Optical probing depth in a wearable device: a Monte Carlo study

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Motivation

- Wide employment of wearable devices with optical probing system for regular measurement of human physiological parameters
- Employment of optical diagnostic techniques to measure heart rate and blood oxygenation in wearable devices
- Assessing the probing depth when selecting the parameters of the measuring system for optimal device performance
- Impossibility to determine the probing depth in an experiment due to a requirement to place a detector inside the biological tissue

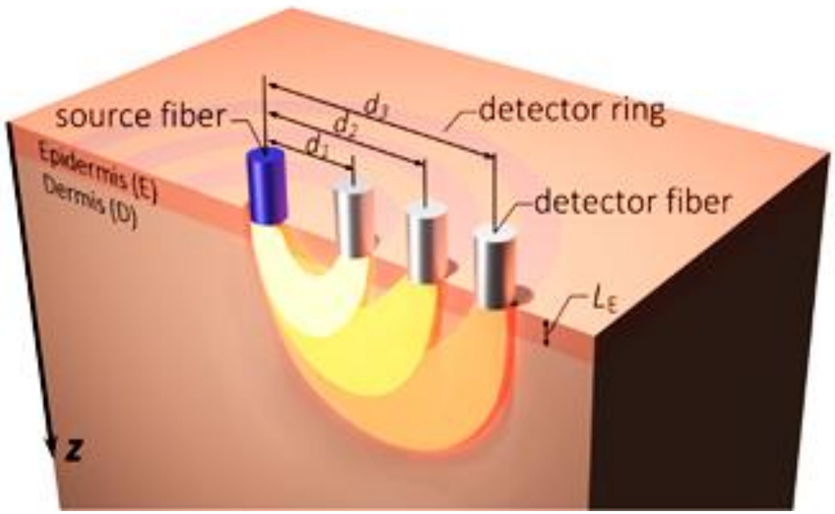
- Application of numerical modeling of signal formation in optical systems by the Monte Carlo technique allowing for tracing individual photon trajectories

Objective

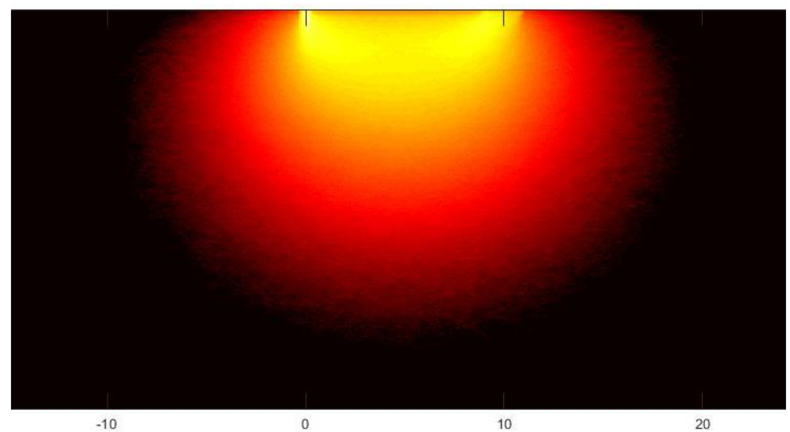
Analysis of probing depth for configuration typical for wearable devices for probing wavelengths of 530, 655, and 940 nm using Monte Carlo technique. This approach allows to simultaneously obtain the dependence of tissue reflectance on source-detector distance and corresponding distribution of maximal probing depths that are reached by individual photon trajectories in the medium.

Optical diffusion methods for studying biological tissue

Basic principle of optical diffusion spectroscopy

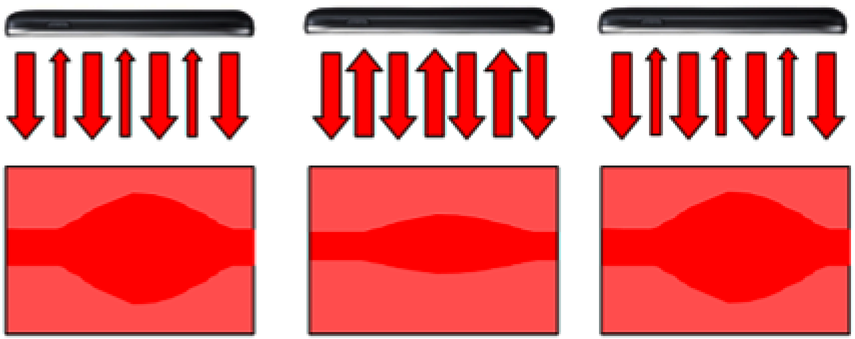


Photon trajectory map calculated by Monte Carlo technique

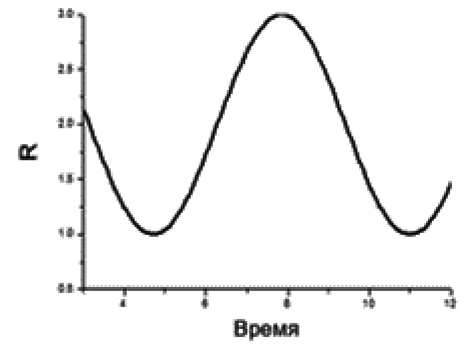


Optical Methods in Wearable Devices

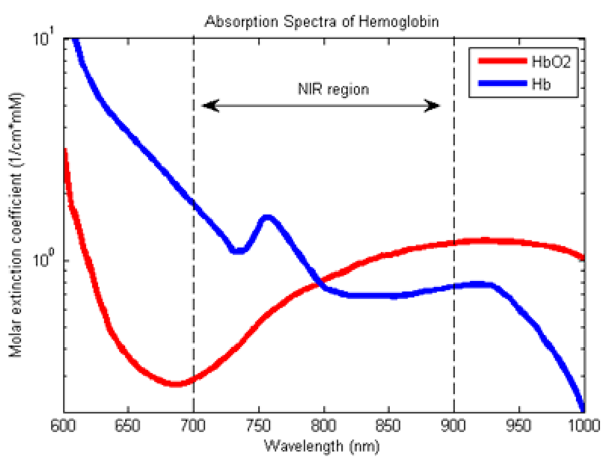
Optical pulse measurement



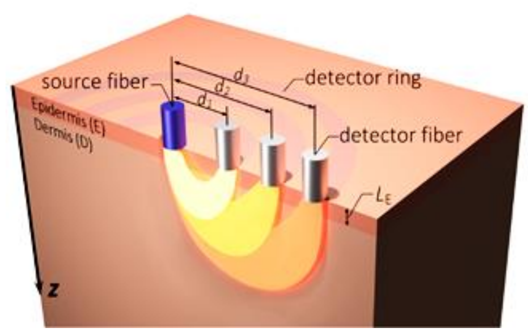
Registration of pulse wave



Optical measurement of blood oxygenation



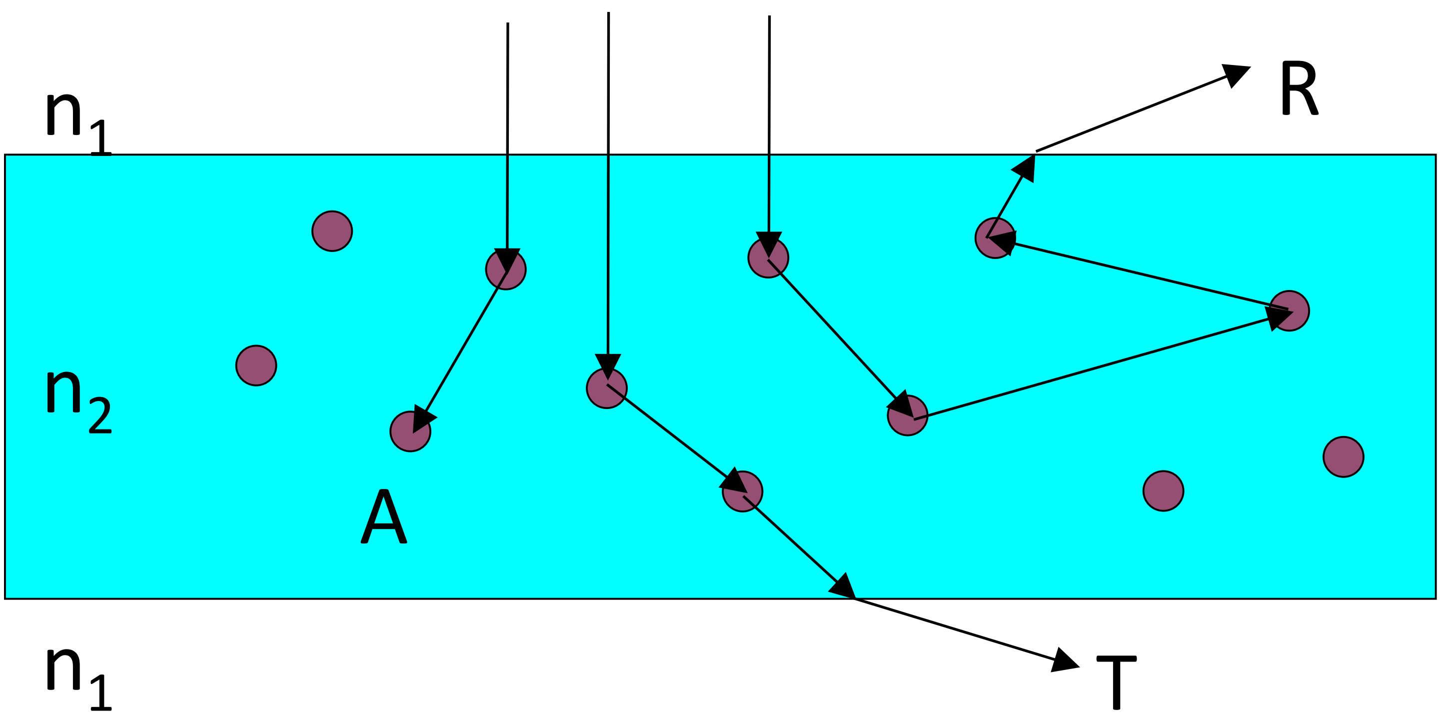
Dual Wavelength Probing



Reconstruction of the oxygenation value

98%

Monte Carlo Technique



R: reflected photon

A: absorbed photon

T: transmitted photon

Input parameters

μ_s : scattering coefficient

μ_a : absorption coefficient

$p(\boldsymbol{s},\boldsymbol{s'})$: scattering phase function

g: anisotropy factor

n: refractive index

Optical properties of skin layers

Wavelength (nm)	μ_s, mm^{-1}	μ_a, mm^{-1}
Epidermis		
530	71.03	1.454
655	52.99	0.852
940	33.23	0.199
Dermis		
530	40.19	0.21
655	28.94	0.065
940	15.44	0.058

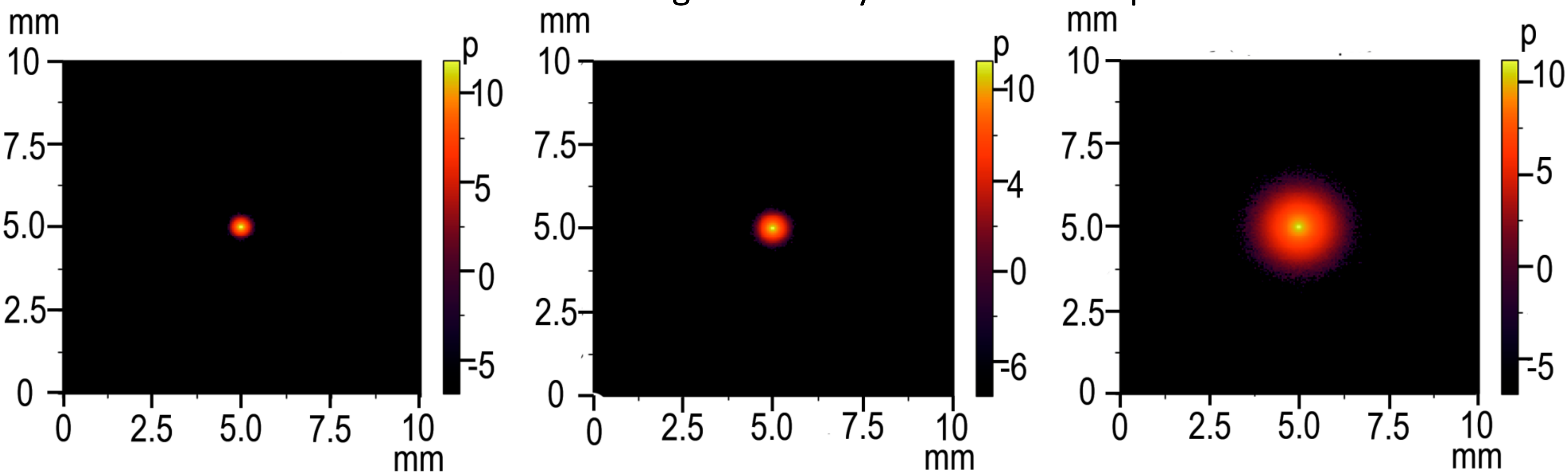
$n = 1.37$; $g = 0.9$

E. Sergeeva, D. Kurakina, I. Turchin, M.Yu. Kirillin, A refined analytical model for reconstruction problems in diffuse reflectance spectroscopy, *Journal of Innovative Optical Health Sciences,* 2342002 (2024).

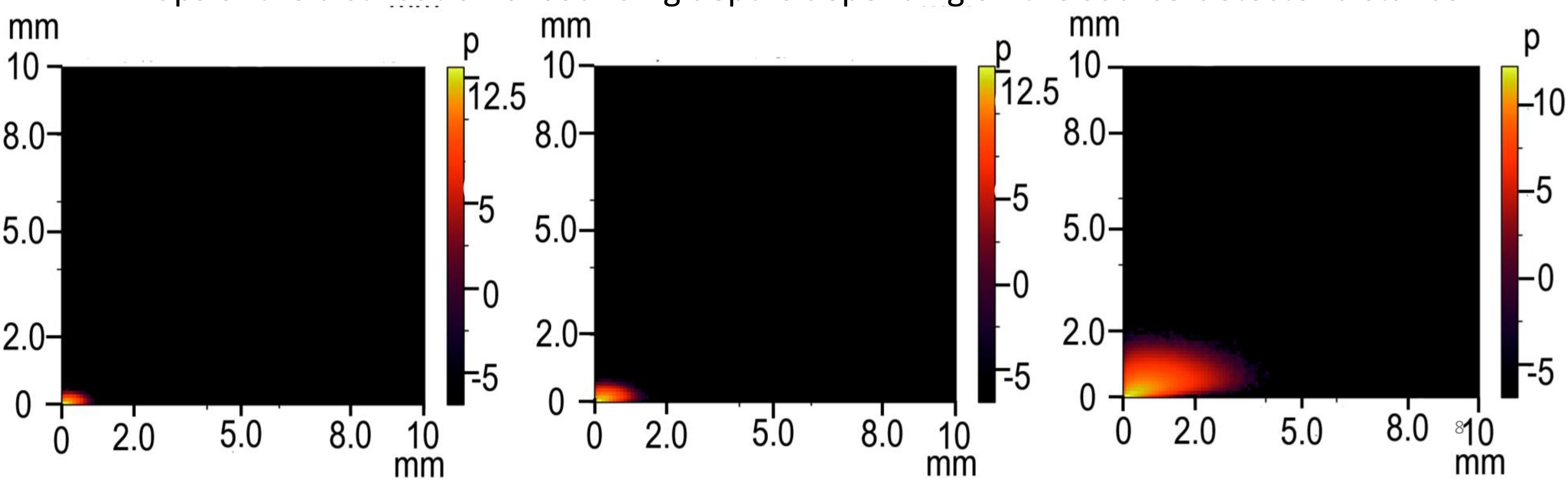
Analysis of Probing Depth in Wearable Optical Devices:

OP: epidermis

Backscattered light intensity distribution maps



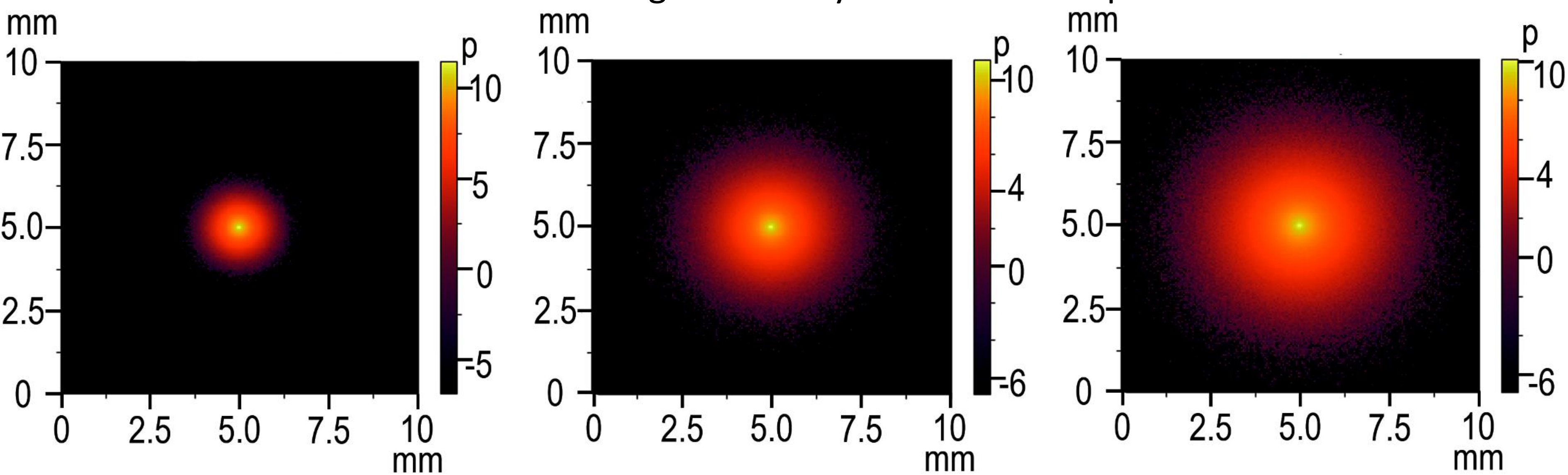
Maps of the distribution of sounding depths depending on the source-detector distance



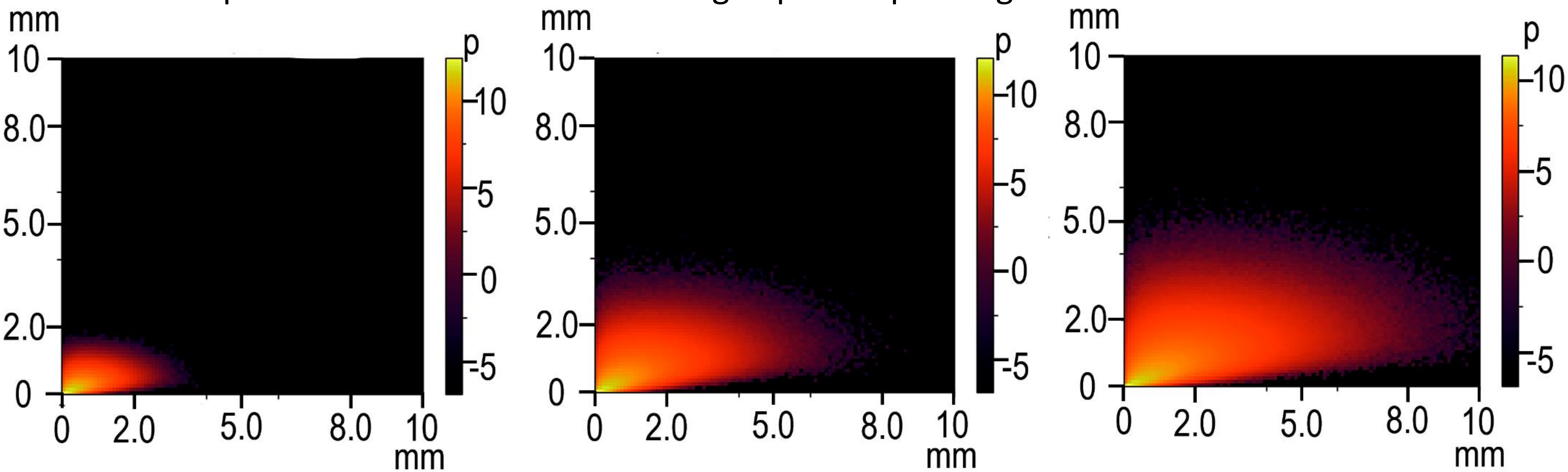
Analysis of Probing Depth in Wearable Optical Devices:

OP: dermis

Backscattered light intensity distribution maps



Maps of the distribution of sounding depths depending on the source-detector distance

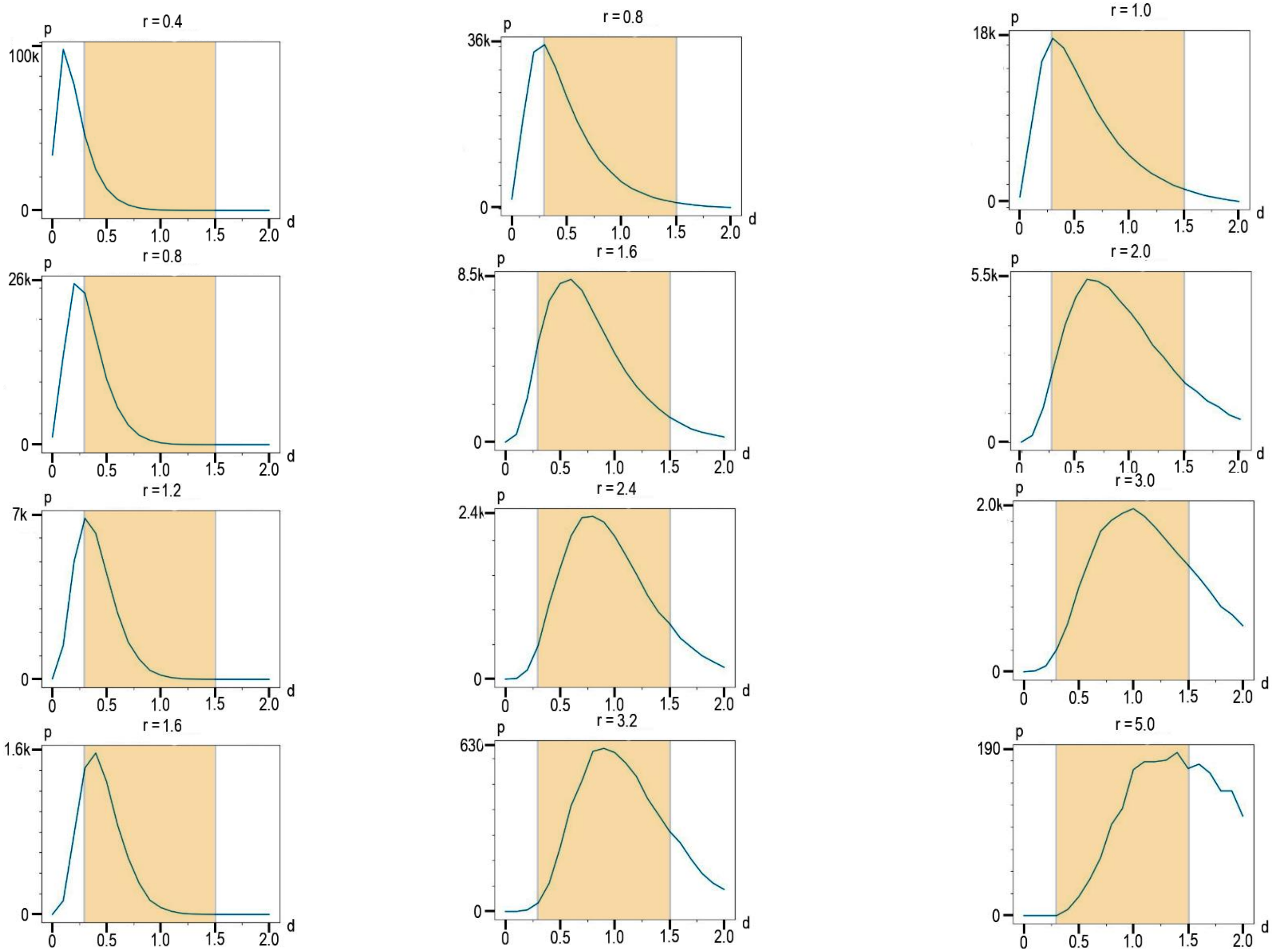


Analysis of Probing Depth in Wearable Optical Devices:

OP: dermis

Probing depth distributions versus source-detector distance

λ = 530 nm λ = 655 nm λ = 940 nm



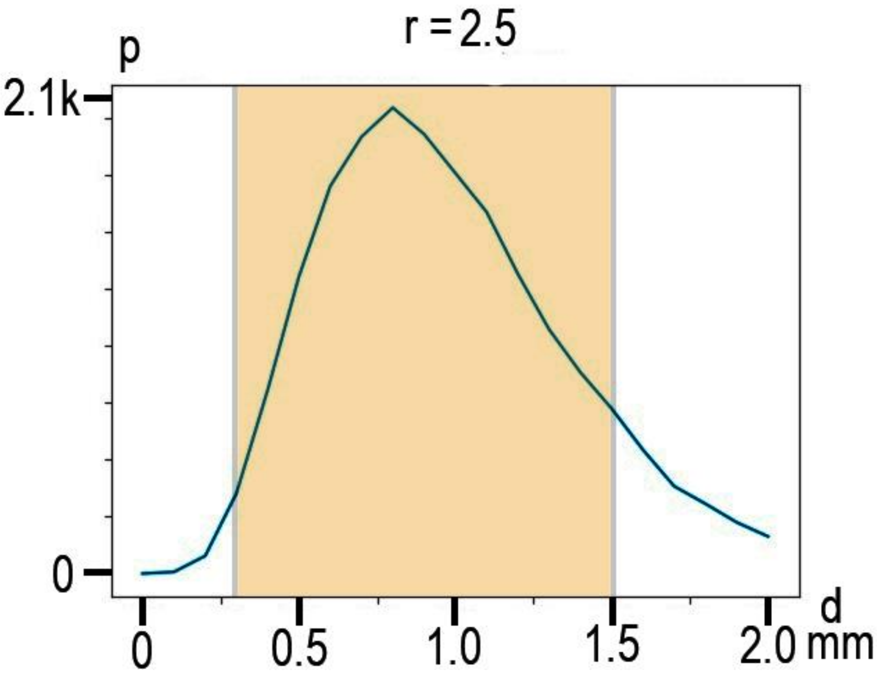
Physiological depths of the dermis: 0.3-1.5 mm (shown with beige strip)

Analysis of Probing Depth in Wearable Optical Devices:

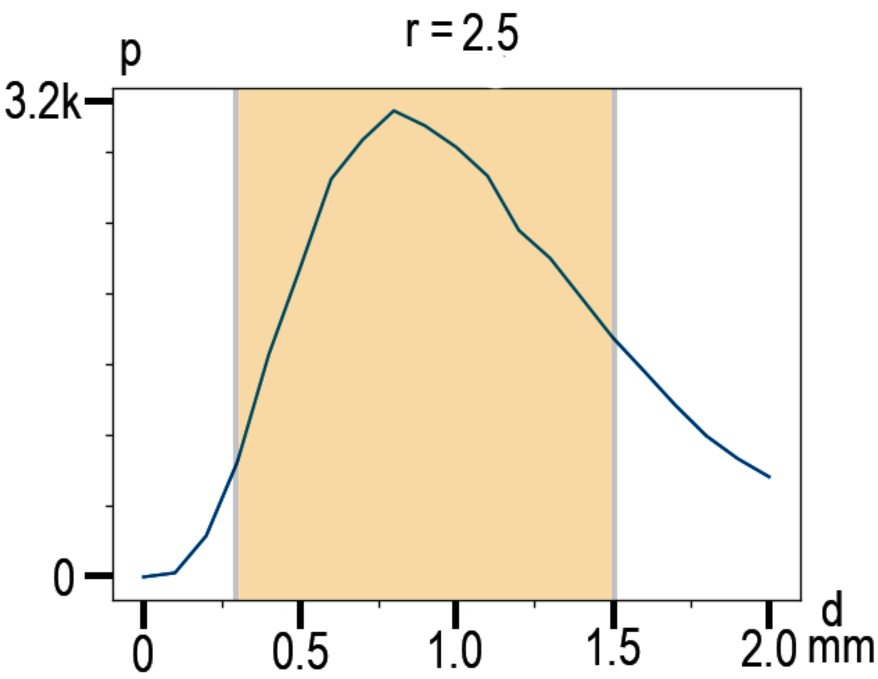
OP: dermis

Probing depth distributions for oxygenation measurements wavelengths

λ = 655 nm



λ = 940 nm



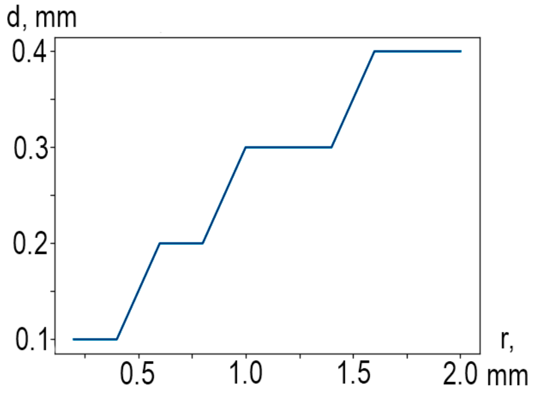
Similar distributions providing the same probing volume are achieved for *d* = 2.5 mm

Analysis of Probing Depth in Wearable Optical Devices:

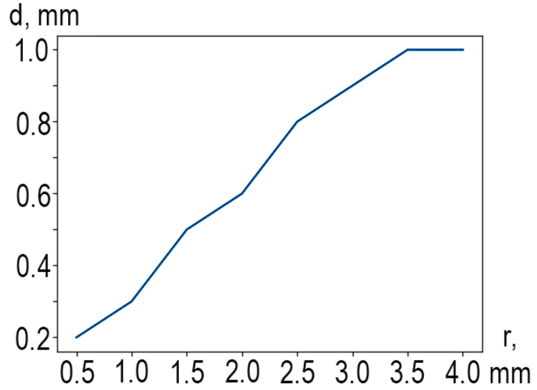
OP: dermis

Most probable probing depth *d* versus source detector distance *r*

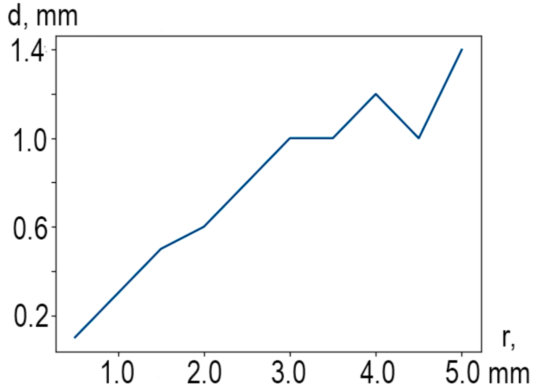
λ = 530 nm



λ = 655 nm



λ = 940 nm



r within [1, 2] mm

↓

d within [0.3, 1.5] mm

r within [1, 4] mm

↓

d within [0.3, 1.5] mm

r within [2.5, 4] mm

↓

d within [0.7, 1] mm

r within [1, 5] mm

↓

d within [0.3, 1.5] mm

r within [2.5, 3.5] mm

↓

d within [0.7, 1] mm

Conclusion

- For the wavelength of 530 nm the range of the probing depth of 0.3 - 0.4 mm are achieved for the source-detector distances of 1 - 2 mm. Since blood absorption in the red and NIR ranges is smaller, the wavelengths from these ranges provide deeper probing.

- For the wavelength of 655 nm, the probing depth range of 0.3 - 1 mm is achieved for the source-detector distance of 1 - 4 mm, and the maximum proximity of the probing depth to the center of the dermis layer (0.8 - 1 mm) is achieved with a source-detector distance in the range: 2.5 - 4 mm.

- For the wavelength of 940 nm the probing depth range of 0.6 - 1.4 mm is achieved from the source-detector distance of 2 - 5 mm, with the maximum proximity of the probing depth to the center of the dermis layer (0.8 - 1 mm) for the source-detector distance in the range of 2.5-3.5 mm.

- For oxygenation measurements in wearable devices at wavelengths of 655 and 940 nm, the optimal source-detector distance is 2.5 mm for both wavelengths, providing the probing depth of 0.8 mm for wavelengths.


Thanks for your attention!