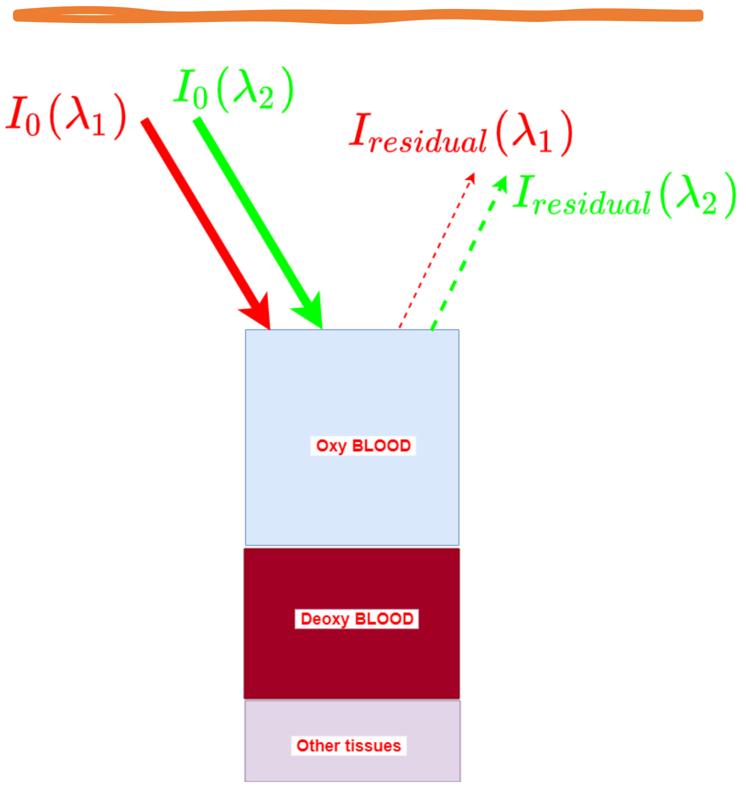


Oxygenated and Deoxygenated blood absorb light differently



$$I_{residual} = f(\underbrace{\{\overbrace{\text{Concentration}}^{?}, \overbrace{\text{Absorption coefficient}}^{\text{Fixed}}\}_{Hb}}_{\text{DeOxy blood}}, \underbrace{\{\overbrace{\text{Concentration}}^{?}, \overbrace{\text{Absorption coefficient}}^{\text{Fixed}}\}_{O_2}}_{\text{Oxy blood}})$$

Using two different wavelength, we can get their relative concentration (SpO2)



$$\begin{cases} I_{residual}(\lambda_1) = f(\{\rho_{Hb}, \epsilon_{Hb}(\lambda_1)\}, \{\rho_{O_2}, \epsilon_{O_2}(\lambda_1)\}) \\ I_{residual}(\lambda_2) = f(\{\rho_{Hb}, \epsilon_{Hb}(\lambda_2)\}, \{\rho_{O_2}, \epsilon_{O_2}(\lambda_2)\}) \end{cases}$$

$$SpO_2 = \frac{\rho_{0_2}}{\rho_{0_2} + \rho_{Hb}}$$

.. and isolate the Light absorption ratio (RR)

1. Oxy blood, DeOxy blood, DC tissues:

$$I_{residual}(\lambda) = I_0(\lambda)\exp^{-(d\rho_{Hb}\epsilon(\lambda)_{Hb})-(d\rho_{O_2}\epsilon(\lambda)_{O_2})-(d\rho_{DC}\epsilon(\lambda)_{DC})}$$

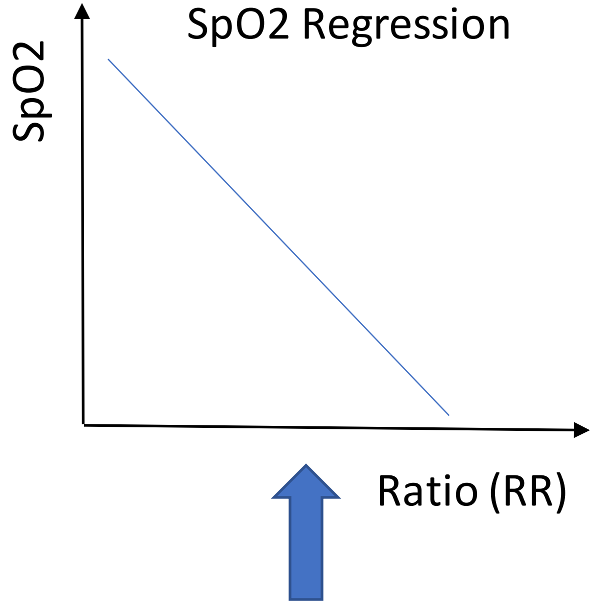
Oxy Blood — DeOxy Blood — DC Tissues

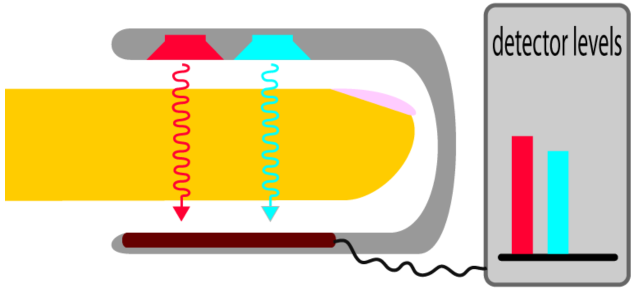
2. Considering two time instant and wavelength :

3. Light Absorption Ratio :

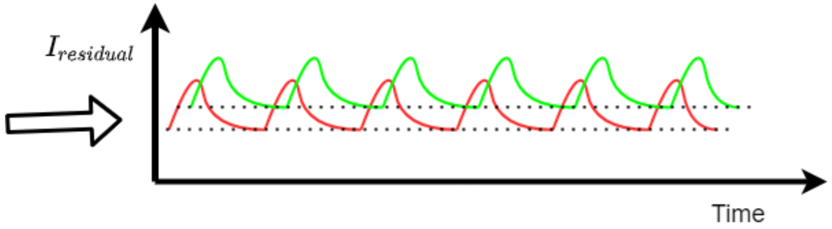
$$RR_{\lambda_1,\lambda_2} = \frac{\ln(\frac{I_{t1}(\lambda_1)}{I_{t2}(\lambda_1)})}{\ln(\frac{I^{t1}(\lambda_2)}{I^{t2}(\lambda_2)})} \Rightarrow SpO_2 = a \times RR + b$$

Overview : From light absorption ratio to SpO2





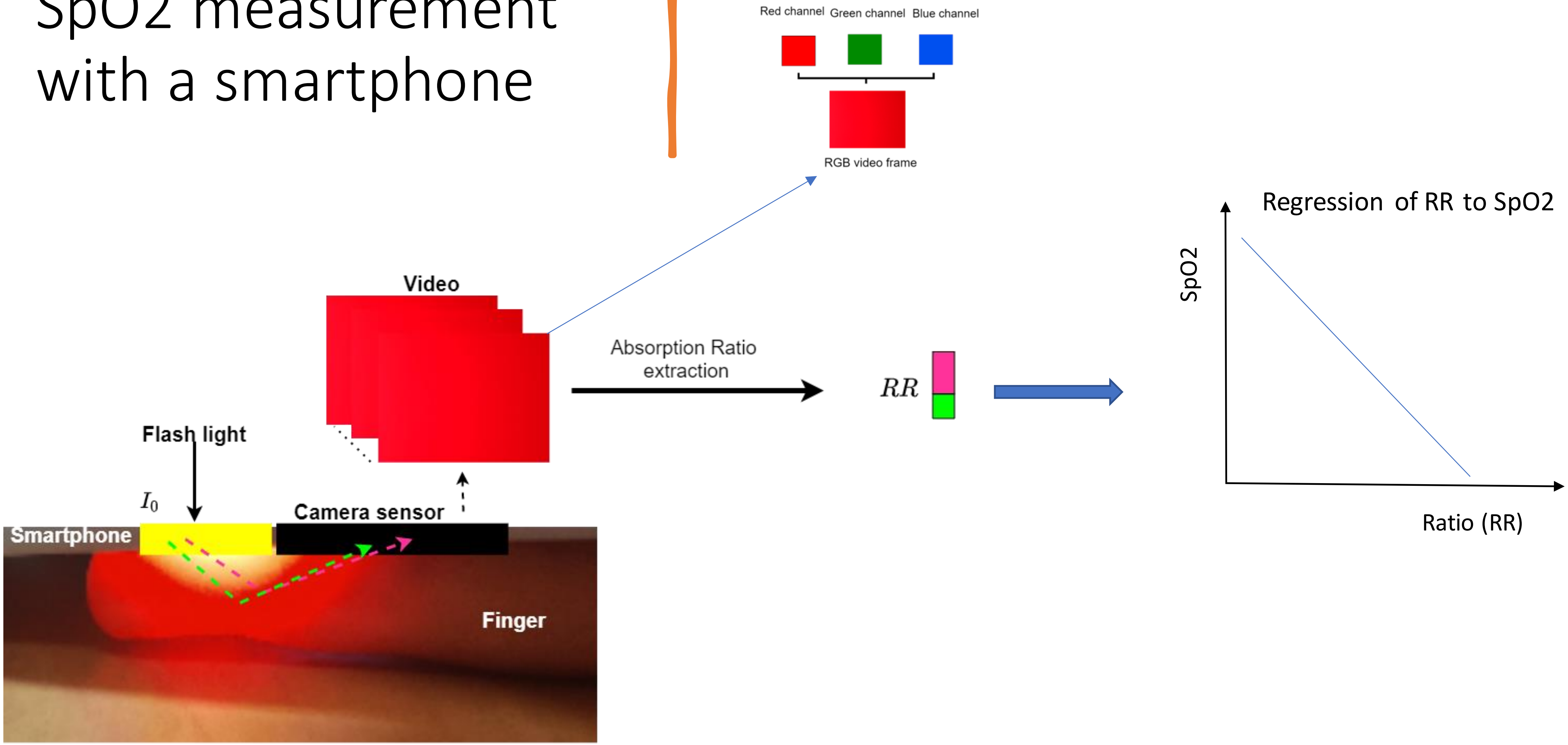
Sensing device



Photoplethysmogram (PPG) signals

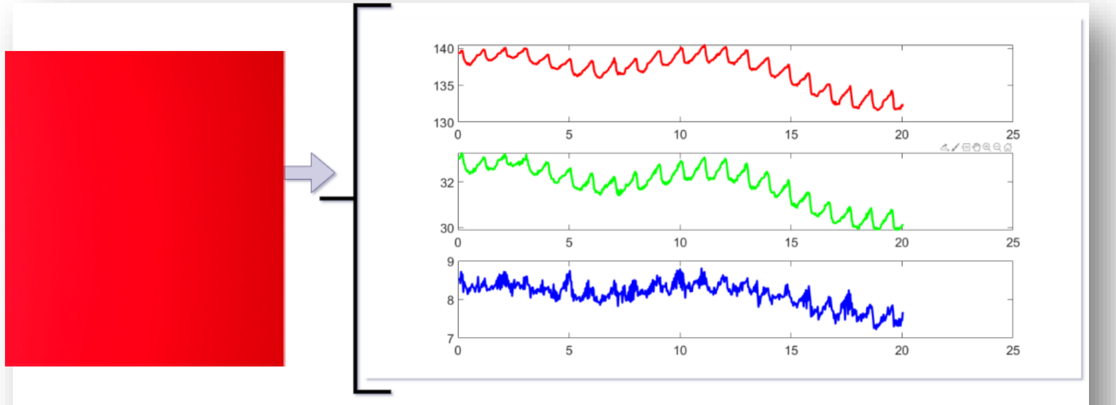
$$RR(Red, Green) = \frac{\frac{\text{Pulsatile absorption}(Red)}{\text{Baseline absorption}(Red)}}{\frac{\text{Pulsatile absorption}(Green)}{\text{Baseline absorption}(Green)}}$$

SpO2 measurement with a smartphone



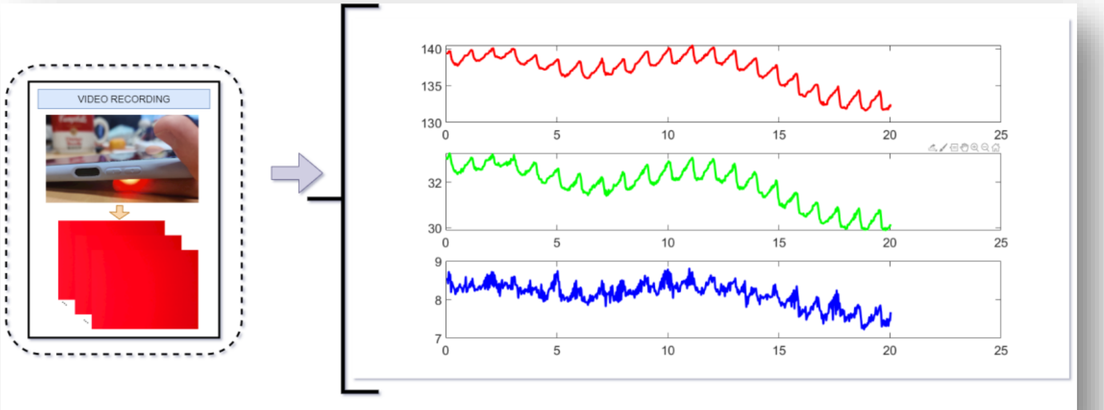
Challenge 1 : The Region of Interest (ROI)

- **Baseline approach**: average light intensities over the whole frame.



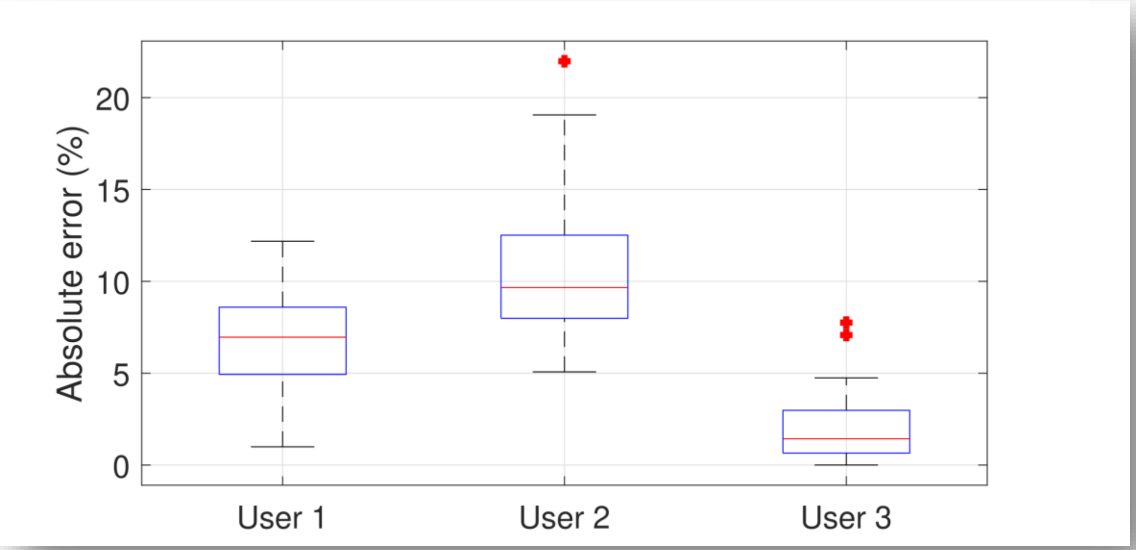
Three channel PPG signals Red, Green, Blue (RGB)

Challenge 2 : RR consistency



Three channel PPG signals Red, Green, Blue (RGB)

$$\{RR_1, RR_2, \ldots, RR_Z\}$$



Significant SpO2 prediction error, up to 15% !

Overarching challenges facing SmartPhOx

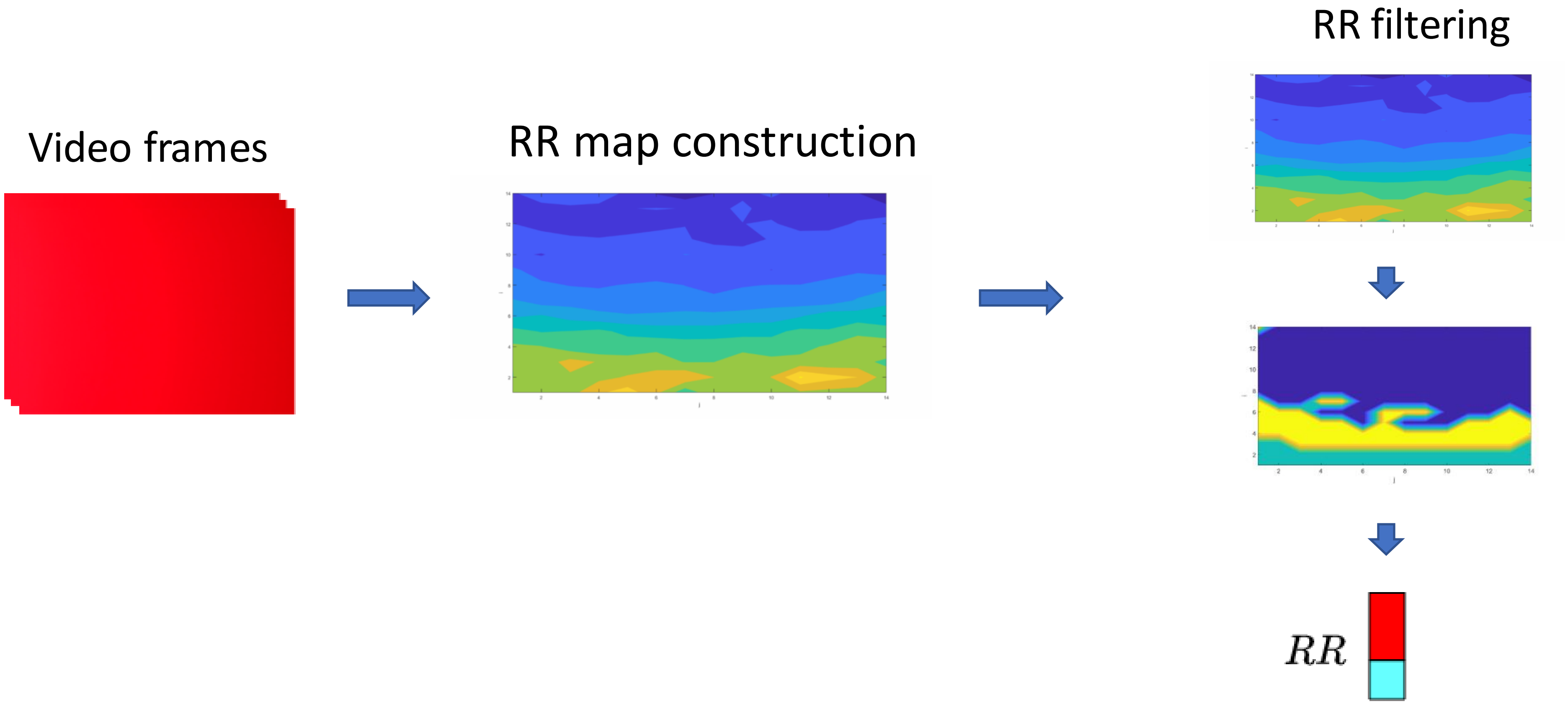
Identify the right ROI

Identify consistent RR :
same SpO2 => same RR

SmartPhOx system

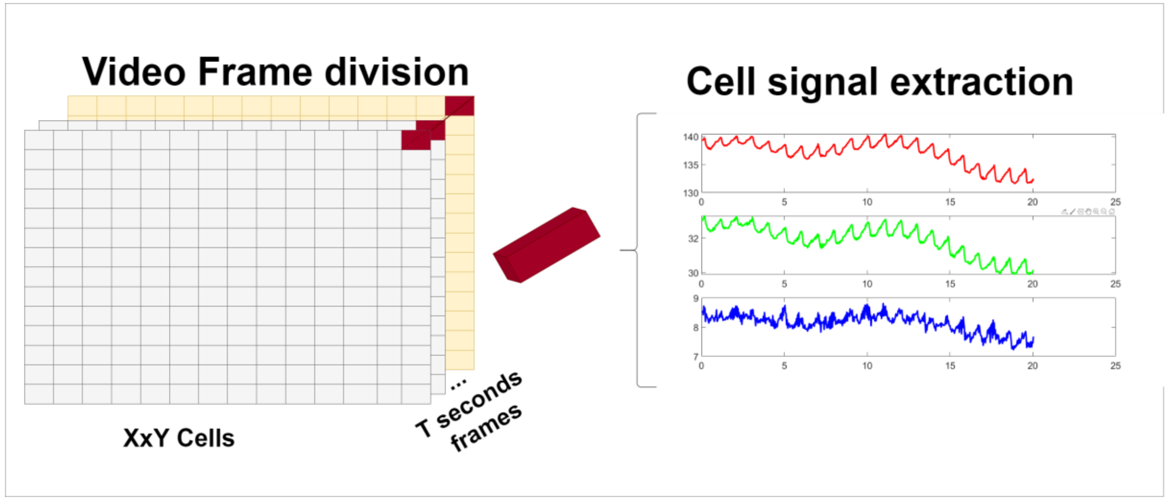
SmartPhOx approach face theses challenges :

Consider each area of the image as a separate light sensors and filter for the best RR



RR map construction

Video frames



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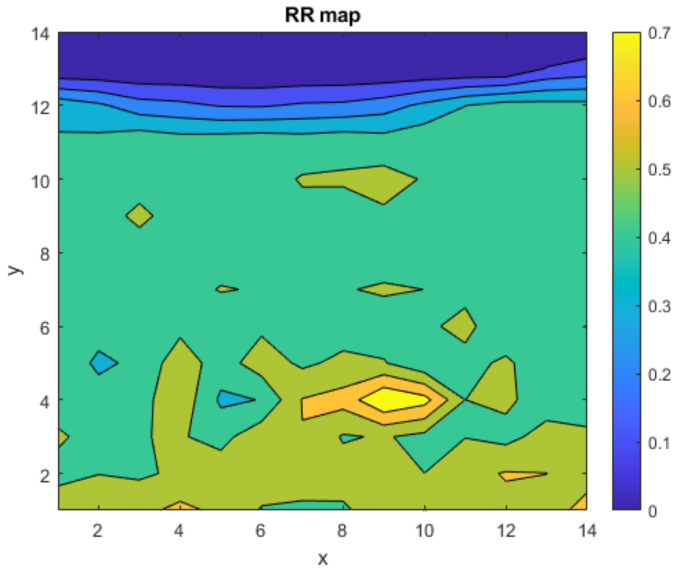


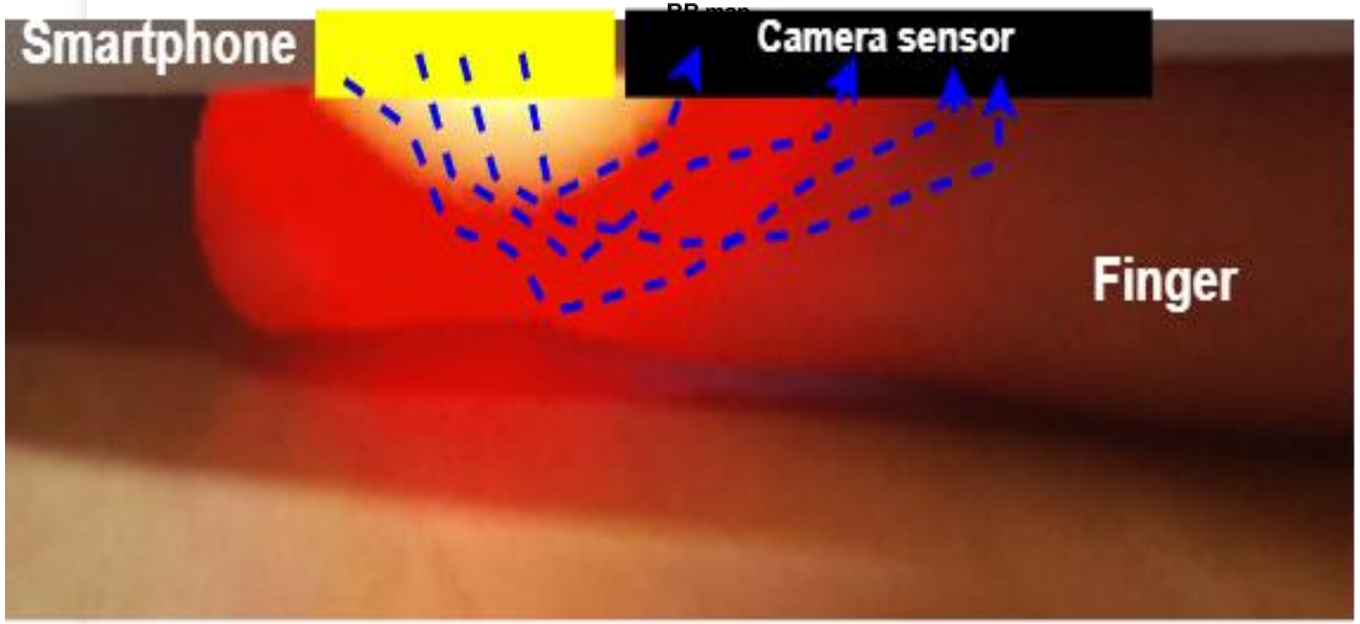
RR filtering :

How to retrieve the 'right' RR ?

- Each cell produces different RR : some are up to 6 times larger than others !

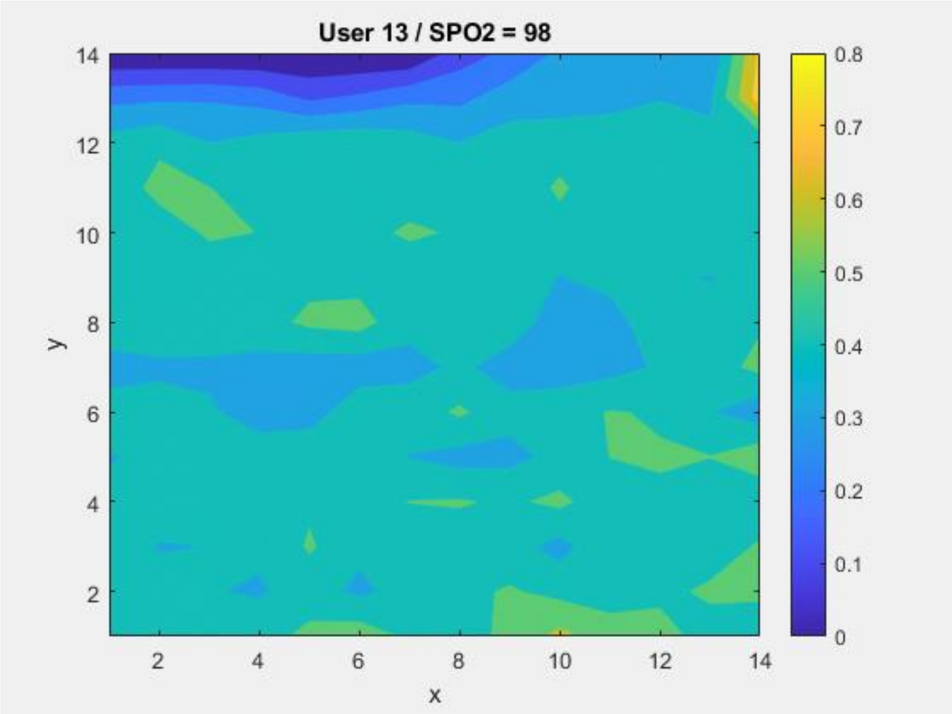
- Light rays travelling along different paths are attenuated differently at each wavelength.

- The RRs are all relevant, but not consistent with each other.

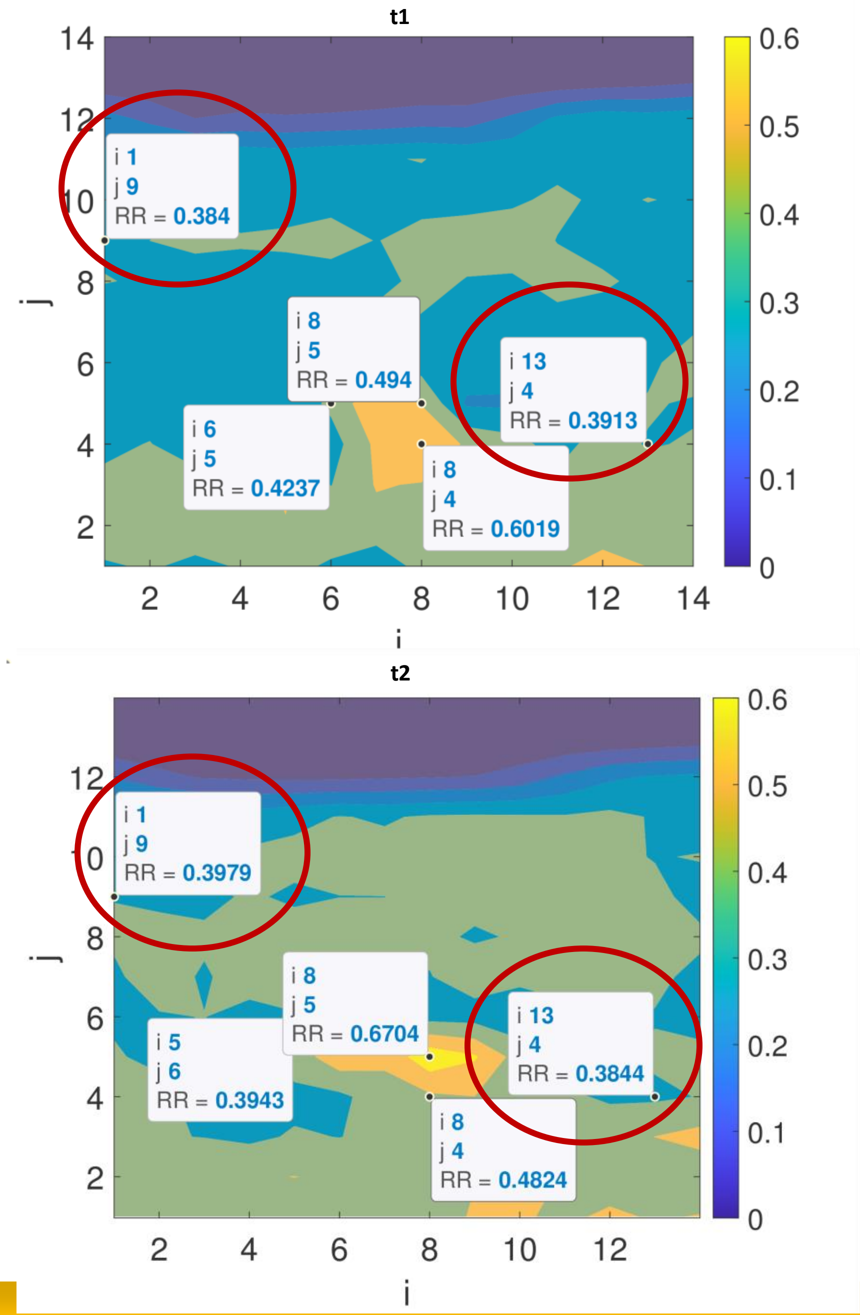


RR filtering :
The RR map evolve in time

- The RR of each cell varies over time, even though the SpO2 remains unchanged.
- This is related to the micromovements of the finger that cause the light paths to change.



RR filtering :
Some cell produces similar RR



Idea : The Meta Region of Interest

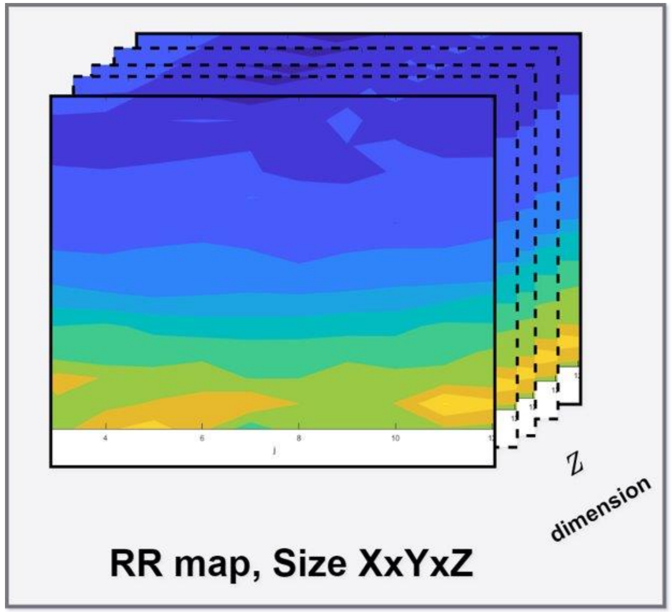
1. Group cells that produce similar RRs, to obtain space-time consistent regions.
2. Select the best consistent region as the Meta-ROI.
3. Select as RR the one produced by the Meta-ROI.

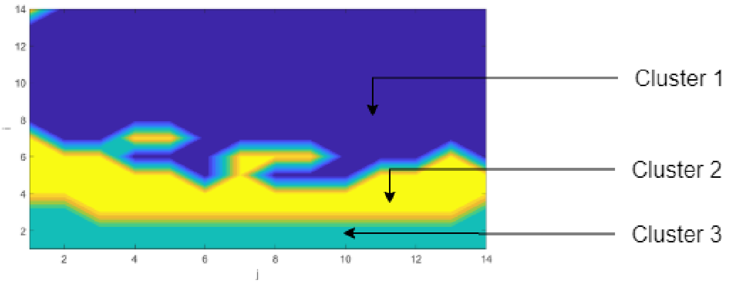
RR filtering :

Space-time consistent cell clusturing

How to get K ?

Davies-Bouldin Index [2]





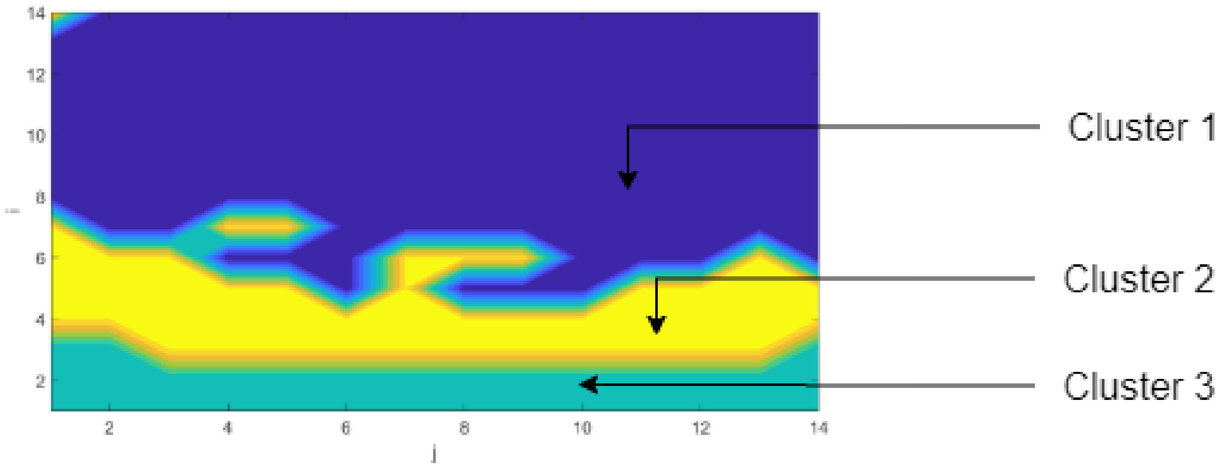
Compute the RR map of Size XxYxZ

Space-time consistent regions clusturing

[2] Davies, David L.; Bouldin, Donald W. (1979). "A Cluster Separation Measure". *IEEE Transactions on Pattern Analysis and Machine Intelligence*. PAMI-1 (2): 224–227. doi:10.1109/TPAMI.1979.4766909.

RR map filtering :

Select the best cluster as the Meta-ROI



Space-time consistent regions

- How to compare consistent regions ?
  - Quantify the temporal stability of a region
  - Meaningfull comparison between regions

$$CV(cluster_i) = \frac{\text{Standart deviation of centroid RR values of } cluster_i}{\text{Average RR value of the centroid of } cluster_i}$$

SmartPhOx RR filtering algorithm

Input: RR map of dimension Z

Iteration on K

- Kmean to obtain the clustering
- Calculate the Davies-Boulding index DBk
- If DBk is minimum
  - calculate all coefficients of variation
  - Meta ROI <- Cluster with lowest coefficient of variation

Output: RR produced by the Meta-ROI

Performance evaluation

Evaluation plan

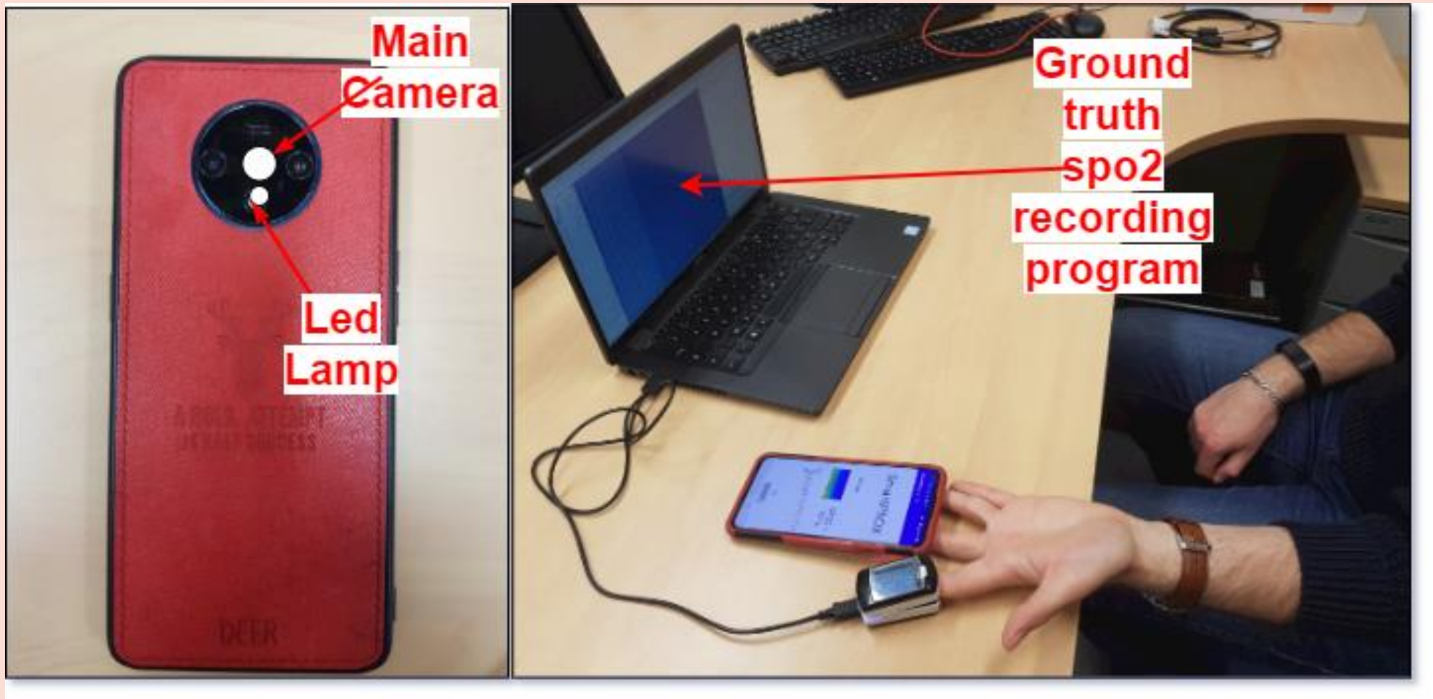
SmartPhOx absolute performance :

SmartPhOx vs complete smartphone-based SOA solution

Varying SmartPhOx key parameters

SmartPhOx robustness against experimental settings

Evaluation setup



Data set	
Participant	37
Oxygen Levels	85% – 99%
Ages	18 - 60

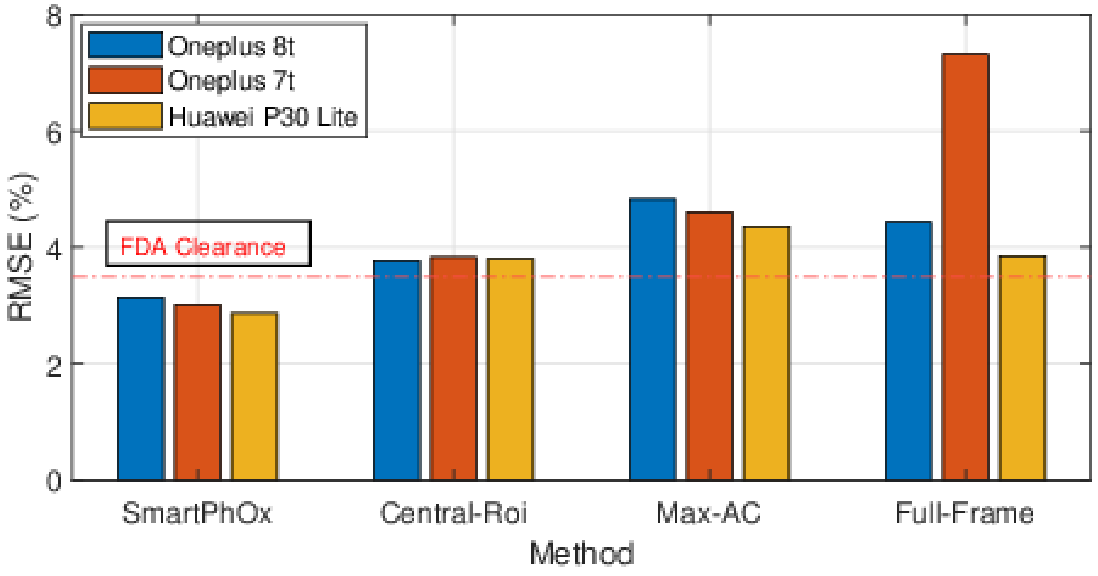
Evaluation : SmartPhOx RMSE

Leave one out cross-validation

Alternative SOA ROI selection strategy.

- Full frame: average intensity over the whole frame
- Central-ROI: central area 50x50 px
- Max-AC: the cell producing the signals with the highest pulsatile part.

Evaluation : SmartPhOx RMSE



- SmartPhOx is the only strategy that meet the 3.5% FDA accuracy threshold (RMSE of 3.04 %)

Evaluation :

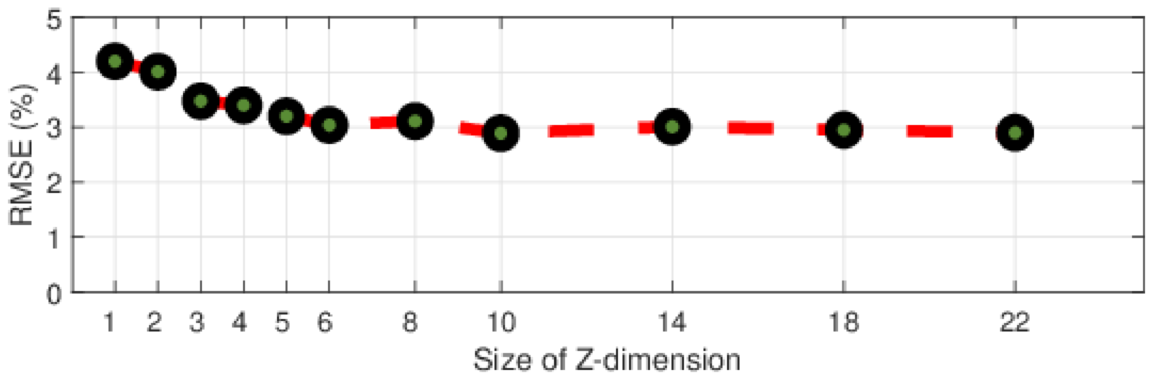
SmartPhOx vs smartphone and hardware addon based SOA solution

	PhO2 [3]	SmartPhOx
80th percentile abs. error	3.5%	3.83%
Hardware add-on	Yes	No

- SmartPhOx meta region of interest approach has fairly the same impact as their custum hardware addon

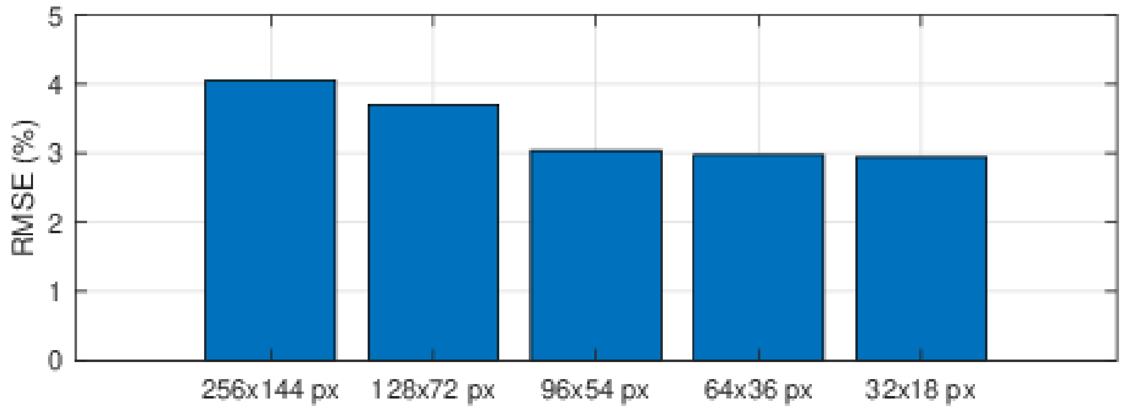
[3] N. Bui, A. Nguyen, P. Nguyen, H. Truong, A. Ashok, T. Dinh, R. Deterding, and T. Vu, "Pho2: Smartphone based blood oxygen level measurement systems using near-ir and red wave-guided light," in Proceedings of the 15th ACM Conference on Embedded Network Sensor Systems, ser. SenSys '17. New York, NY, USA: Association for Computing Machinery, 2017. [Online]. Available: https://doi.org/10.1145/3131672.3131696

Evaluation : Varying key parameters – Z dimension



- From Z = 6 (RMSE = 3.04%) onward, no significant decrease in RMSE

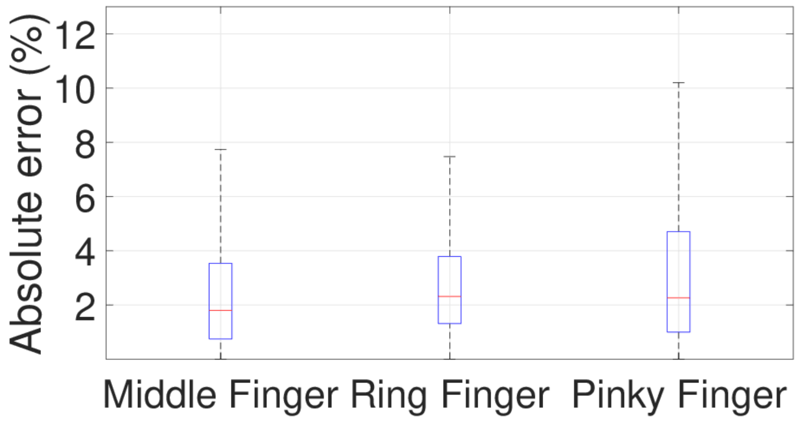
Evaluation : Varying key parameters – Cell size

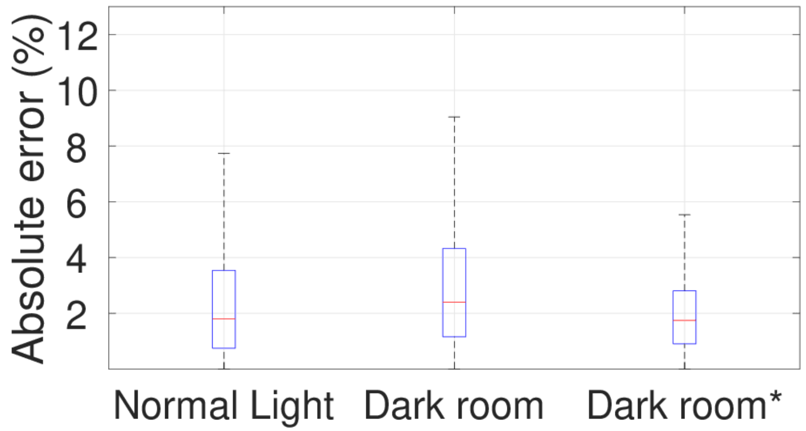


- The higher the number of cells,

the lower is the RMSE (from 4 to 3%)

Evaluation : Varying experimental settings





- Similar error distribution for all fingers;
  - median error of 1.8%; 2.15%; 2.1%

- Robust to differents lightning conditions

* Results obtained with the model trained with dark room data

Conclusion

Conclusion

The first standard smartphone-based pulse oximetry solution to meet FDA requirements for RMSE.

Introducing the RR Map: considering the smartphone camera sensor as a set of independent sensors.

Introduce the concept of meta ROI: use the signal as a filter for itself.

Implementation of an android application and evaluation on 37 volunteers.

Futur works

1

Extend evaluation to non-healthy subjects, ideally COVID patients

2

Extend SpO2 range to 70% - 100%

3

Make it purely passive by using the front camera

Thank you for your attention.

I will be happy to answer your questions ^^

$$Sp02 = \frac{\epsilon_{H_b}(\lambda_1) - \epsilon_{H_b}(\lambda_2)RR_{\lambda_1,\lambda_2}}{(\epsilon_{O_2}(\lambda_2) - \epsilon_{H_b}(\lambda_2))RR_{\lambda_1,\lambda_2} + \epsilon_{H_b}(\lambda_1) - \epsilon_{O_2}(\lambda_1)}.$$

$$SpO_2 = \frac{\rho_{0_2}}{\rho_{0_2} + \rho_{Hb}}$$

Light absorption ratio calculation

$$I_{residual}(\lambda) = I_0(\lambda)\exp^{-d\rho\epsilon(\lambda)}$$

1. Lambert Law : $$I_{residual}(\lambda) = I_0(\lambda)\exp^{-(d\rho_{Hb}\epsilon(\lambda)_{Hb})-(d\rho_{O_2}\epsilon(\lambda)_{O_2})-(d\rho_{DC}\epsilon(\lambda)_{DC})}$$

2. Ratio at two time instant (Systol, diastol) : $$L(\lambda) = ln(\frac{I^{t2}_{residual}}{I^{t1}_{residual}}) = \Delta d(\rho_{Hb}\epsilon_{Hb} + \rho_{O_2}\epsilon_{0_2})$$

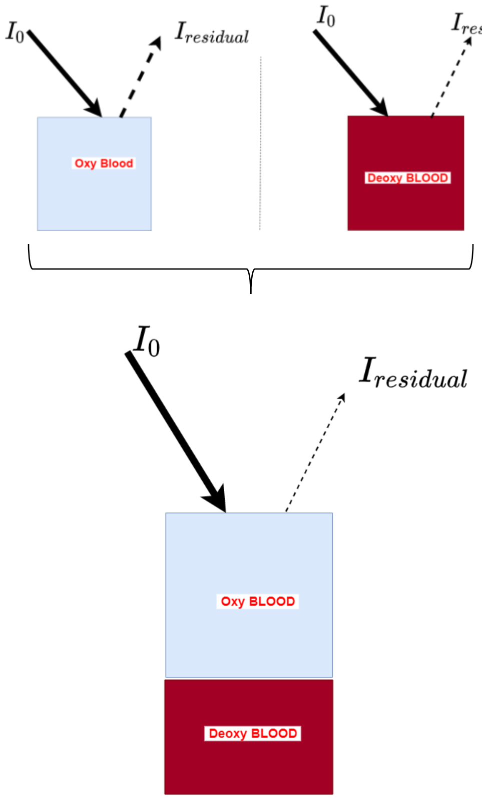
3. Ratio for two wavelength : $$RR_{\lambda_1,\lambda_2} = \frac{L(\lambda_1)}{L(\lambda_2)}$$

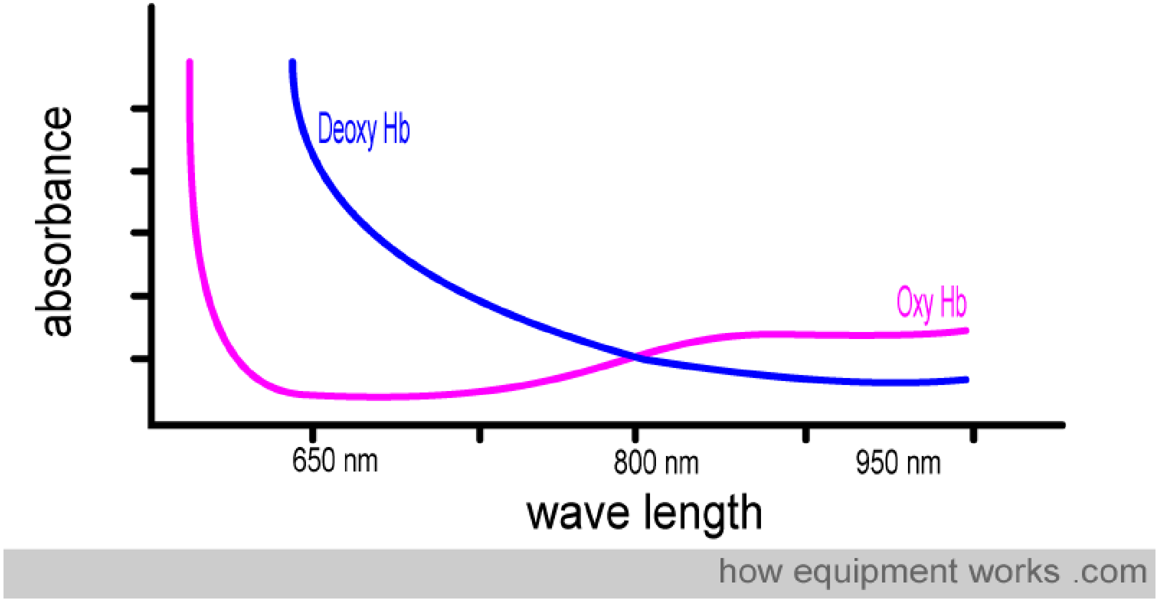
5. SpO2 as a function of RR :

$$Sp02 = \frac{\epsilon_{H_b}(\lambda_1) - \epsilon_{H_b}(\lambda_2)RR_{\lambda_1,\lambda_2}}{(\epsilon_{O_2}(\lambda_2) - \epsilon_{H_b}(\lambda_2))RR_{\lambda_1,\lambda_2} + \epsilon_{H_b}(\lambda_1) - \epsilon_{O_2}(\lambda_1)}.$$

$$RR_{\lambda_1,\lambda_2} = \frac{\ln(\frac{I_{t1}(\lambda_1)}{I_{t2}(\lambda_1)})}{\ln(\frac{I^{t1}(\lambda_2)}{I^{t2}(\lambda_2)})}$$

Basic idea : Oxygenated and Deoxygenated blood absorb light differently trough the light spectrum





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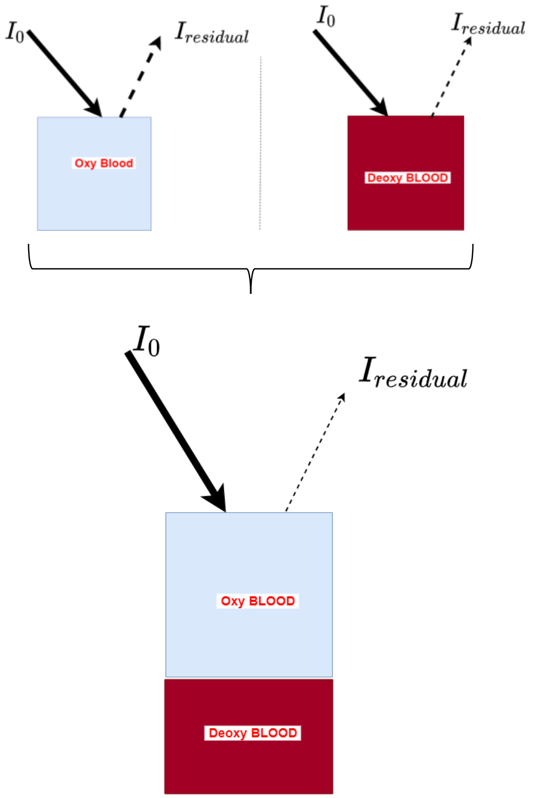
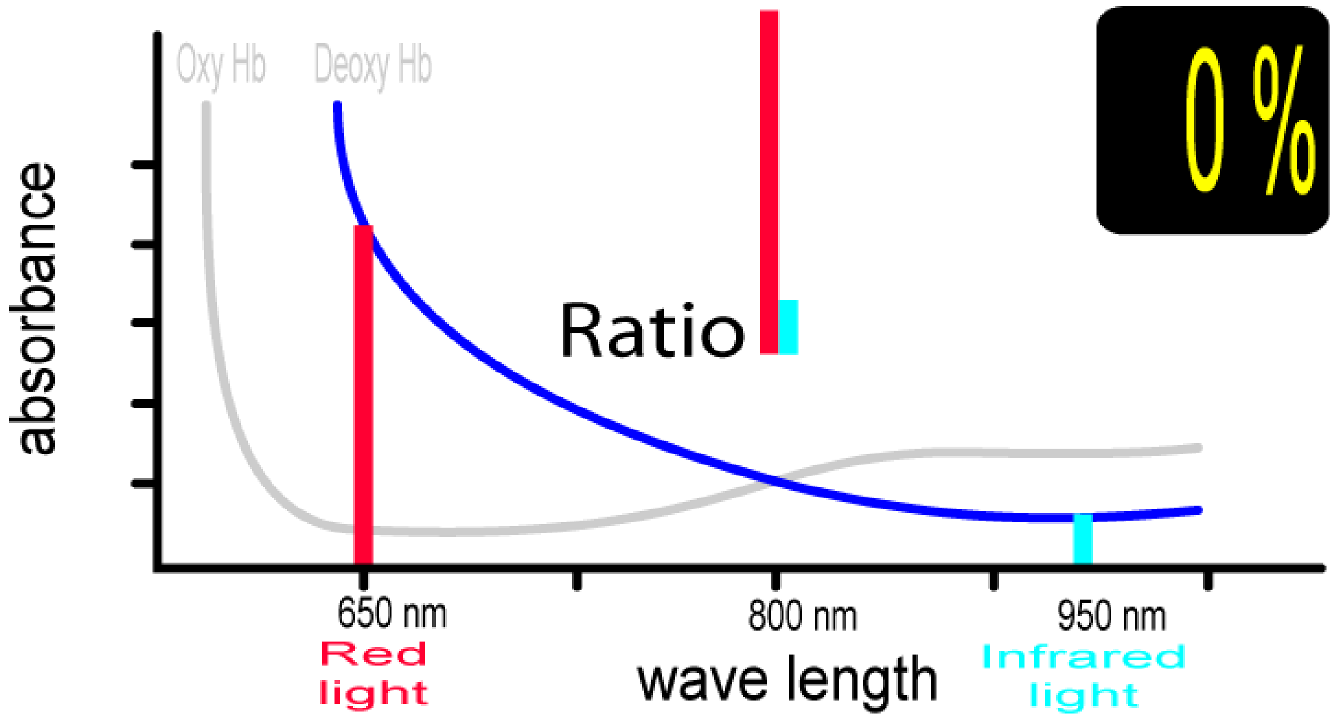
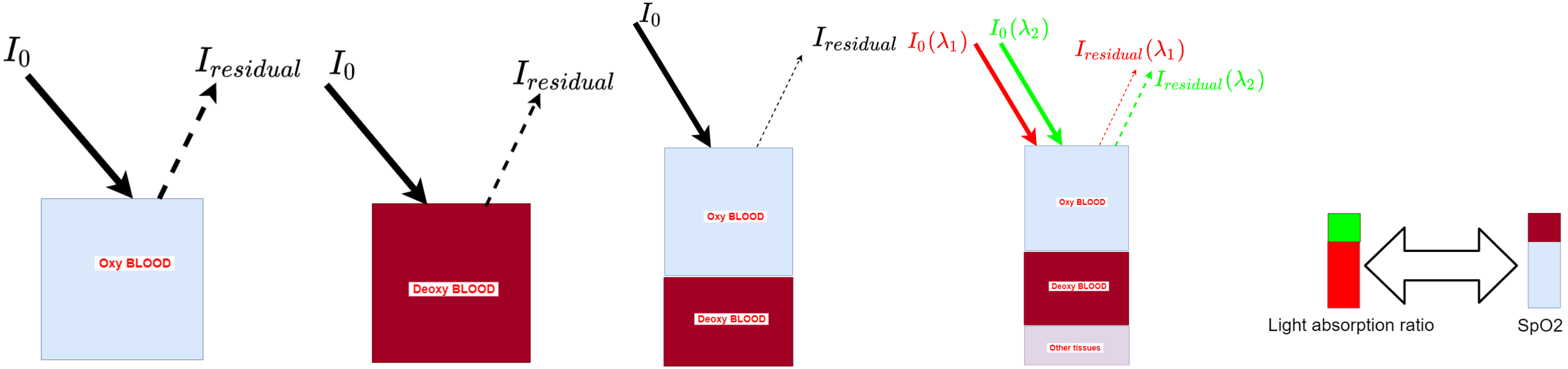




Basic idea : Oxygenated and Deoxygenated blood light absorption ratio



…As a function of Light absorption ratio

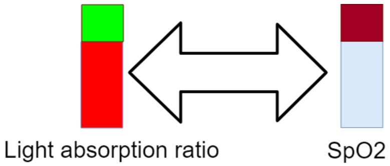
$$SpO_2 = \frac{\rho_{0_2}}{\rho_{0_2} + \rho_{Hb}}$$

$$Sp02 = \frac{\epsilon_{H_b}(\lambda_1) - \epsilon_{H_b}(\lambda_2) RR_{\lambda_1,\lambda_2}}{(\epsilon_{O_2}(\lambda_2) - \epsilon_{H_b}(\lambda_2)) RR_{\lambda_1,\lambda_2} + \epsilon_{H_b}(\lambda_1) - \epsilon_{O_2}(\lambda_1)}.$$

Theoriquement on peut résoudre, mais pratiquement, on

- Unknown parameters : $\epsilon_{Hb}(\lambda_1)$ $\epsilon_{Hb}(\lambda_2)$ $\epsilon_{O_2}(\lambda_1)$ $\epsilon_{O_2}(\lambda_2)$

- Light Absorption Ratio : RR



- Manually learn a regression model :

$$Sp02 = \frac{\epsilon_{H_b}(\lambda_1) - \epsilon_{H_b}(\lambda_2)RR_{\lambda_1,\lambda_2}}{(\epsilon_{O_2}(\lambda_2) - \epsilon_{H_b}(\lambda_2))RR_{\lambda_1,\lambda_2} + \epsilon_{H_b}(\lambda_1) - \epsilon_{O_2}(\lambda_1)}.$$

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$$RR_{\lambda_1,\lambda_2} = \frac{\ln(\frac{I_{t1}(\lambda_1)}{I_{t2}(\lambda_1)})}{\ln(\frac{I^{t1}(\lambda_2)}{I^{t2}(\lambda_2)})}$$