Optical properties of biological tissues for polarized light

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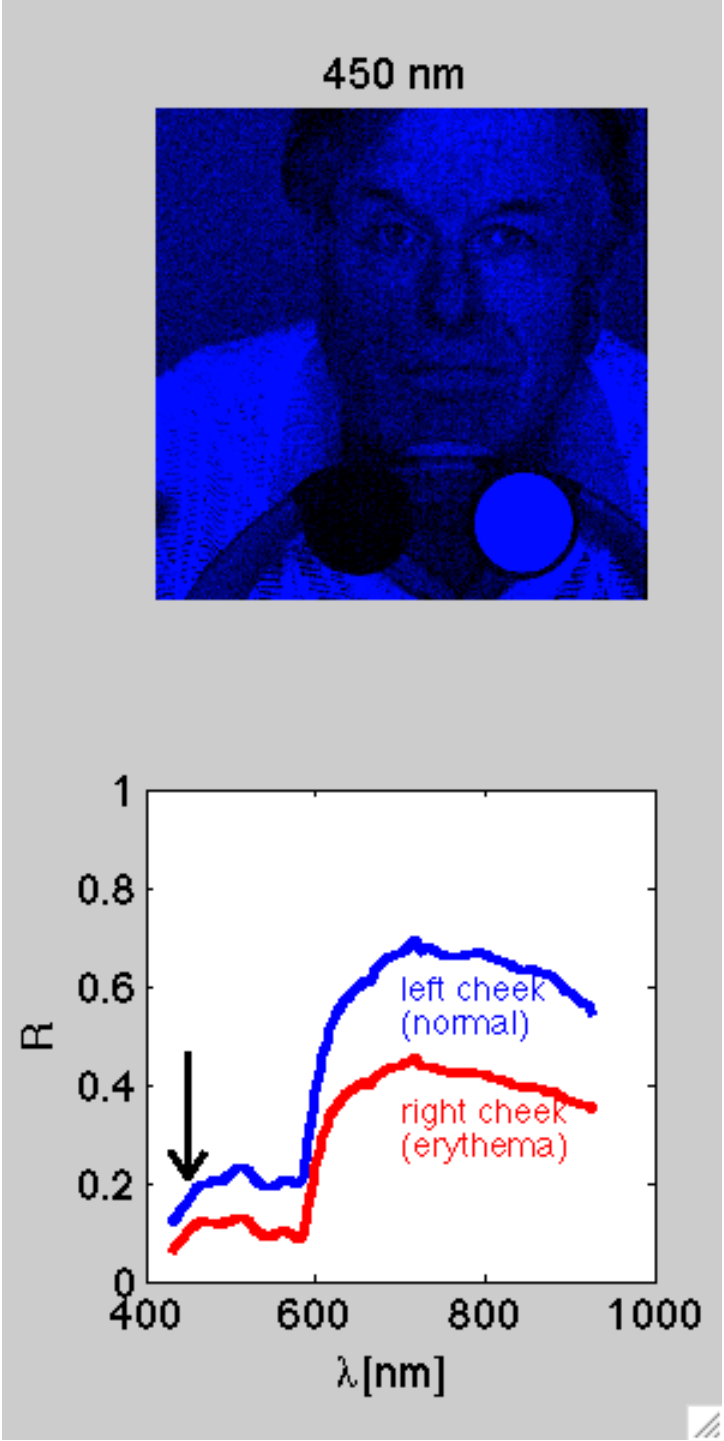
Right cheek erythema induced by hot wet towel.



Polarization…

1. as a contrast mechanism
    - examples in biology (next talks)
2. as a characterization parameter
    - depolarization due to
        a. birefringence
        b. scattering
3. as a gating mechanism
    - HQ image, to select superficially scattered light

Polarization as a characterization parameter

A. Depolarization by birefringence (no scattering)

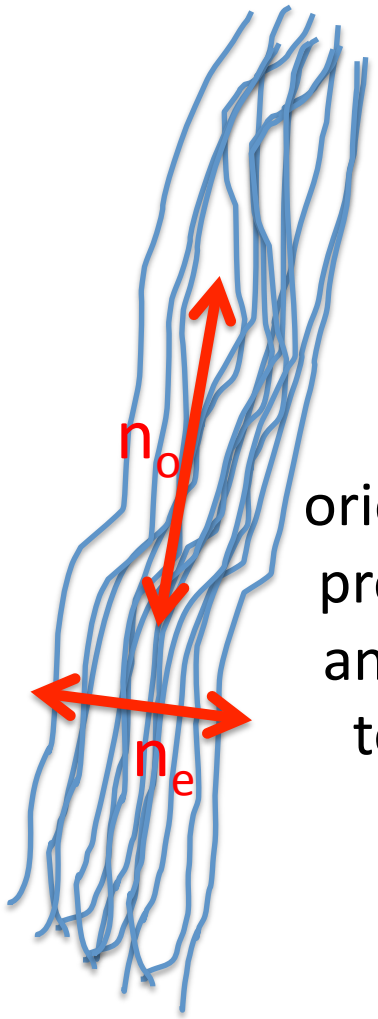
Birefringence

$Dn = n_e - n_o$

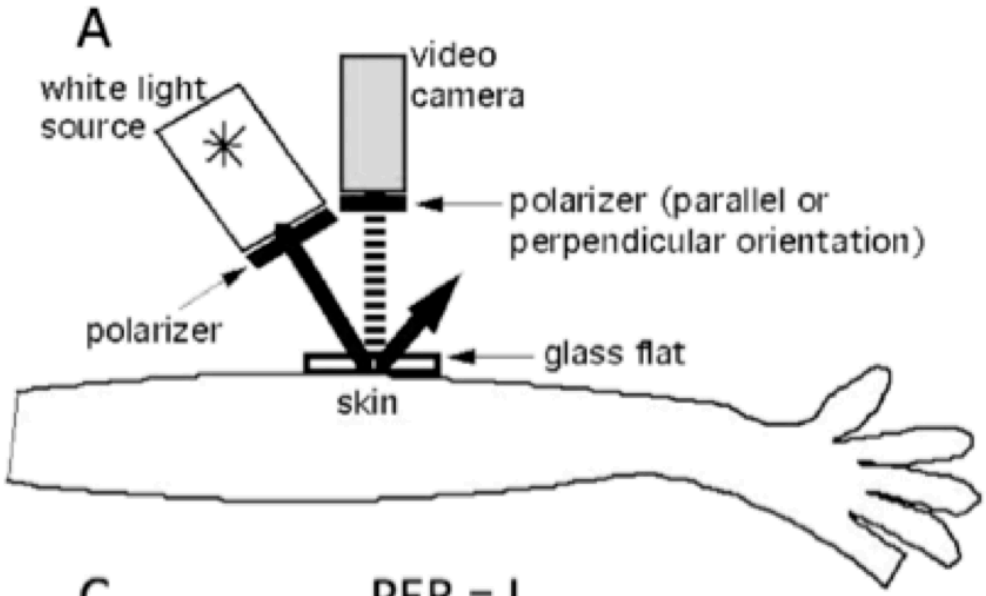
$\approx 1x10^{-3} - 5x10^{-3}$

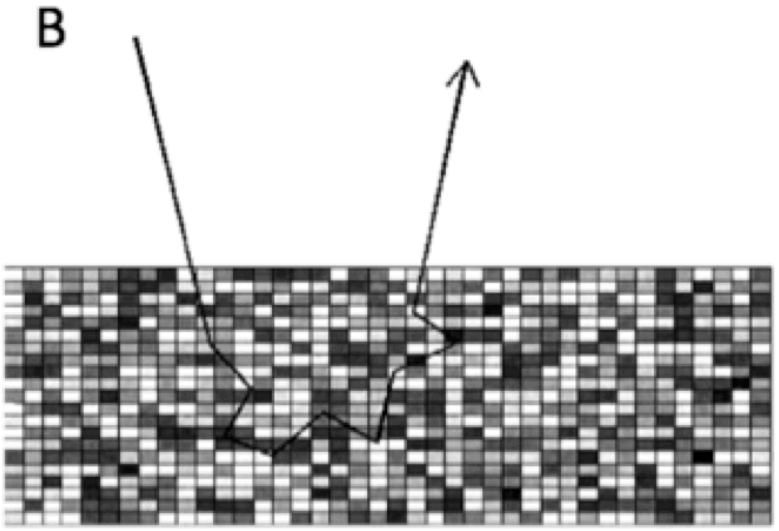
Size of microdomains of birefringence in tissue is

DL ≈ 10-100 mm

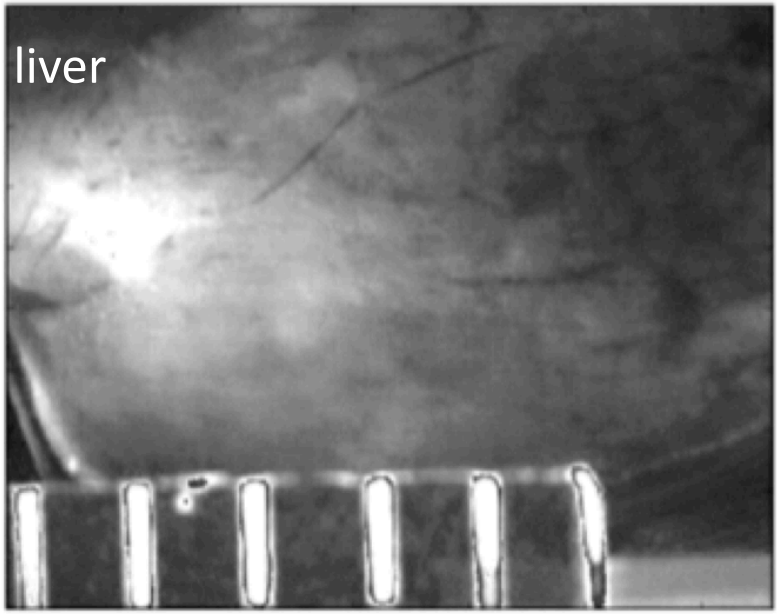


oriented fibers present a fast and slow axis to photons

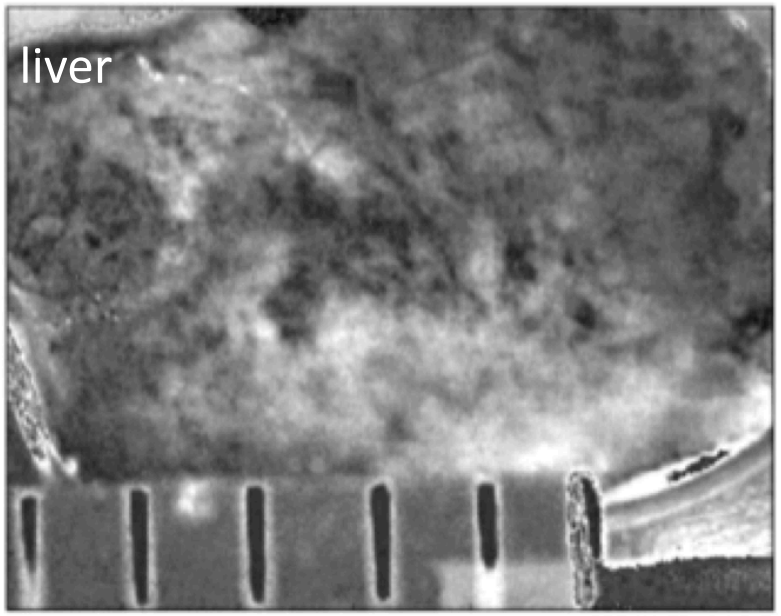




C $PER = I_V$



D $DIFF = I_H - I_V$

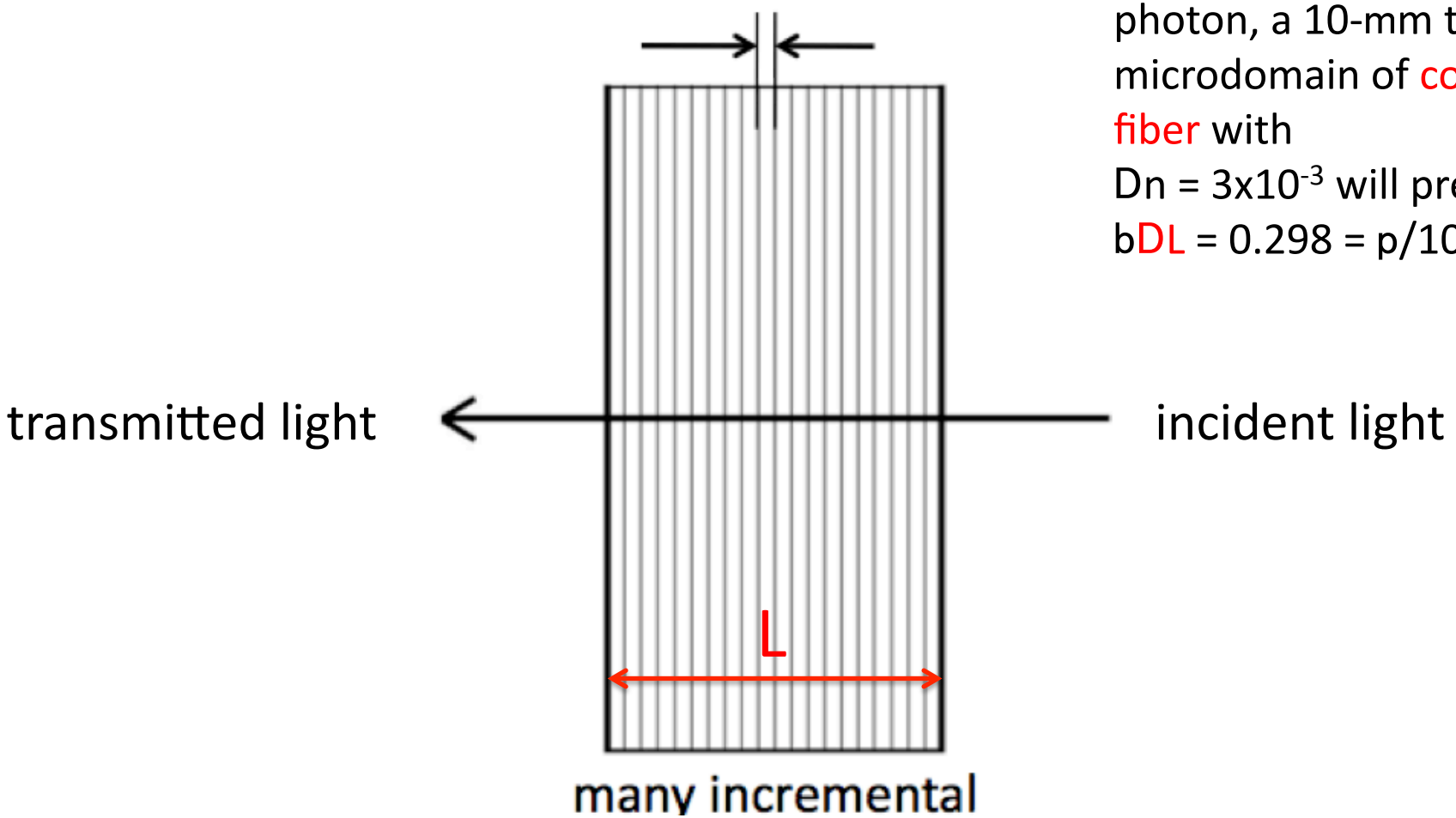


$$b = 2\pi Dn/\lambda$$

incremental retardance

$$Df = 2\pi DnDL/\lambda = bDL$$

For a 633 nm wavelength photon, a 10-mm thick microdomain of collagen fiber with $Dn = 3 \times 10^{-3}$ will present $bDL = 0.298 = \pi/10.5$.



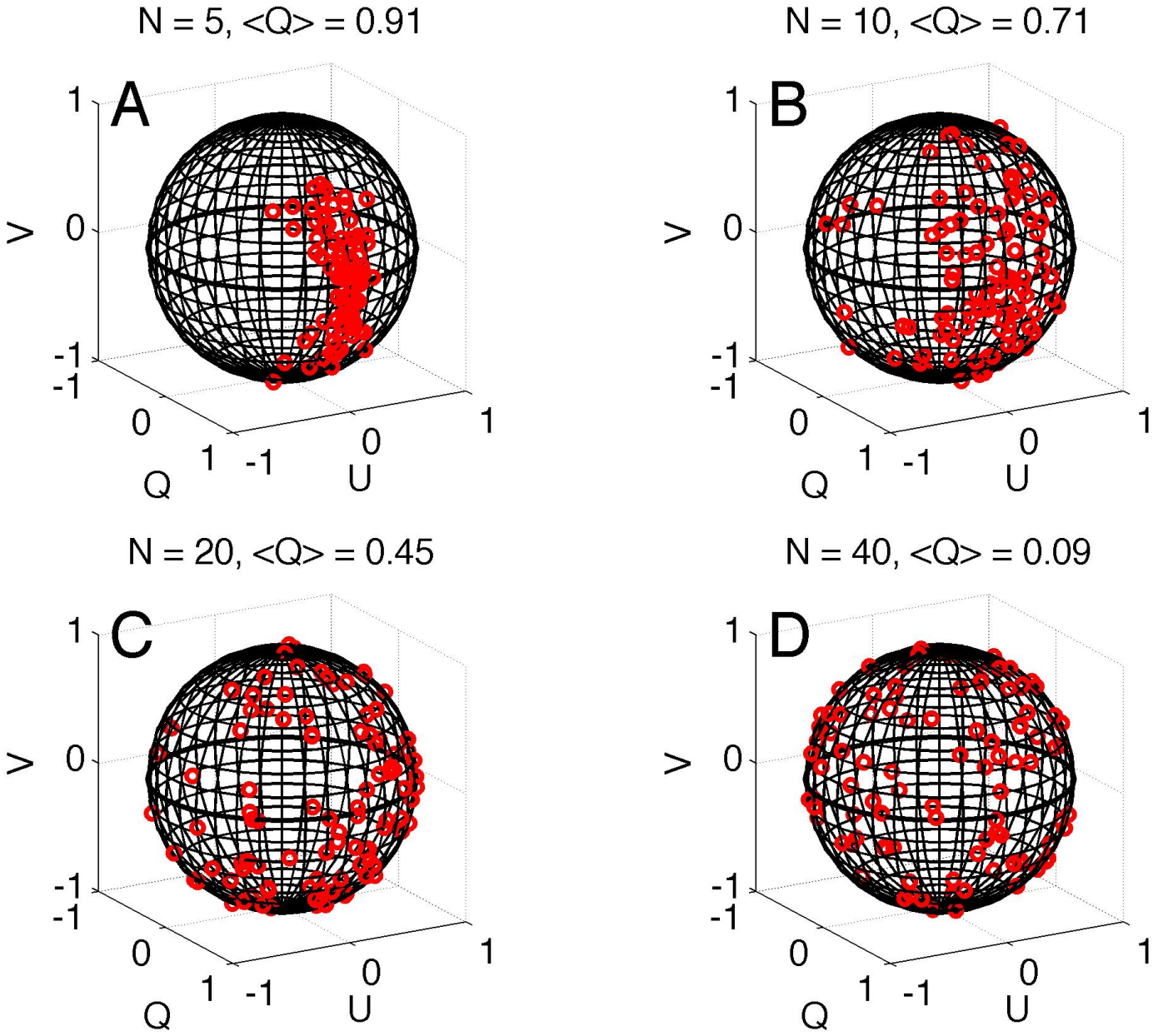
L/DL = N incremental retarders,

randomly oriented

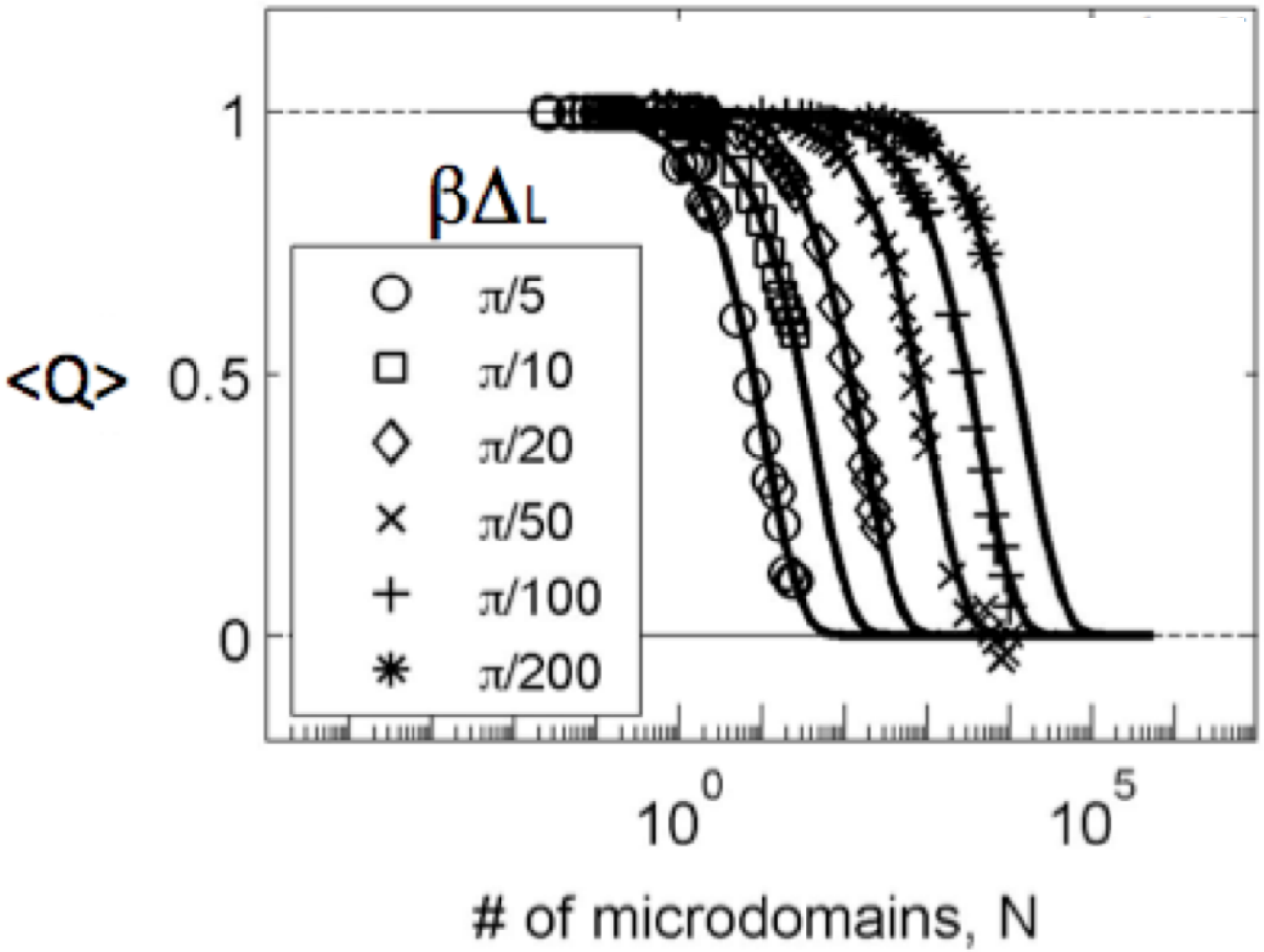
microdomain retardance:

bDL = p/10

$$S_{in} = \begin{vmatrix} 1 \\ 1 \\ 0 \\ 0 \end{vmatrix}$$



$$\langle Q \rangle = e^{-D_{LP}N} \qquad D_{LP} = a\left(\frac{\beta\Delta L}{[rad]}\right)^2$$



Depolarization coefficients m_{LP} and m_{CP}
due to randomly oriented birefringent microdomains

$$\langle Q \rangle = e^{-D_{LP}N} = e^{-D_{LP}\left(L/\Delta L\right)} = e^{-\mu_{LP}L}$$

For the example , if

Dn = 3×10^{-3},

l = 0.633×10^{-4} cm

and DL = 10×10^{-4} cm,

$$\mu_{LP} = D_{LP} / \Delta L$$

$$= a\Delta L \left(\frac{\beta}{[rad]} \right)^2$$

the value of m_{LP} is 21 cm^{-1},

mpf = $1/m_{LP}$ = 476 mm

Depolarization coefficients m_{LP} and m_{CP}
due to randomly oriented birefringent microdomains

$$\langle V \rangle = e^{-D_{CP}N} = e^{-D_{CP}\left(L/\Delta L\right)} = e^{-\mu_{CP}L}$$

For the example , if

Dn = 3×10^{-3},

l = 0.633×10^{-4} cm

and DL = 10×10^{-4} cm,

$$\mu_{LP} = D_{LP} / \Delta L$$

$$= a\Delta L \left(\frac{\beta}{[rad]} \right)^2$$

the value of m_{LP} is 42 cm^{-1},

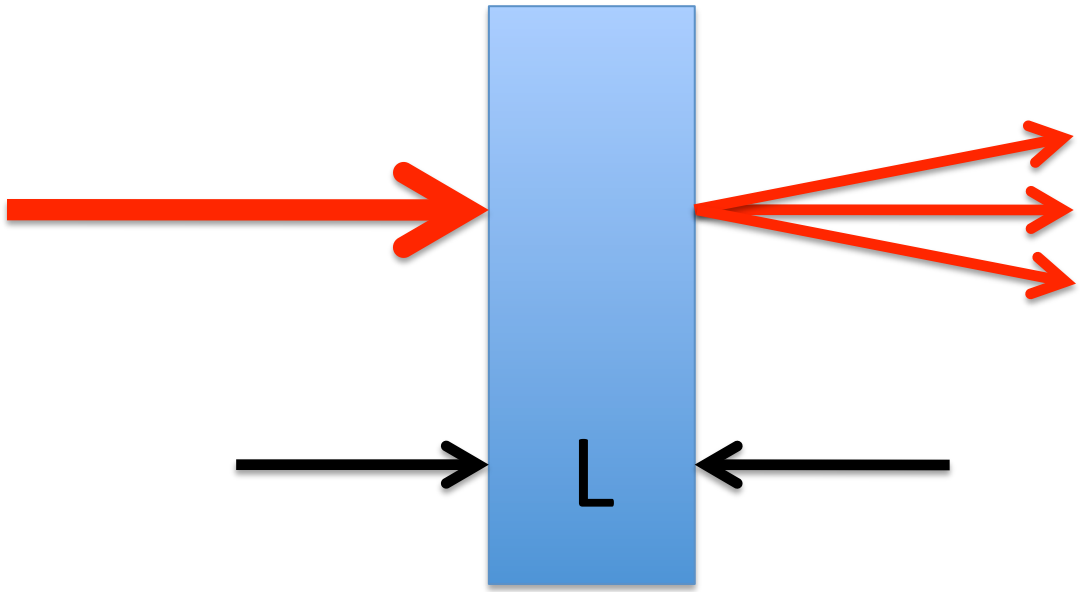
$m_{CP} = 2\ m_{LP}$

mpf = $1/m_{LP}$ = 238 mm

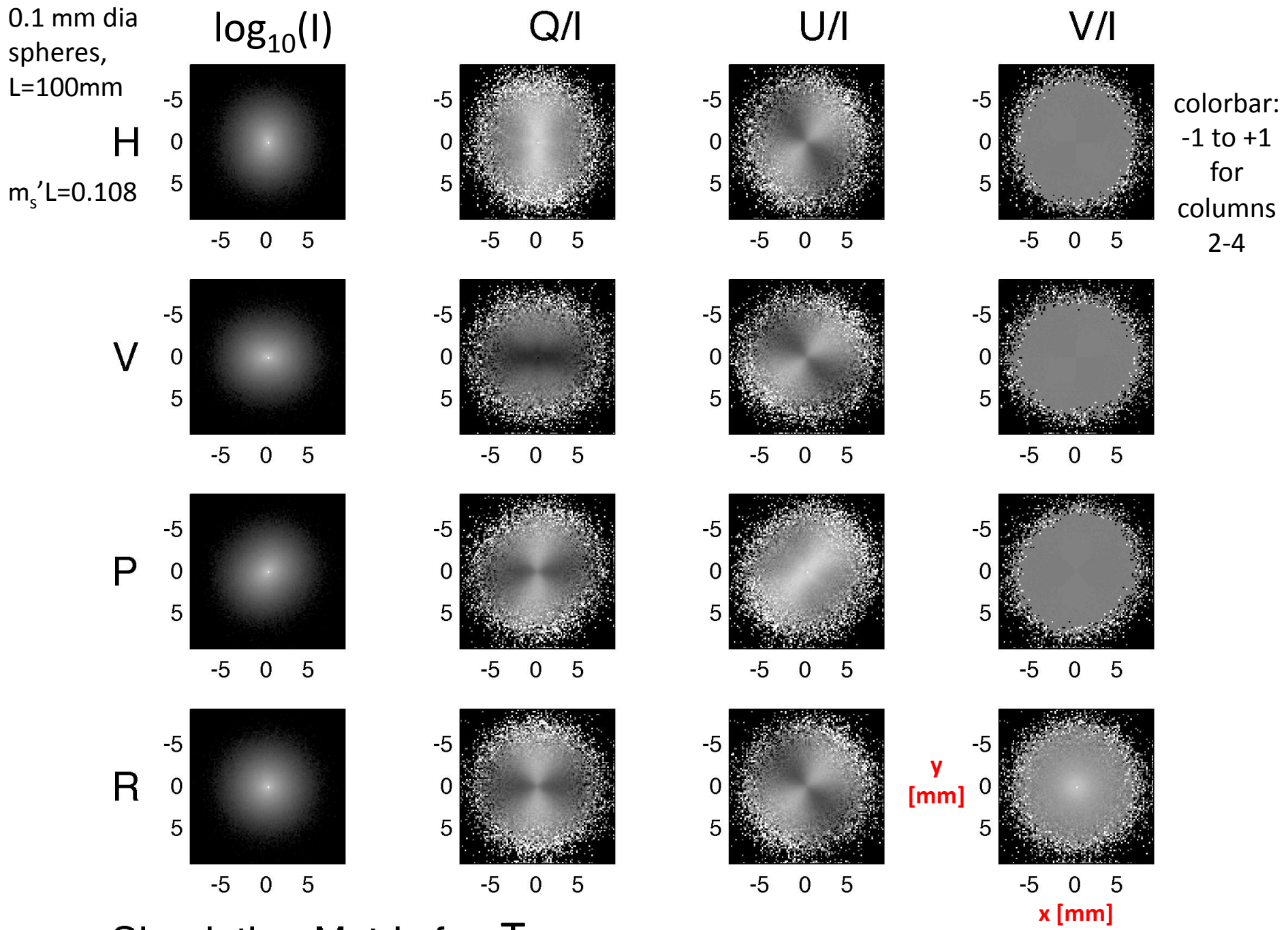
Polarization as a characterization parameter

B. Depolarization by scattering (no birefringence)

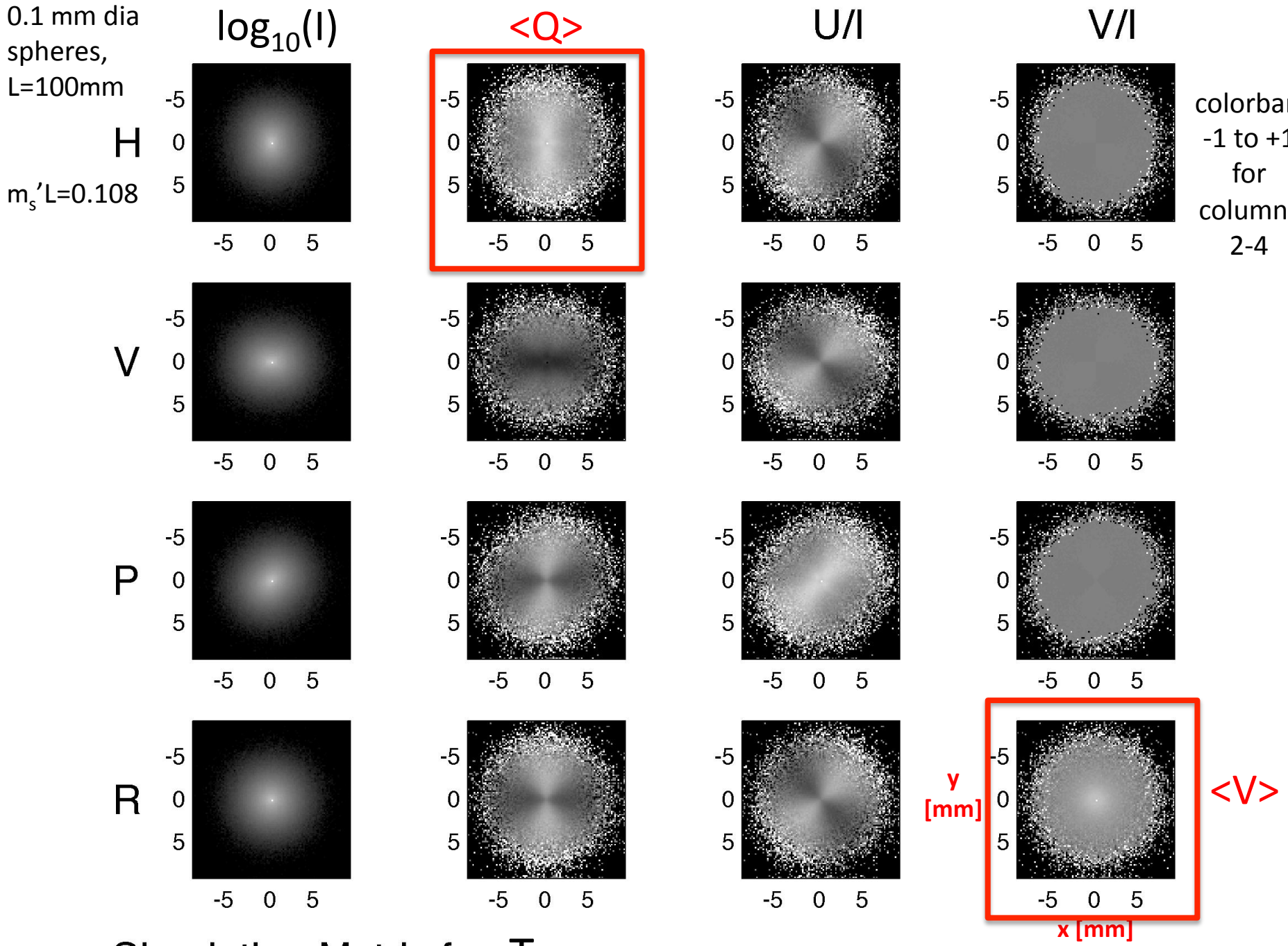
Use polarized light Monte Carlo simulations
For each scattering coefficient m_s [cm^{-1}]
vary the slab thickness L [cm].



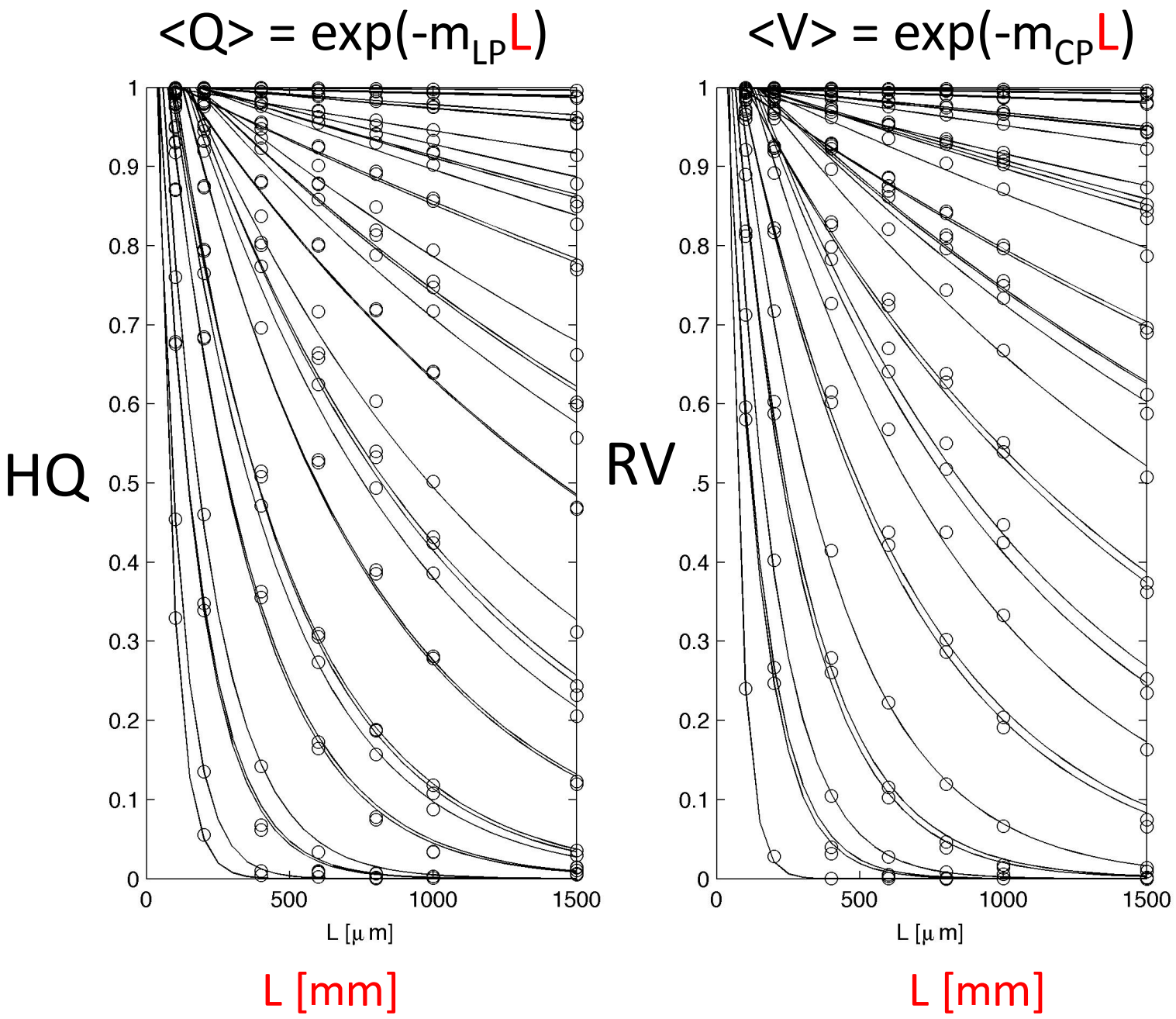
Ramella-Roman JC, SA Prahl, SL Jacques: Three Monte Carlo programs of polarized light transport into scattering media: part I. *Optics Express* 13 (12):4420-4438, 2005.



Simulation Matrix for T



Simulation Matrix for T


<Q> = exp(-m_LP L)
<V> = exp(-m_CP L)
HQ
RV
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0
500
1000
1500
L [μm]
L [mm]
L [mm]

scattering coefficient [cm^{-1}]

Linear depolarization:

$$\langle Q \rangle = e^{-\mu_{LP} L} = e^{-k_{LP} m_s L}$$

$$k_{LP} = \frac{\mu_{LP}}{\mu_s}$$ = efficiency of LP depolarization

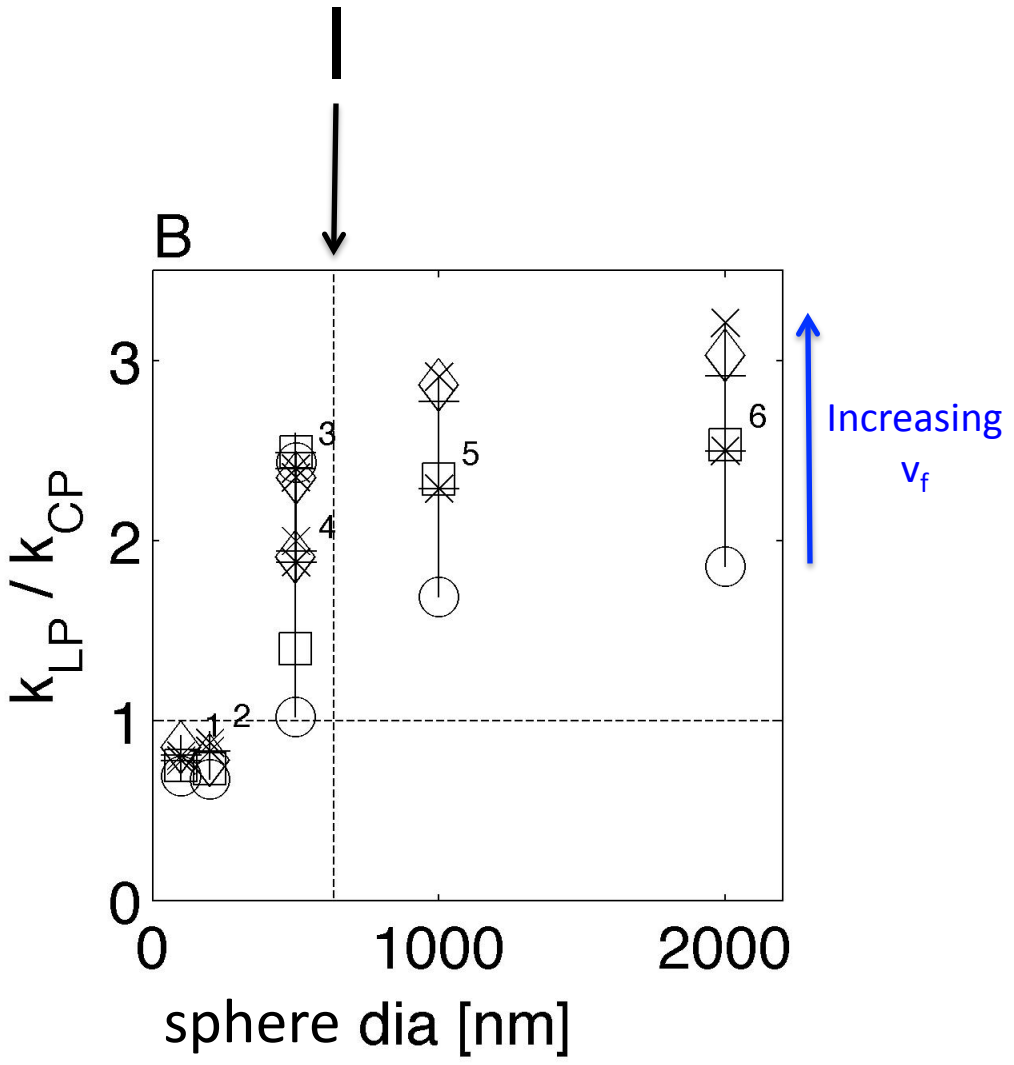
Circular depolarization:

$$\langle V \rangle = e^{-\mu_{CP} L} = e^{-k_{CP} m_s L}$$

$$k_{CP} = \frac{\mu_{CP}}{\mu_s}$$ = efficiency of CP depolarization

Linearly polarized light is more efficiently depolarized than circularly polarized light,
for larger particles.

The same efficiency
for smaller particles.



Depolarization coefficients m_{LP} and m_{CP} due to scattering

Coefficients m_{LP} and m_{CP} due to birefringence

$m_{LP} = k_{LP}\, m_s \approx 0.025\ (200\ cm^{-1}) = 5\ cm^{-1}$

$24\ cm^{-1}$

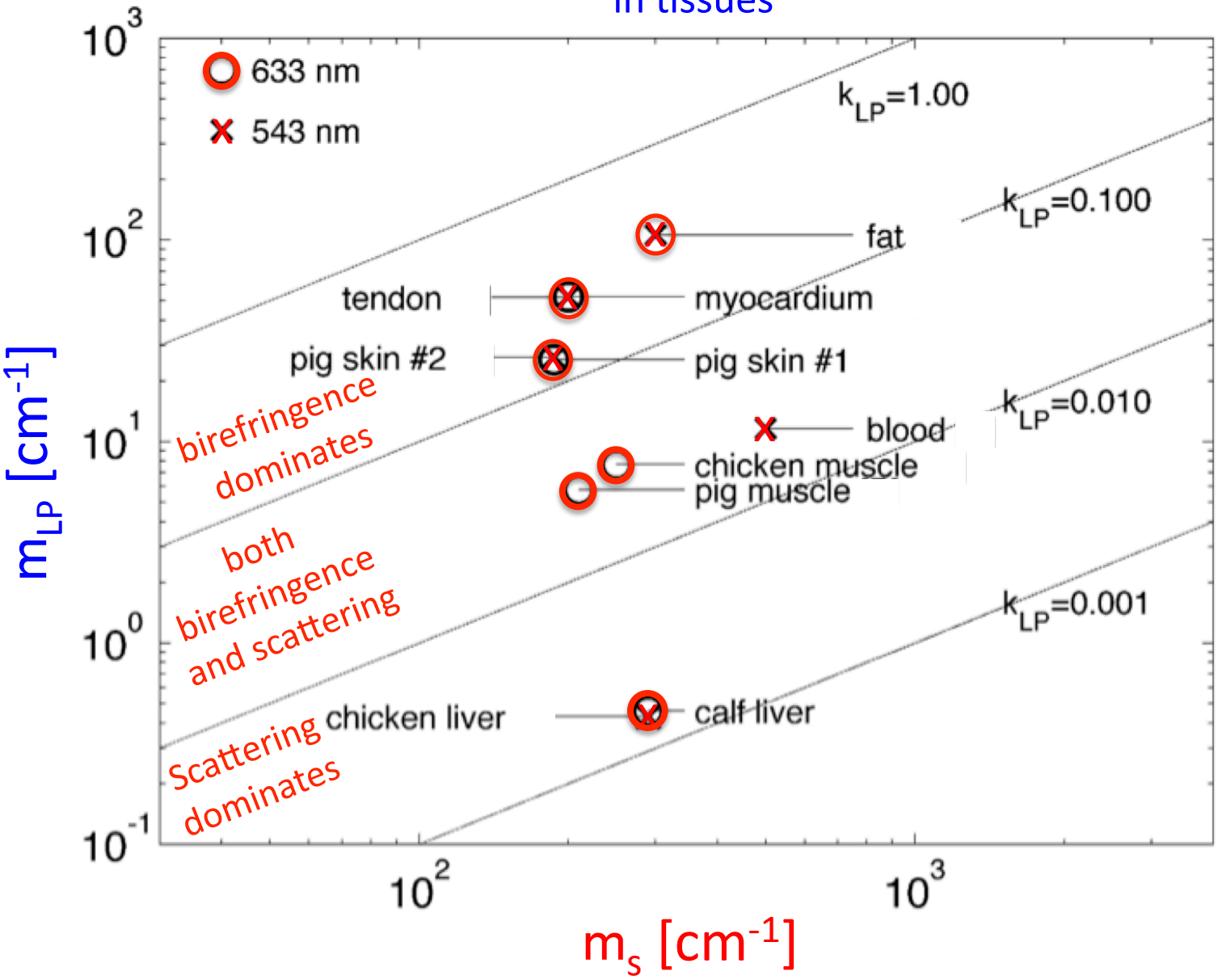
$m_{CP} = k_{CP}\, m_s \approx 0.0125\ (200\ cm^{-1}) = 2.5\ cm^{-1}$

$42\ cm_{-1}$

for collagen fibers

typical m_s value for mid-visible light

Depolarization of linearly polarized light in tissues



Conclusions:

1. Depolarization in tissues is due to both scattering and birefringence.
   -birefringence dominates in collagenous tissues,
   -birefringence and scattering ~equal in muscle,
   -scattering dominates in non-birefringent tissues like liver.
   (fat and blood are likely dominated by scattering, but are very depolarizing)

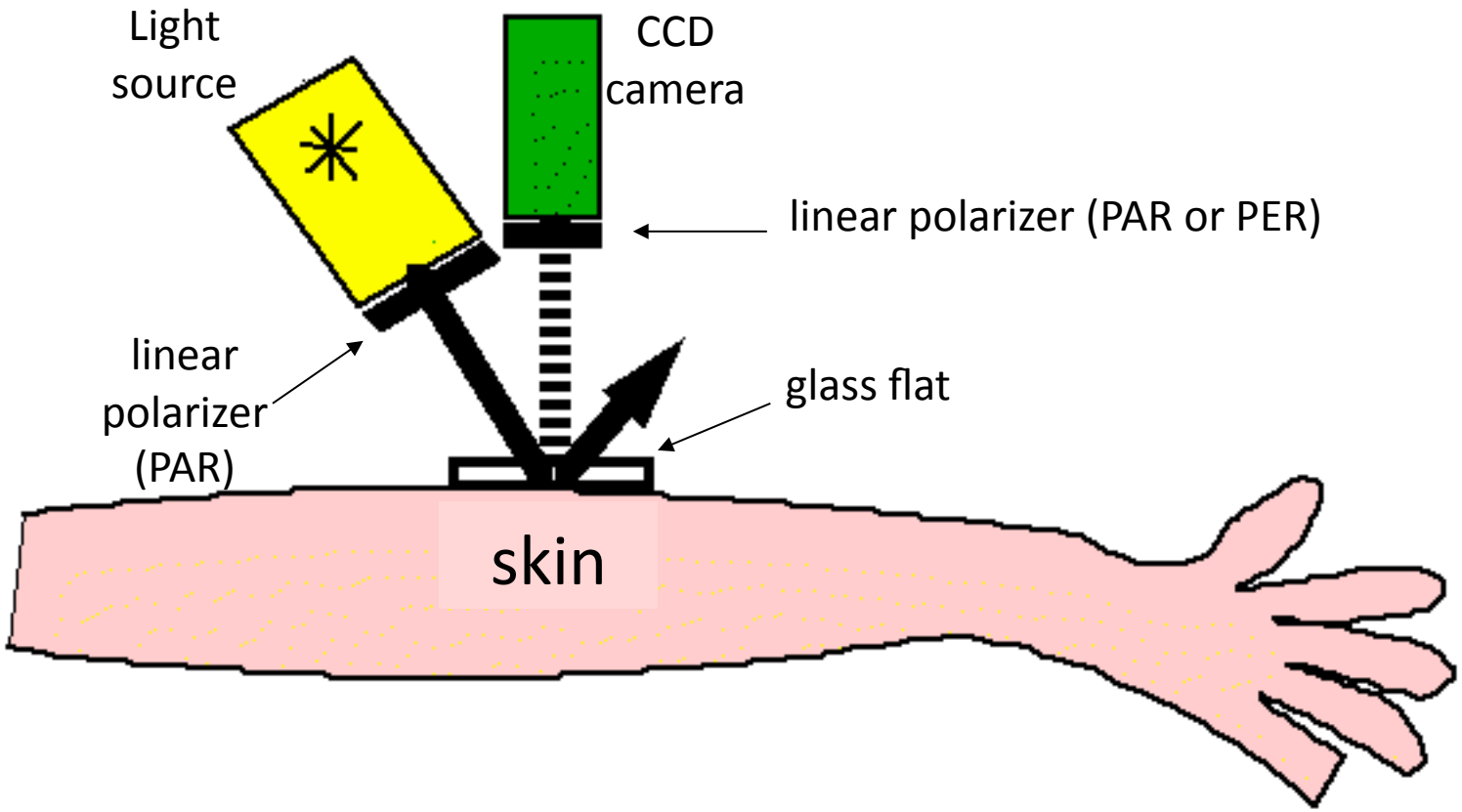
2. Circular polarization is depolarized twice as fast as linear polarization by birefringence.

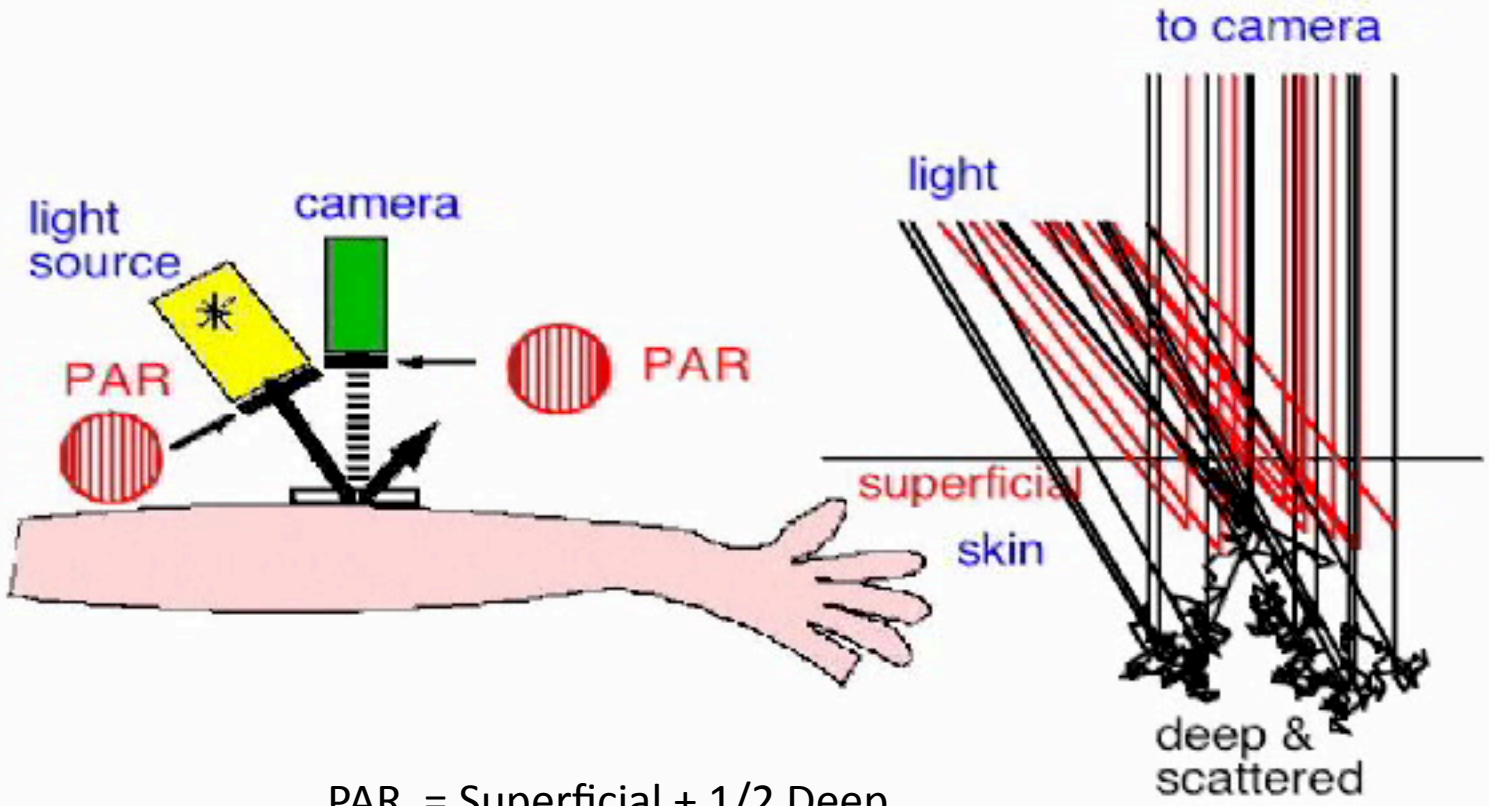
3. Circular polarization is depolarized more slowly than linear polarization by scattering when scattering particles are large.
   ~Equal depolarization by scattering when particles small.

$$\mu_{i,j} = \frac{-\partial M_{i,j}}{\partial L} \frac{1}{M_{i,j}}$$

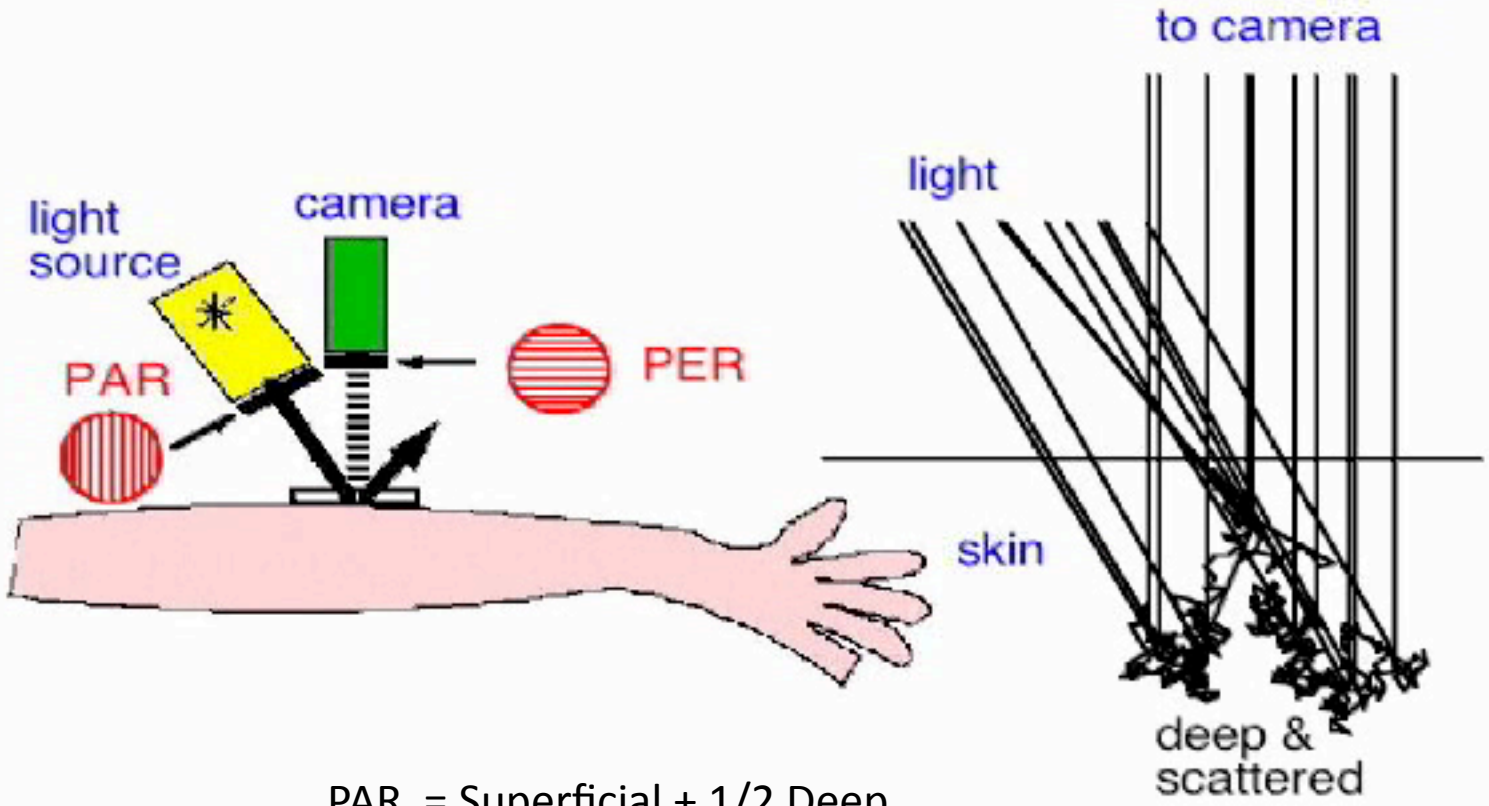
Polarization as a gating mechanism

1. Use incoherent light
2. Avoid surface glare



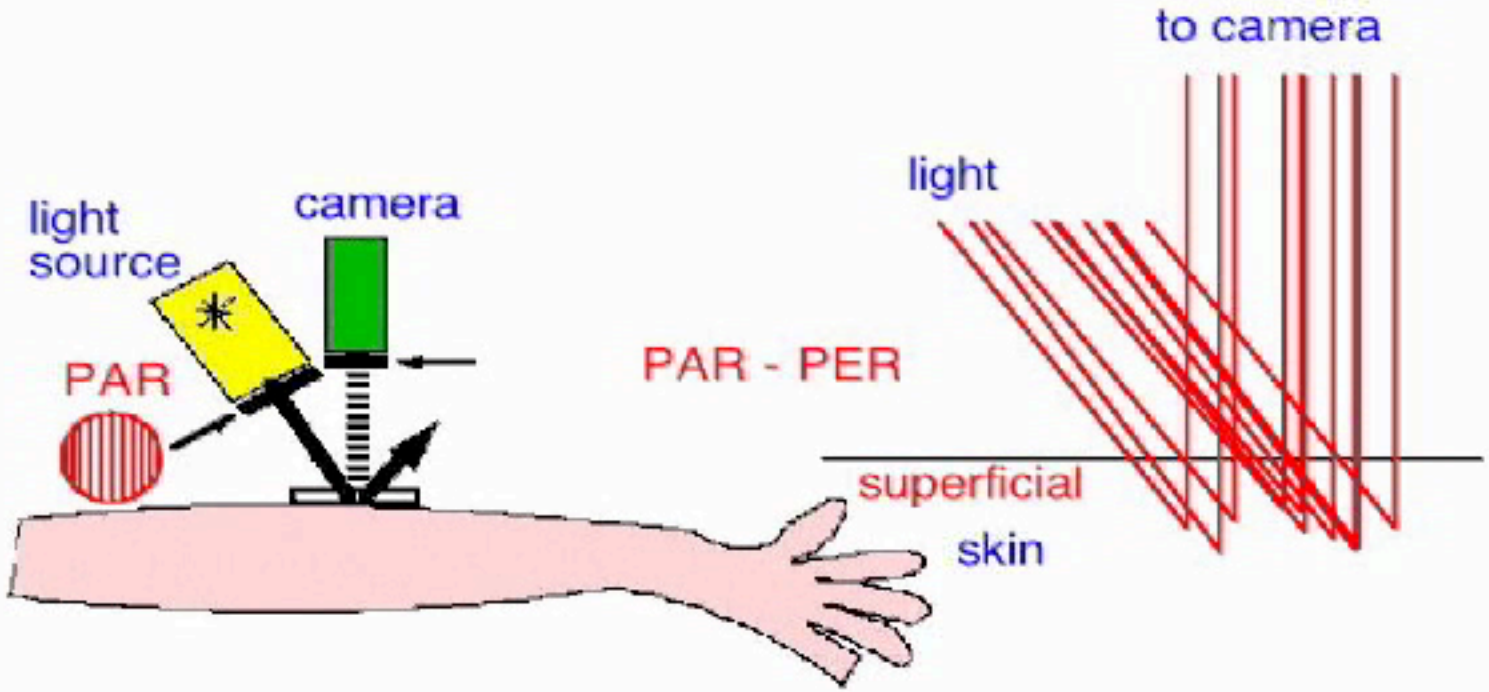


PAR = Superficial + 1/2 Deep



PAR = Superficial + 1/2 Deep

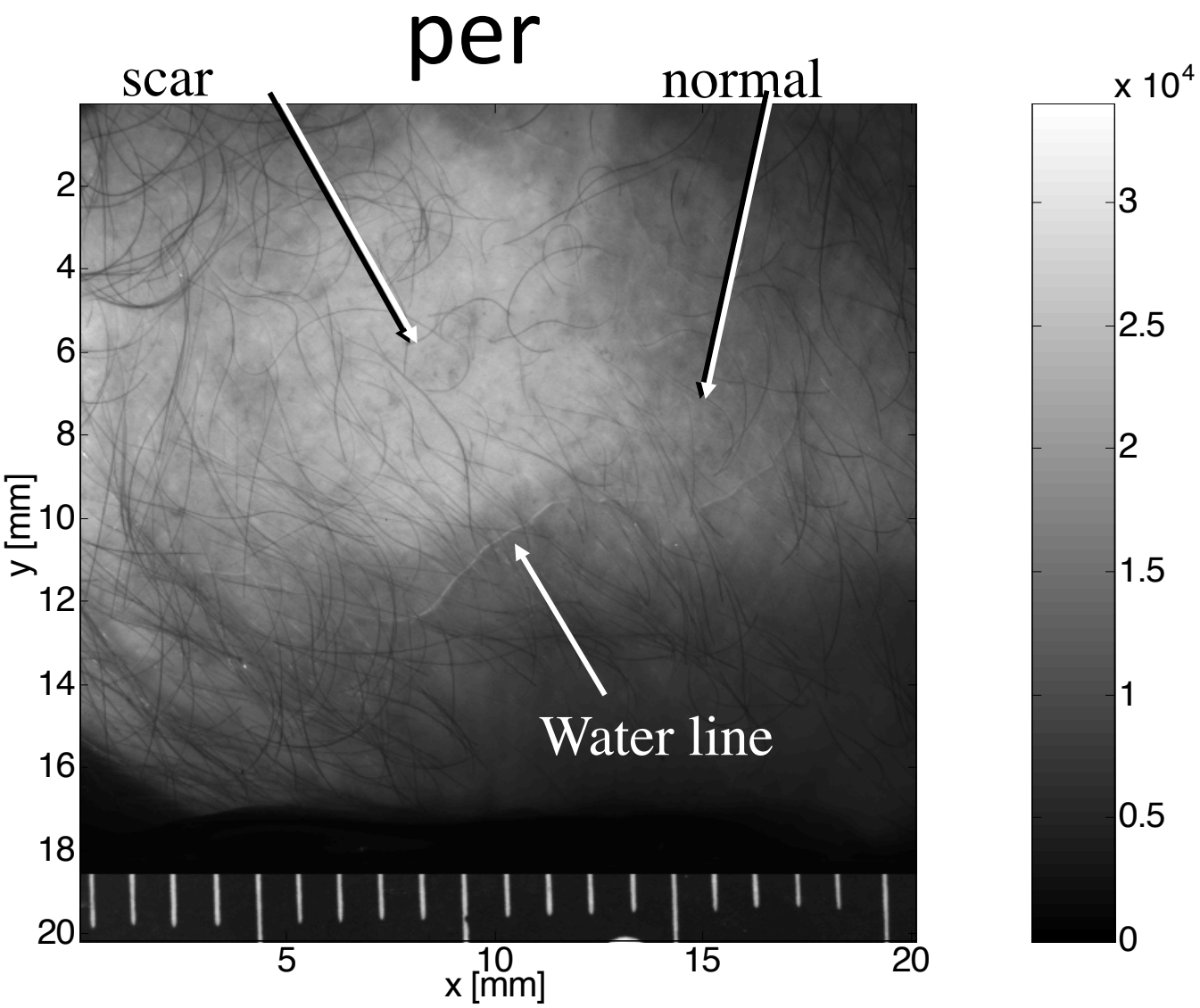
PER = 1/2 Deep

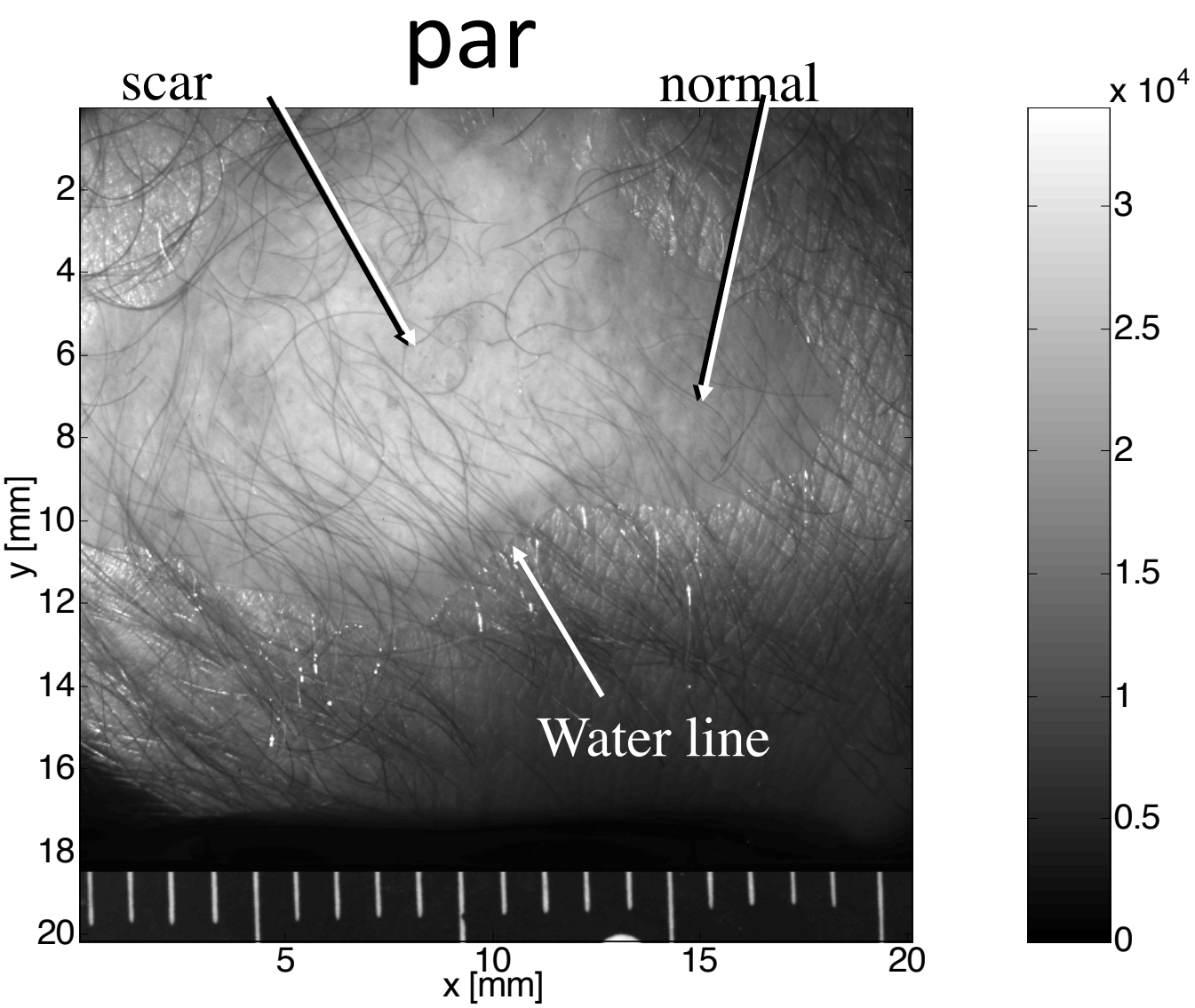


PAR = Superficial + 1/2 Deep

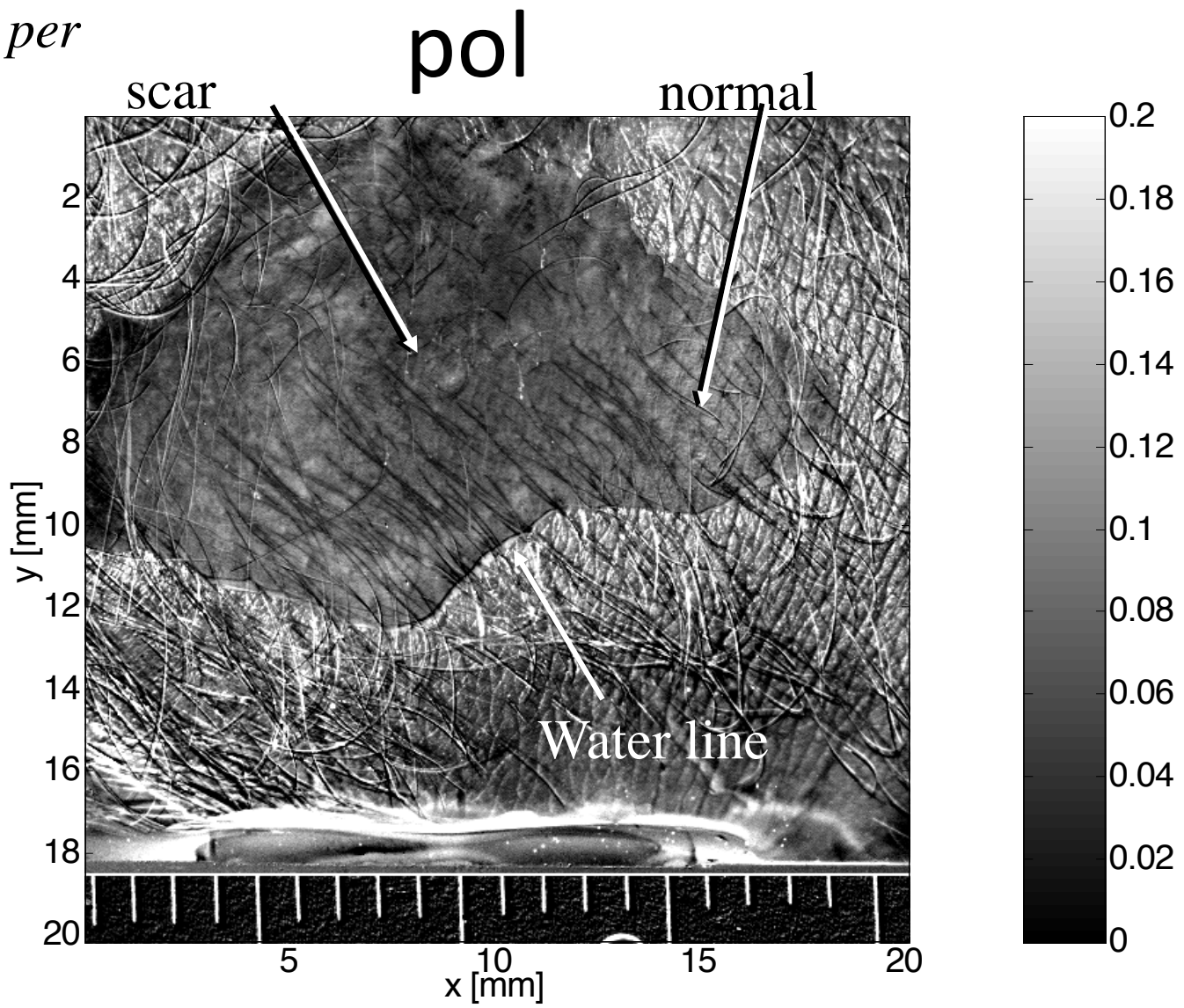
PER = 1/2 Deep

PAR – PER = Superficial


per
scar
normal
Water line
y [mm]
x [mm]
2
4
6
8
10
12
14
16
18
20
5
10
15
20
x 10^4
3
2.5
2
1.5
1
0.5
0


par
scar
normal
Water line
y [mm]
x [mm]
2
4
6
8
10
12
14
16
18
20
5
10
15
20
x 10^4
3
2.5
2
1.5
1
0.5
0

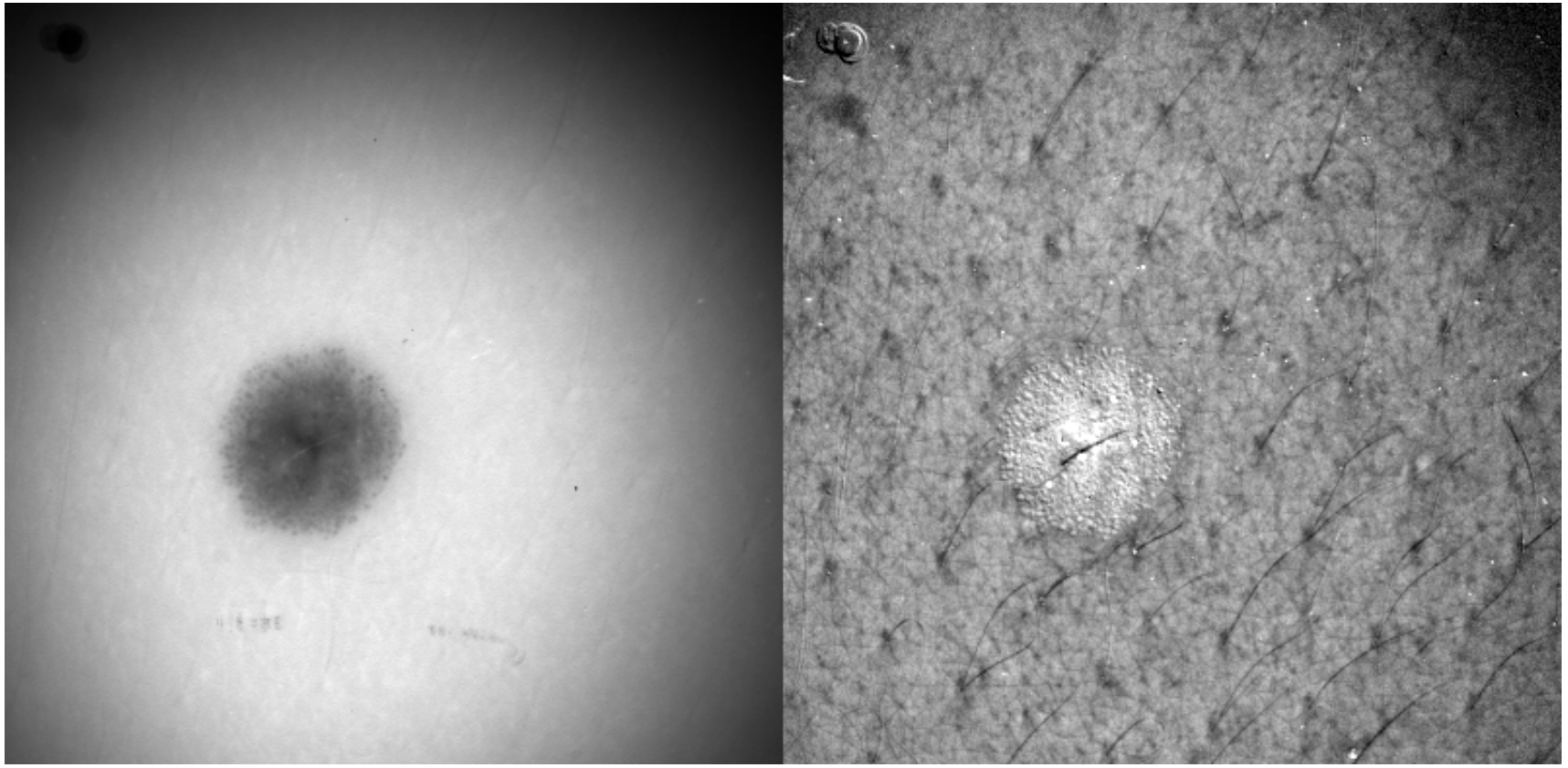
$$pol = \frac{par - per}{par + per}$$

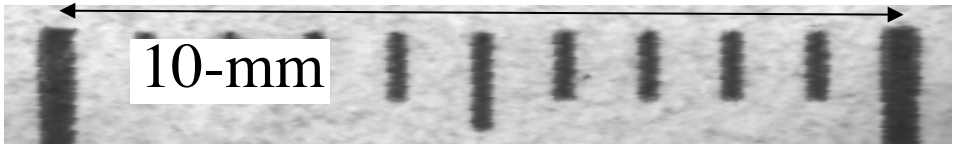


per

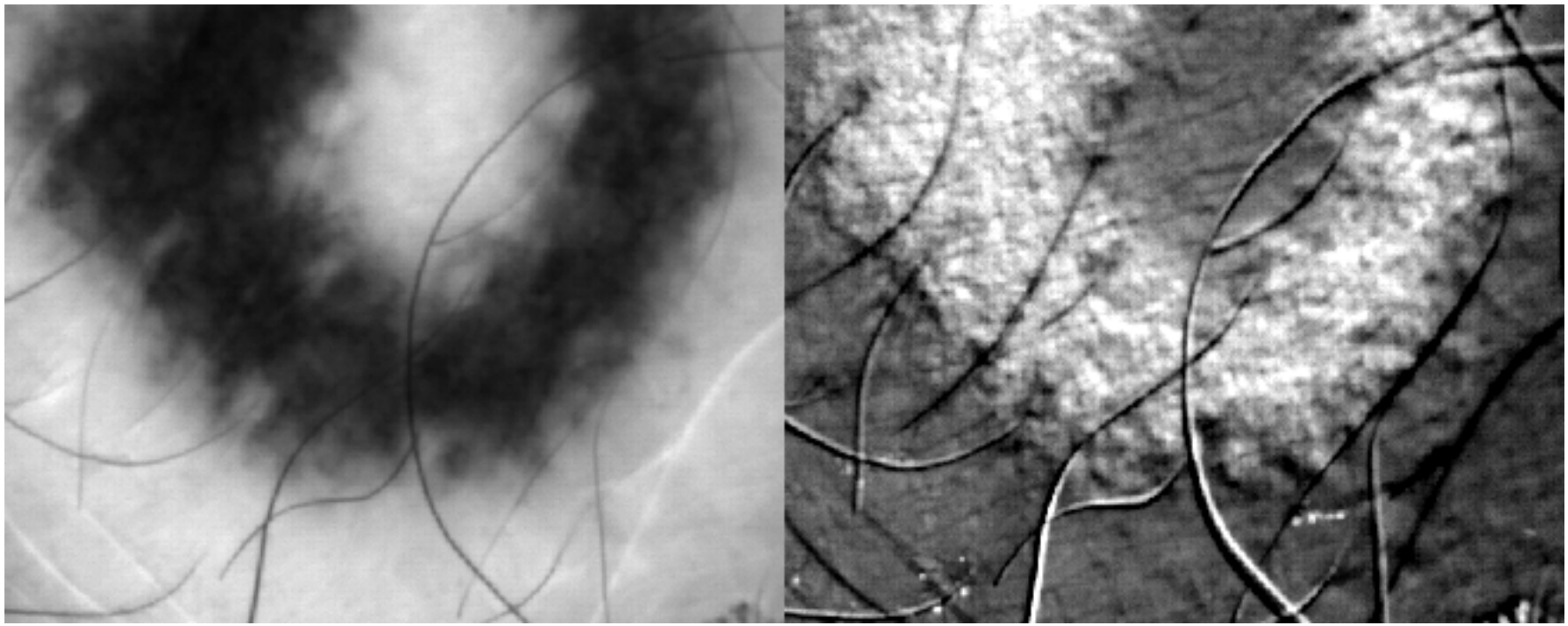
compound nevus

pol



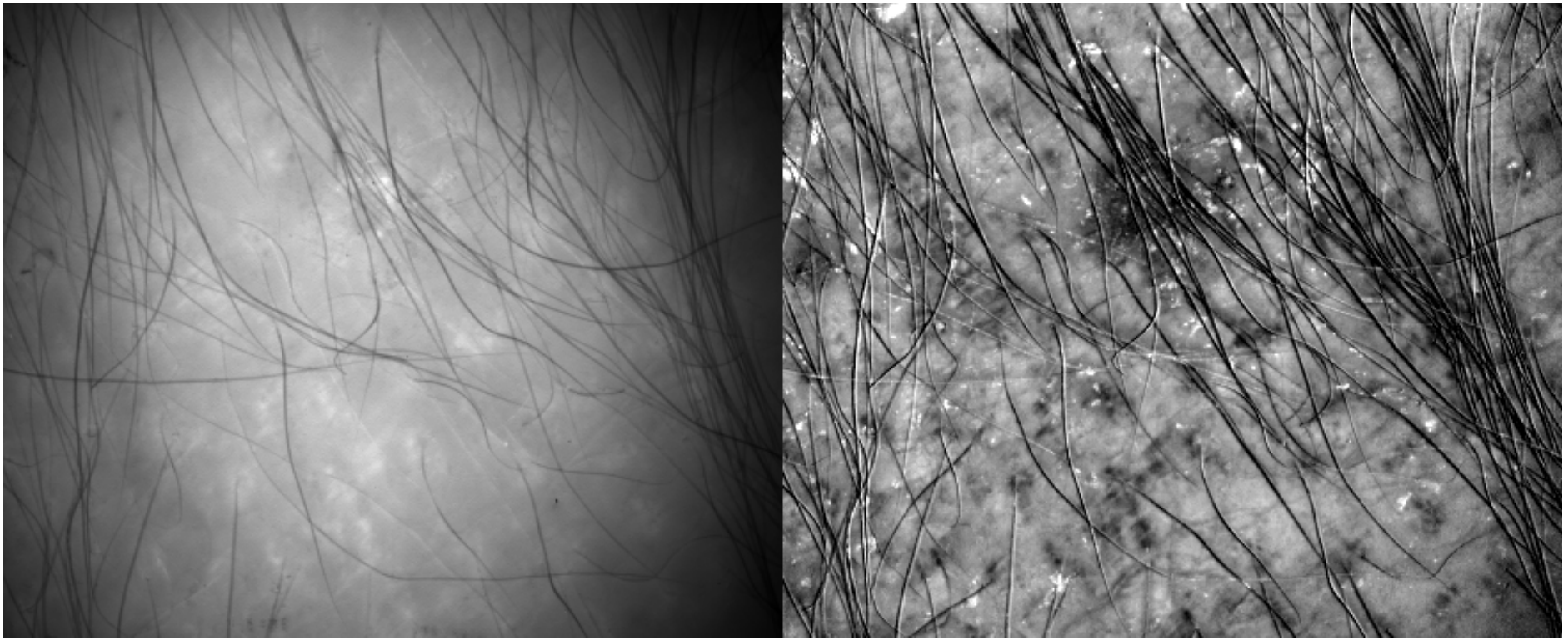


per tattoo pol



pre-malignant

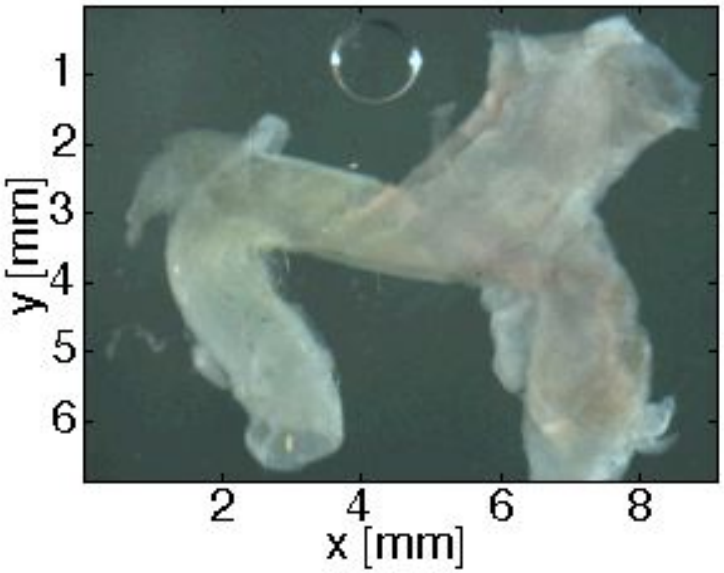
per actinic keratosis pol

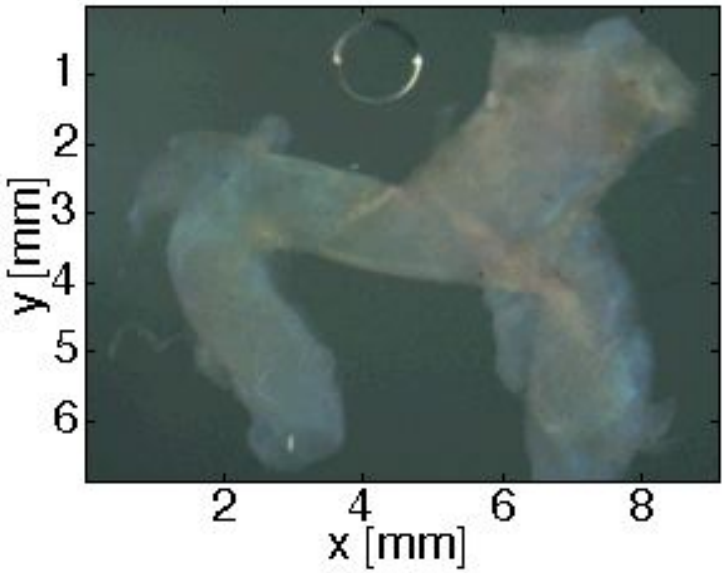


par

Mouse esophagus

per





par-per

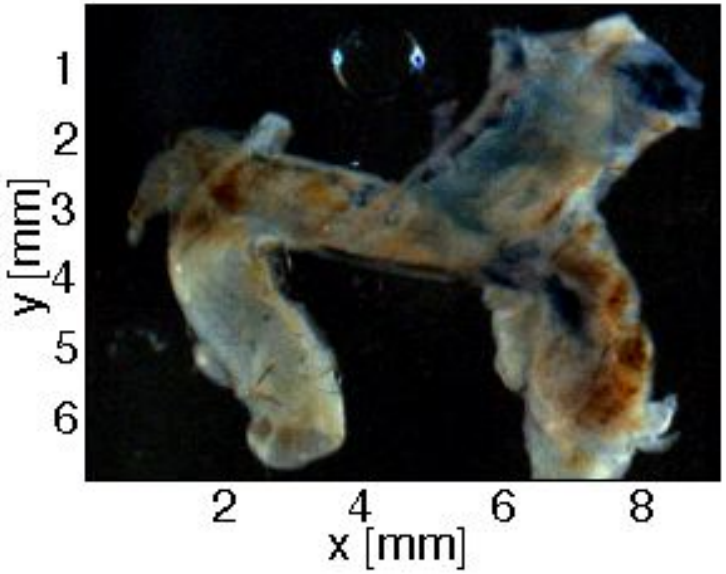
Colored POL image is

PAR - PER

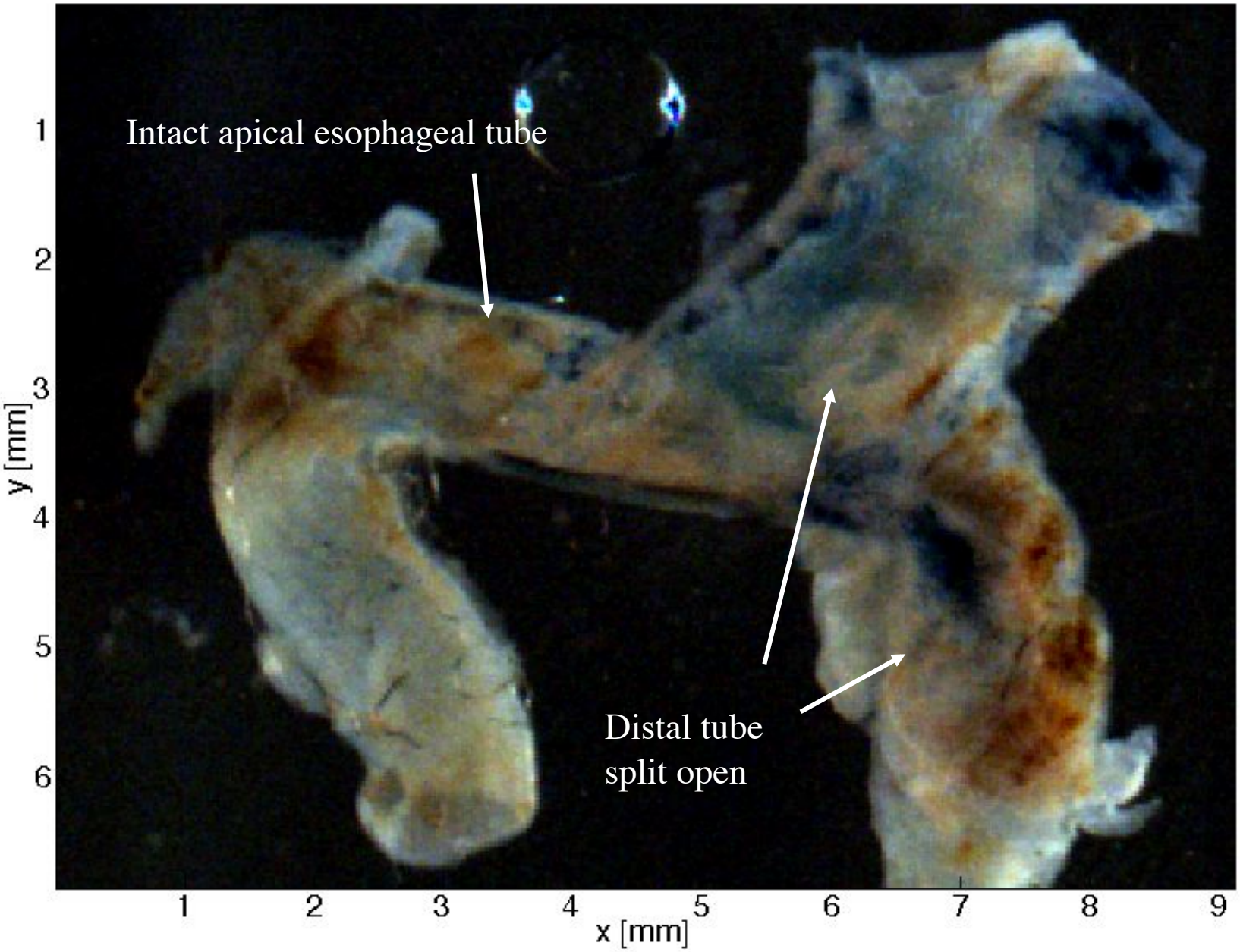
processed for each of the 3 channels of color camera.

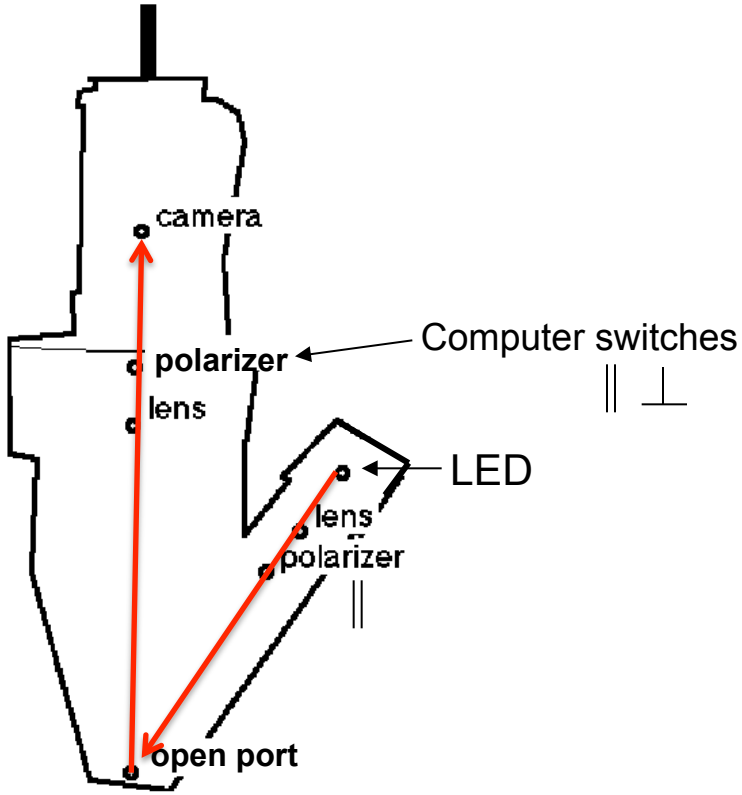
Properly color balanced,

so TRUE COLORS !!



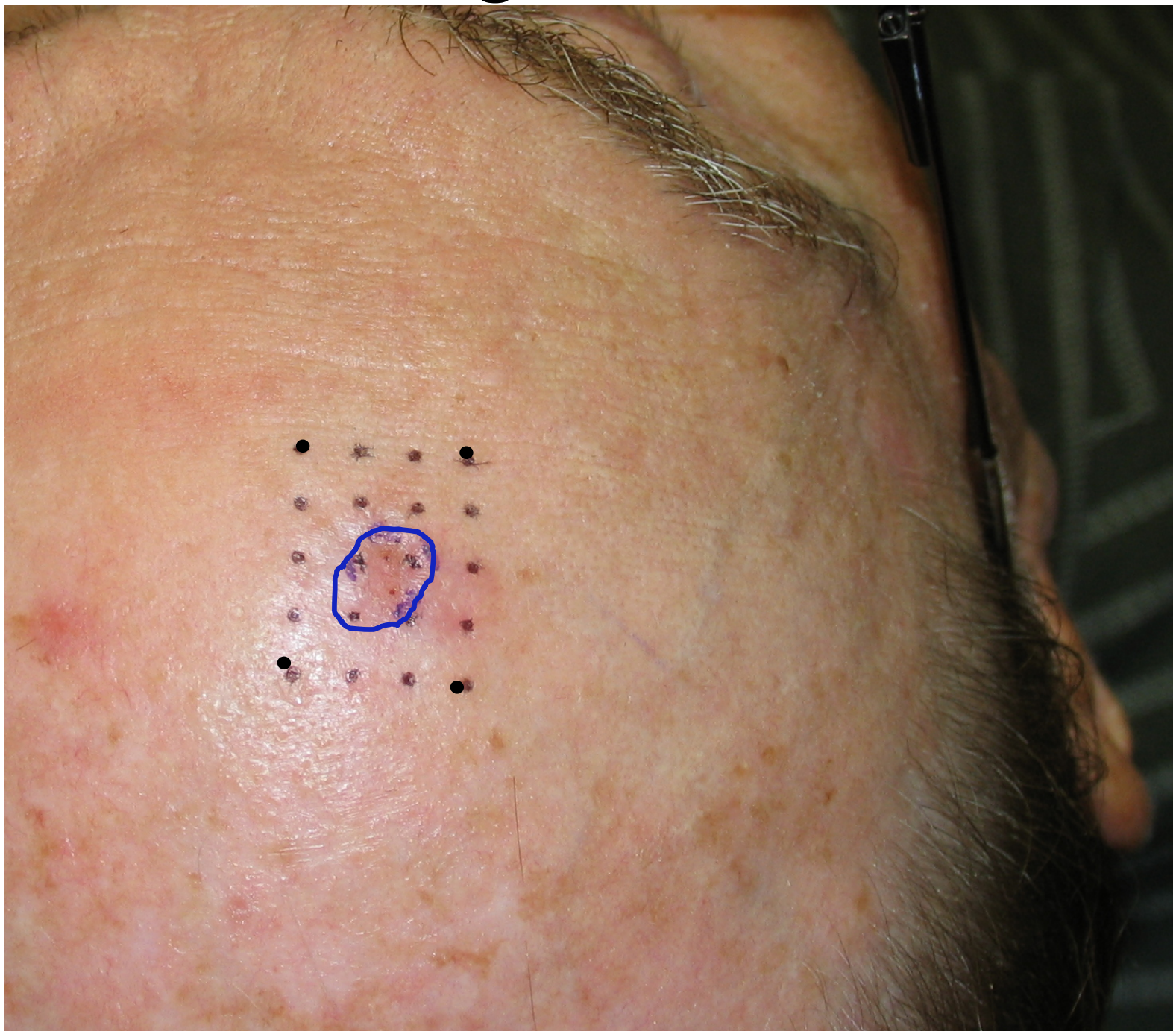
par-per


Intact apical esophageal tube
Distal tube
split open
y [mm]
1
2
3
4
5
6
x [mm]
1
2
3
4
5
6
7
8
9

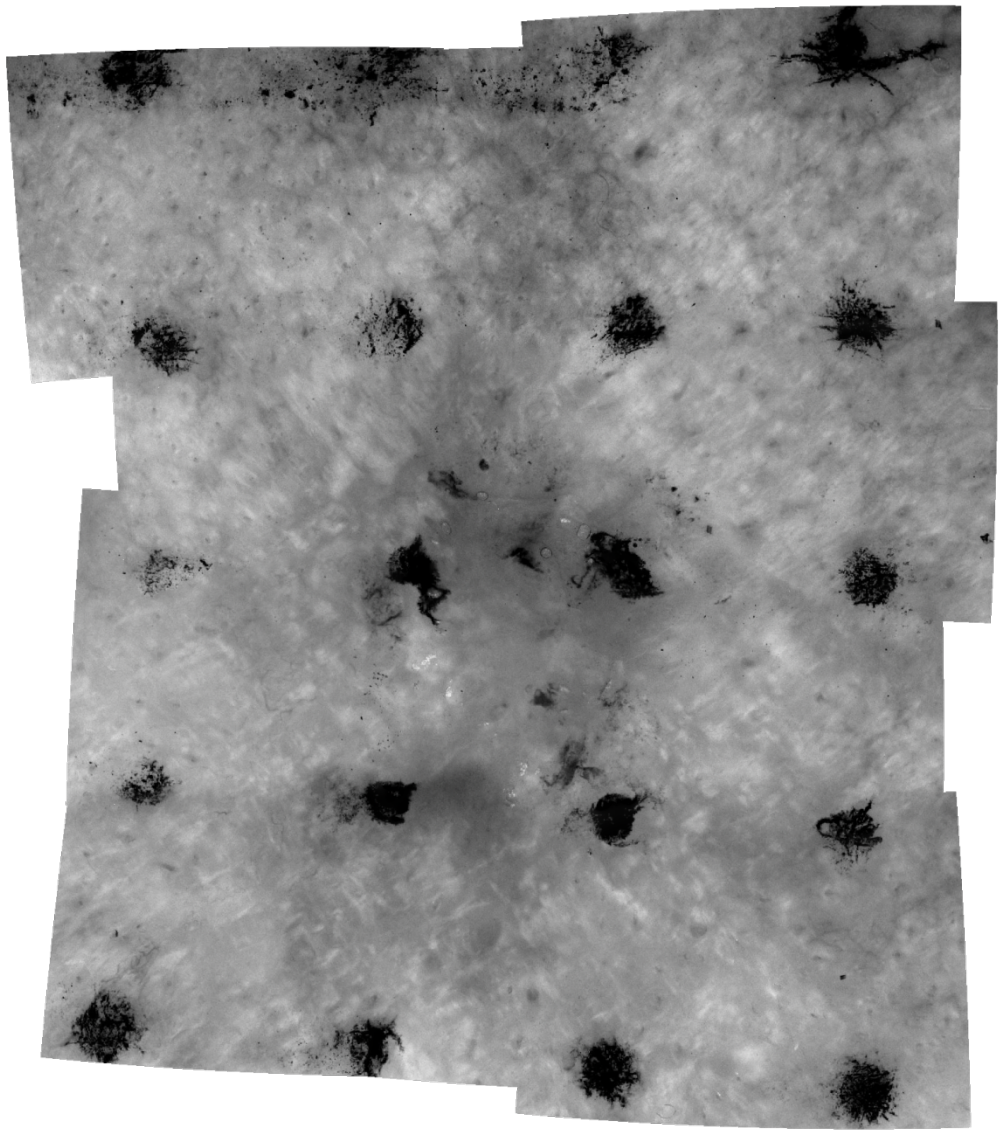

camera
polarizer
lens
Computer switches
LED
lens
polarizer
open port

BCC on the right forehead

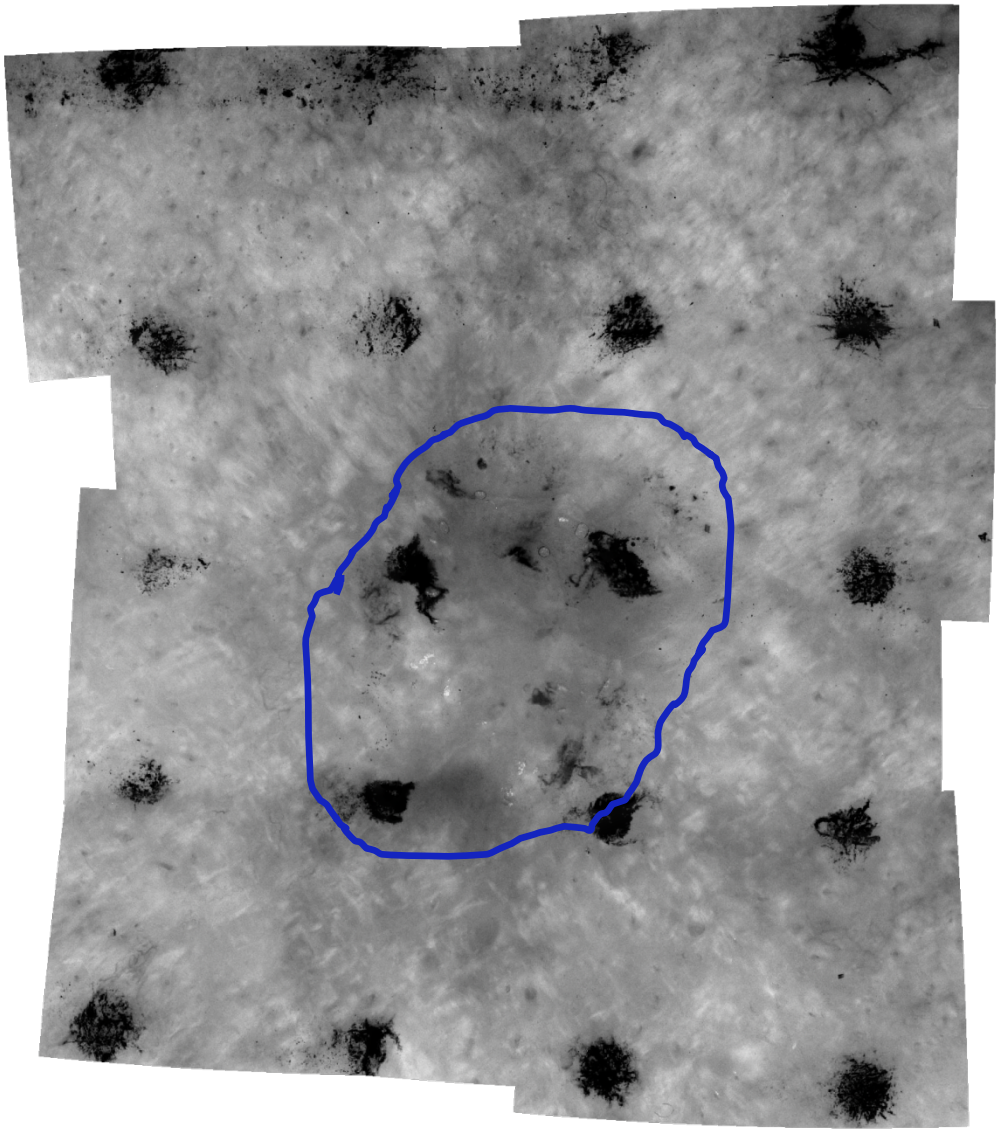
BCC on the right forehead



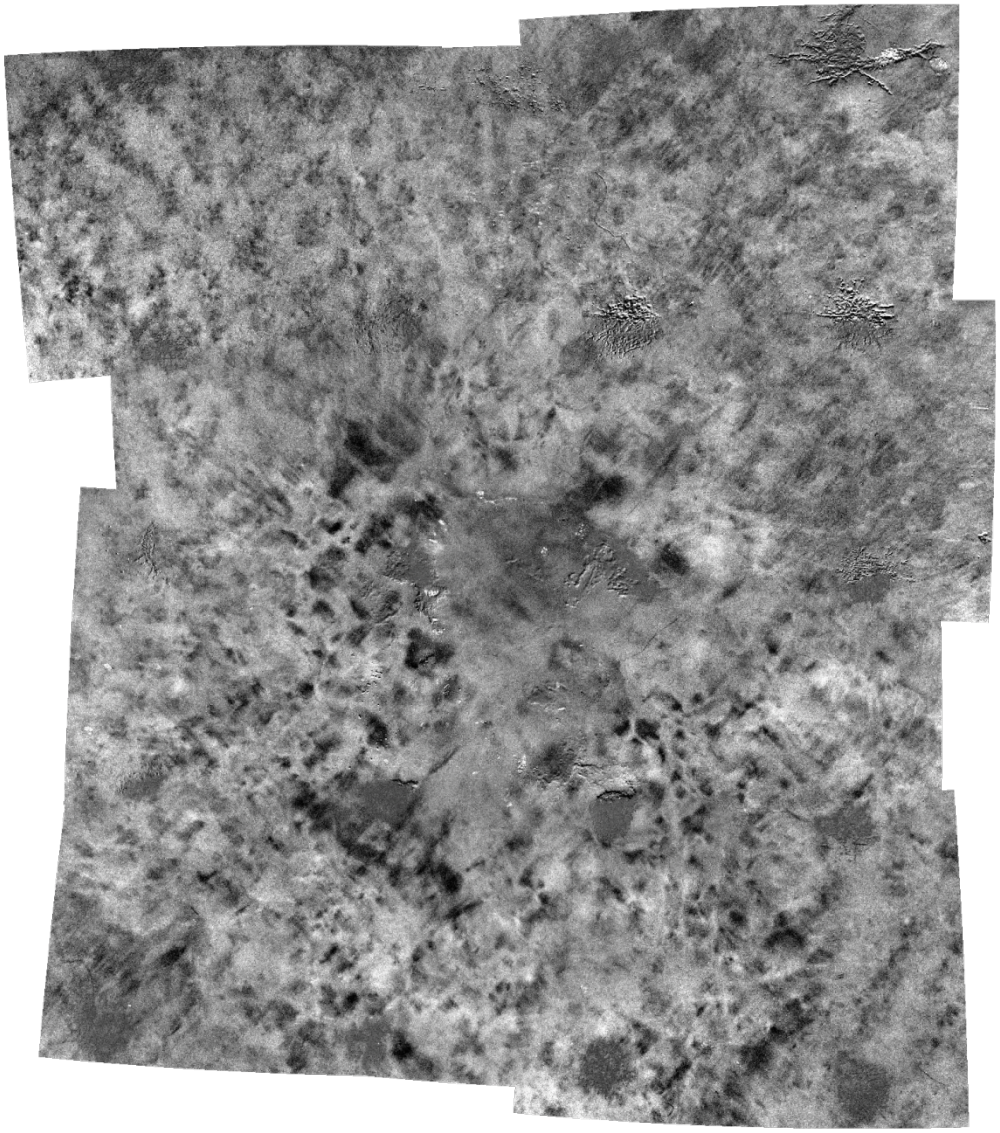
PER



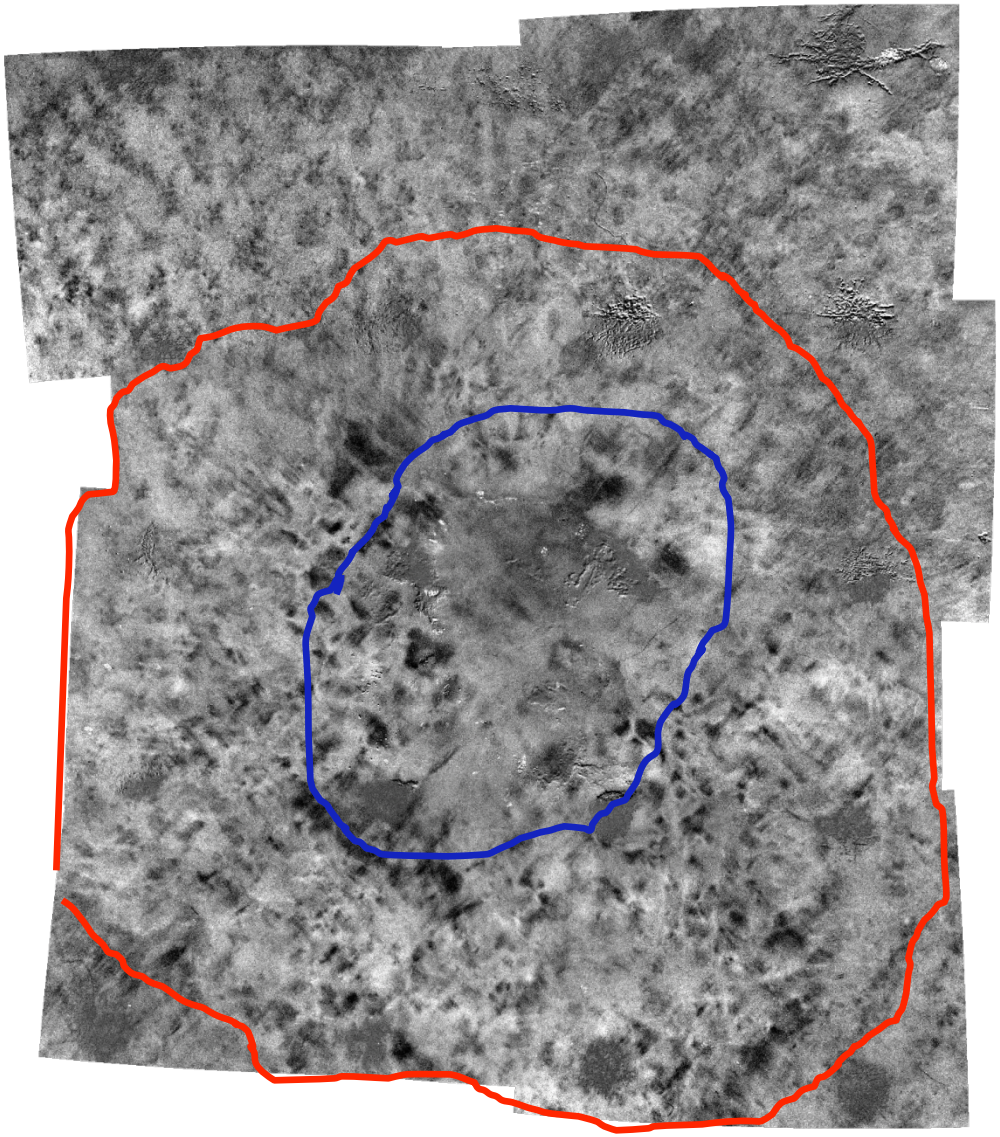
PER



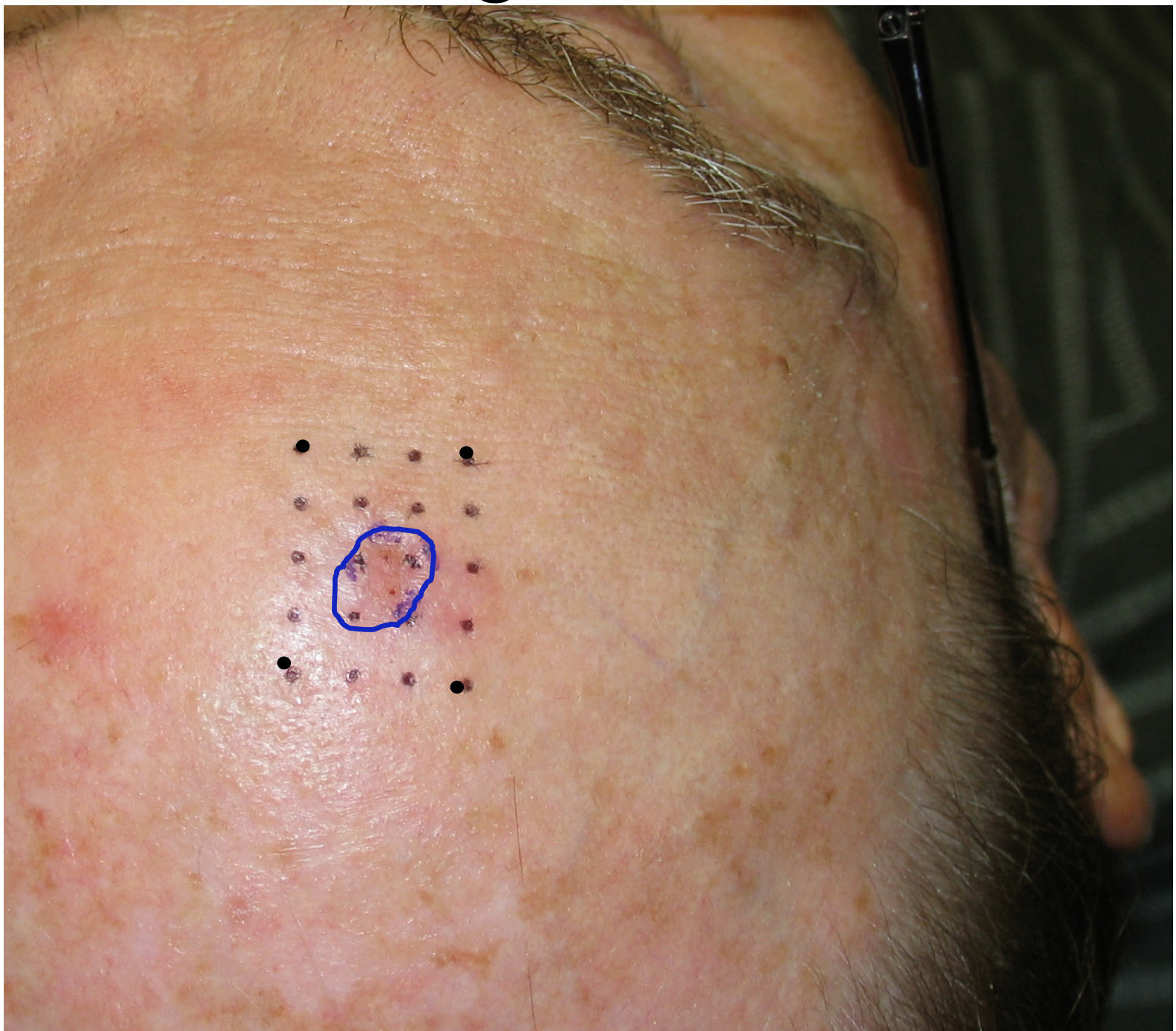
PAR-PER



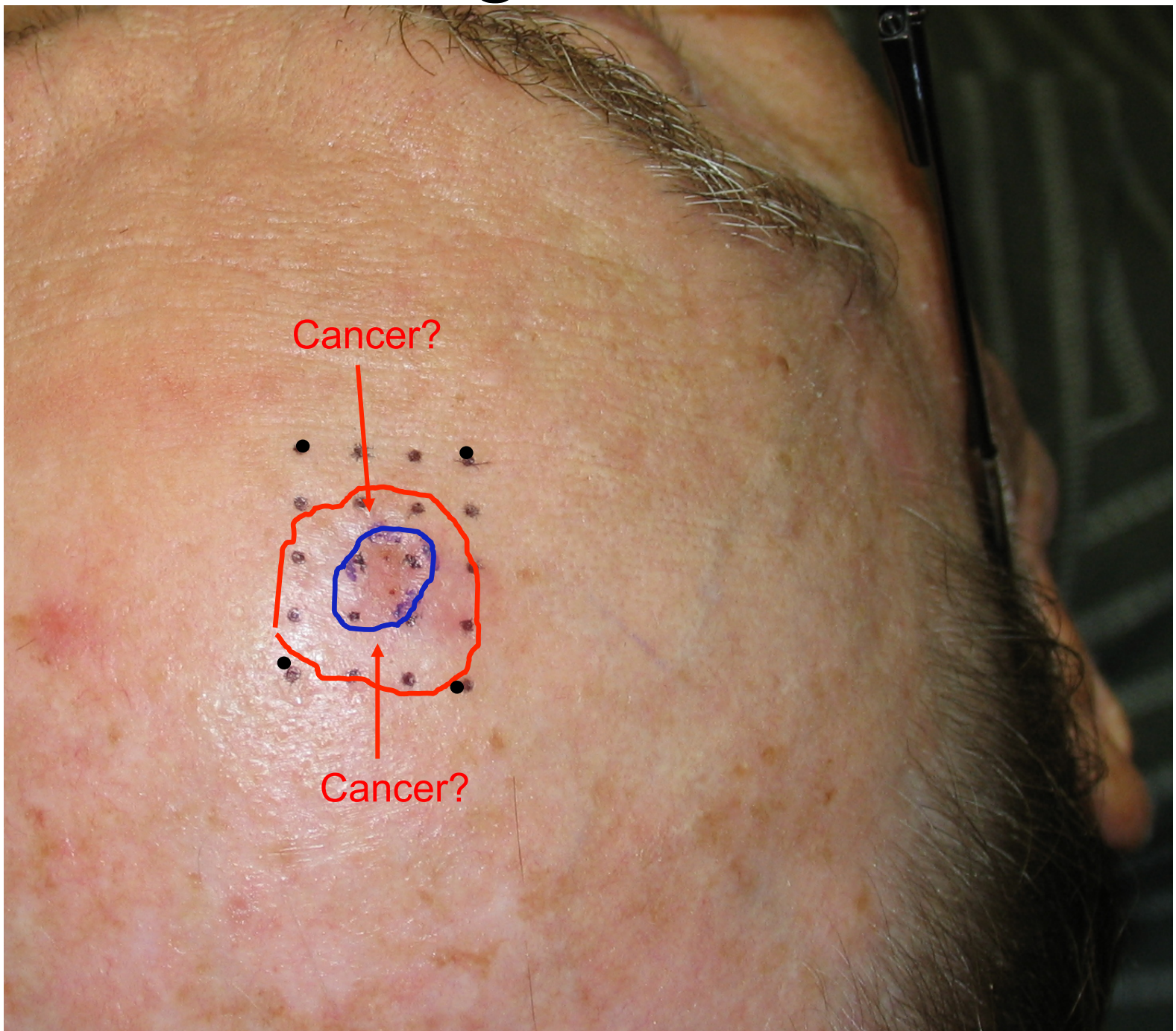
PAR-PER



BCC on the right forehead



BCC on the right forehead



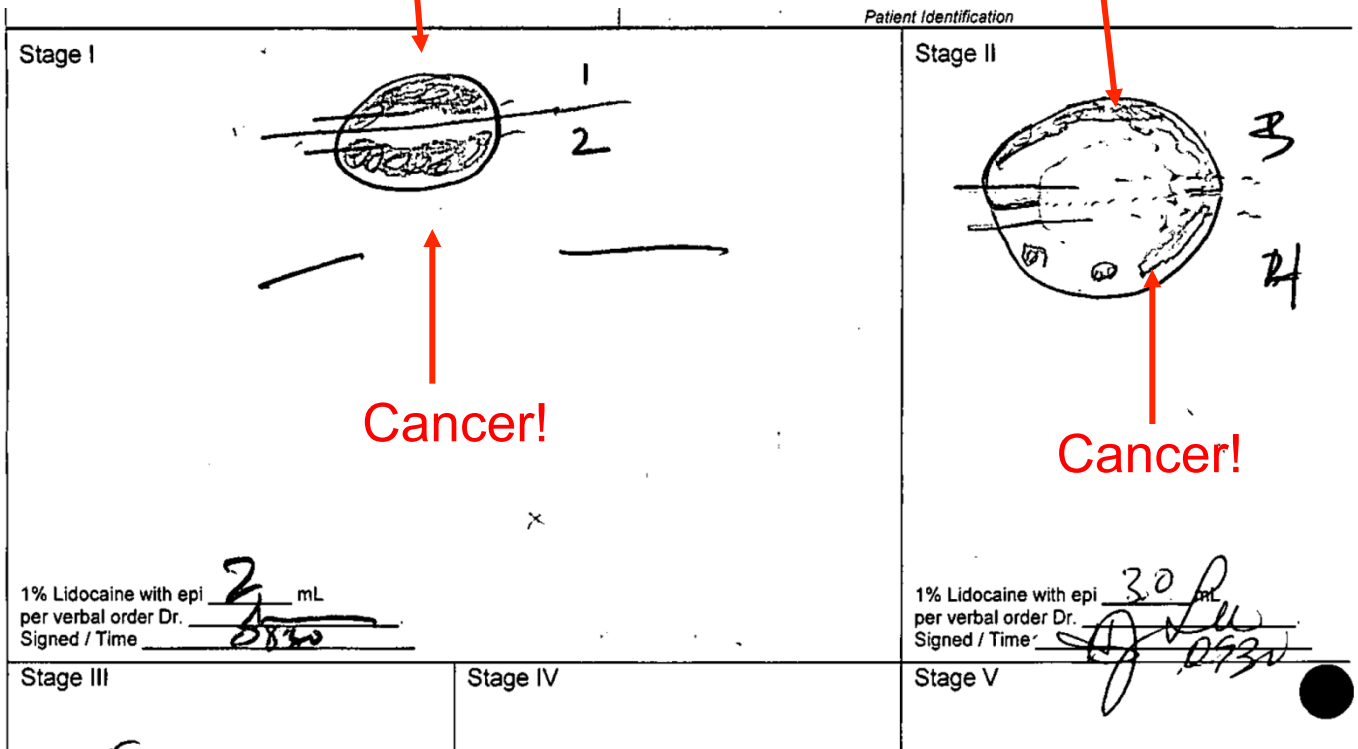
BCC on the right forehead

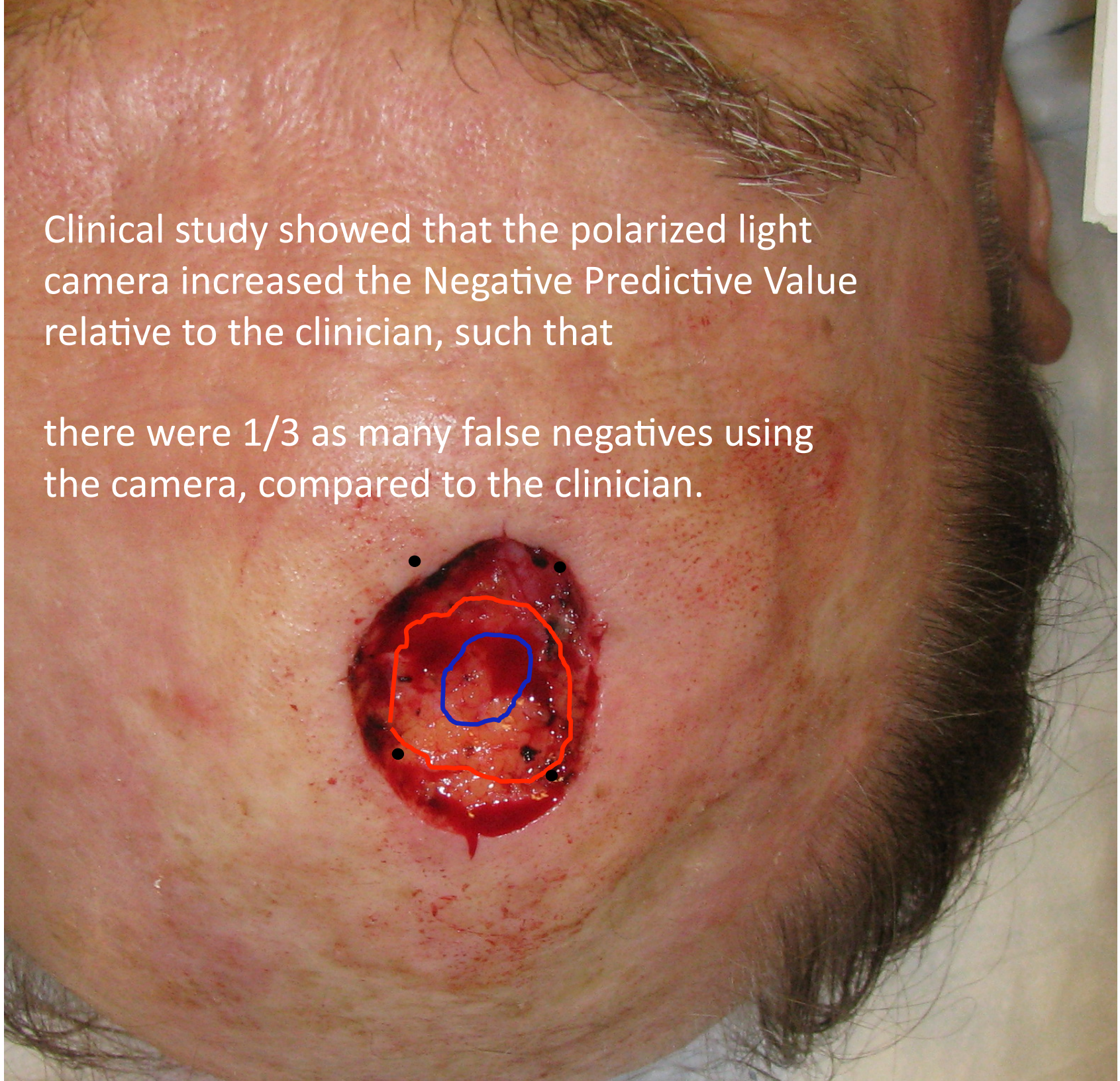
YES !

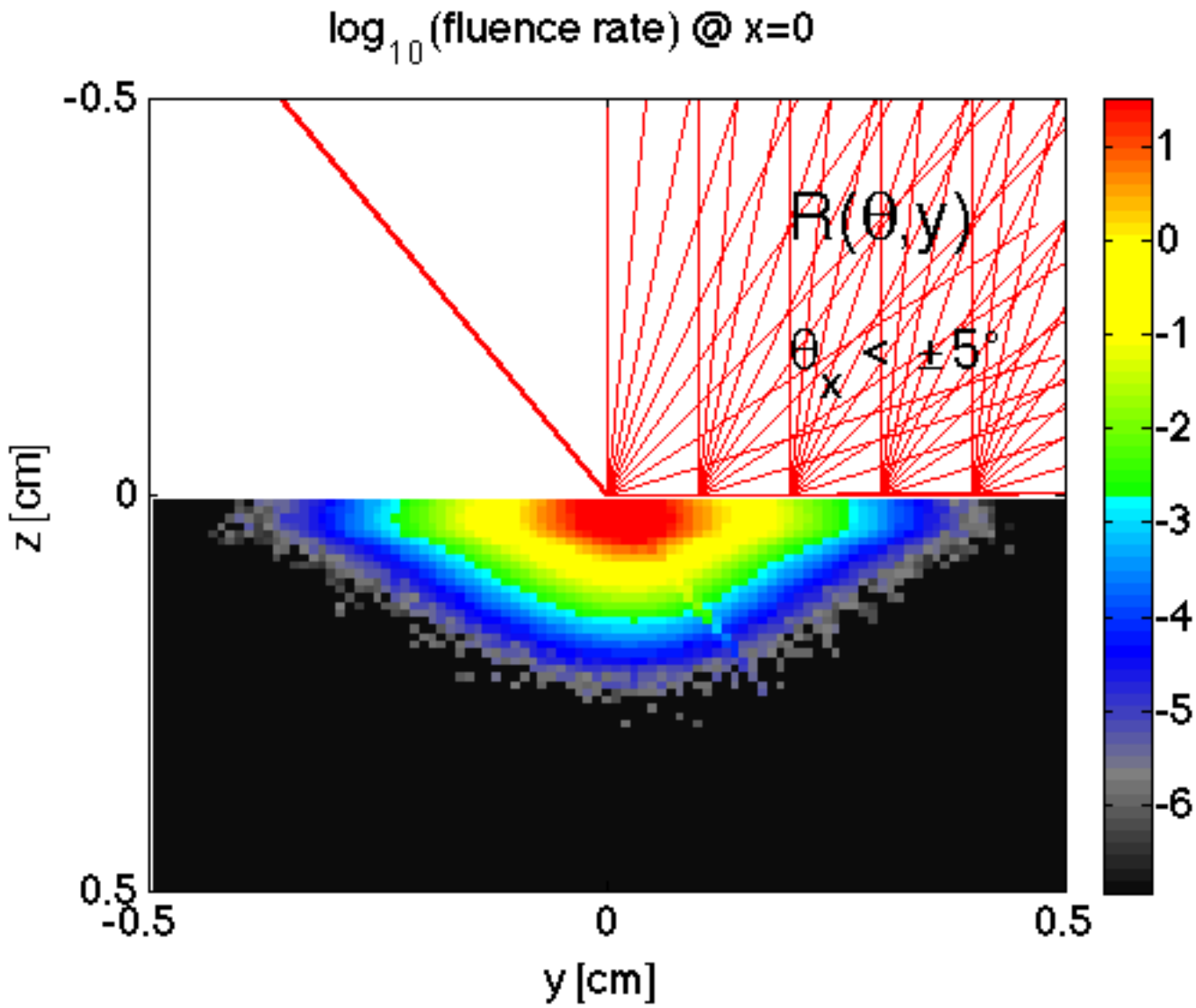
Cancer!

Pathology Report

Cancer!




Clinical study showed that the polarized light camera increased the Negative Predictive Value relative to the clinician, such that
there were 1/3 as many false negatives using the camera, compared to the clinician.


log10(fluence rate) @ x=0
R(θ,y)
θx < ±5°
-0.5
0
0.5
z [cm]
-0.5
0
0.5
y [cm]
1
0
-1
-2
-3
-4
-5
-6

The end