A Guide to Radiochromic Film Dosimetry with EBT2 and EBT3

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Advanced Materials Group
Ashland Specialty Ingredients

Spain, April 2014

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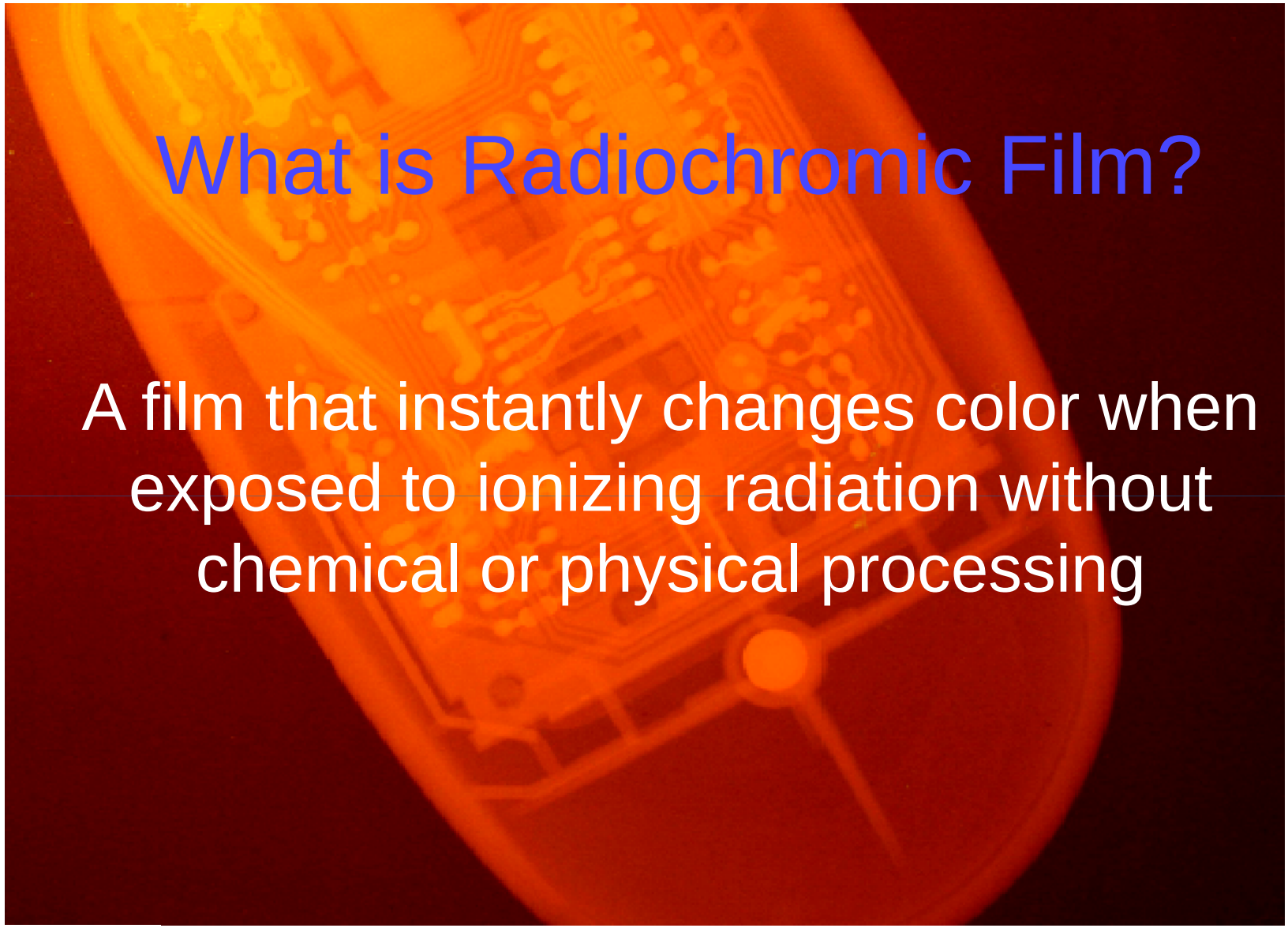

What is Radiochromic Film?

A film that instantly changes color when exposed to ionizing radiation without chemical or physical processing

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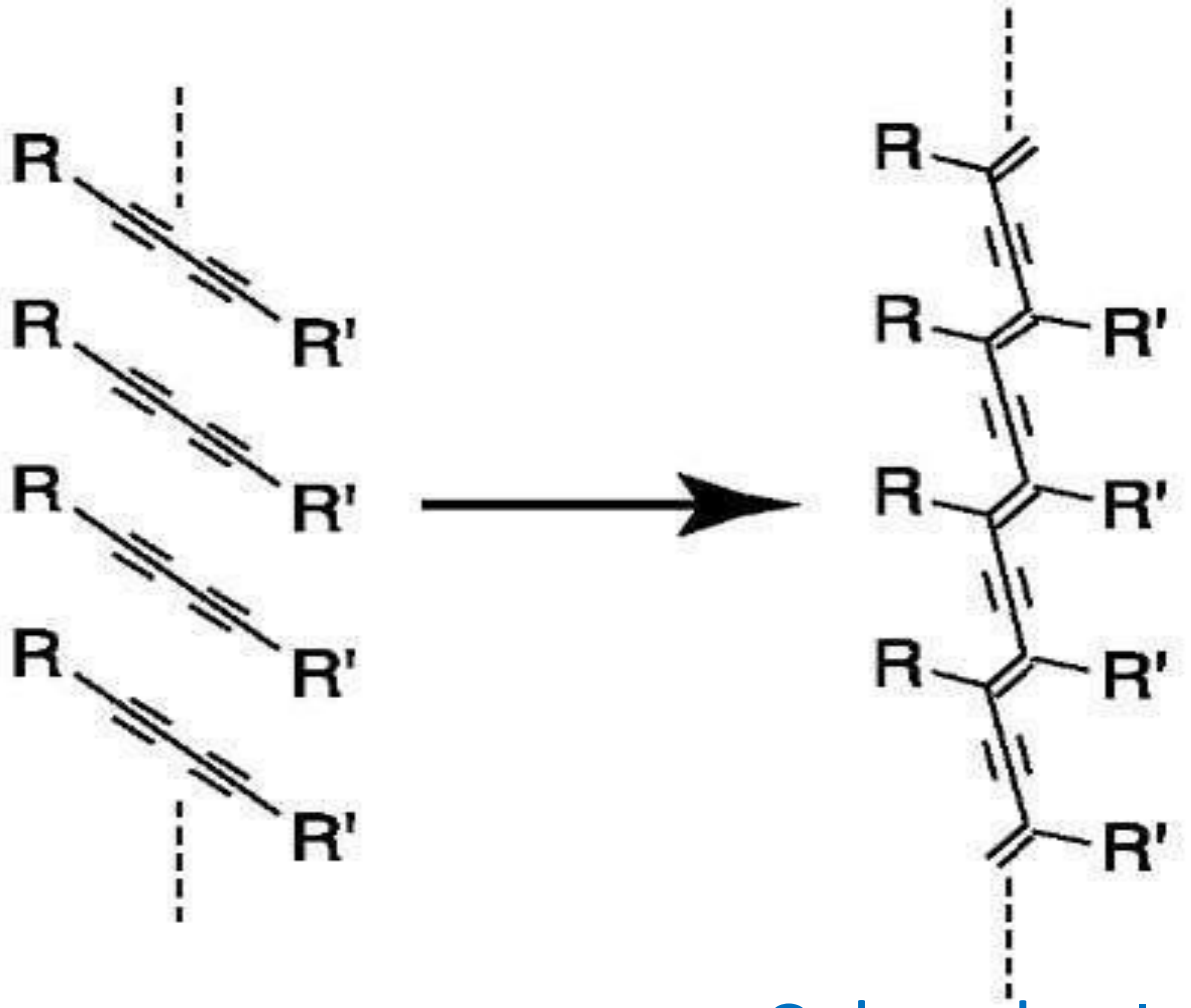
Core Technology



Colorless monomer

Colored polymer

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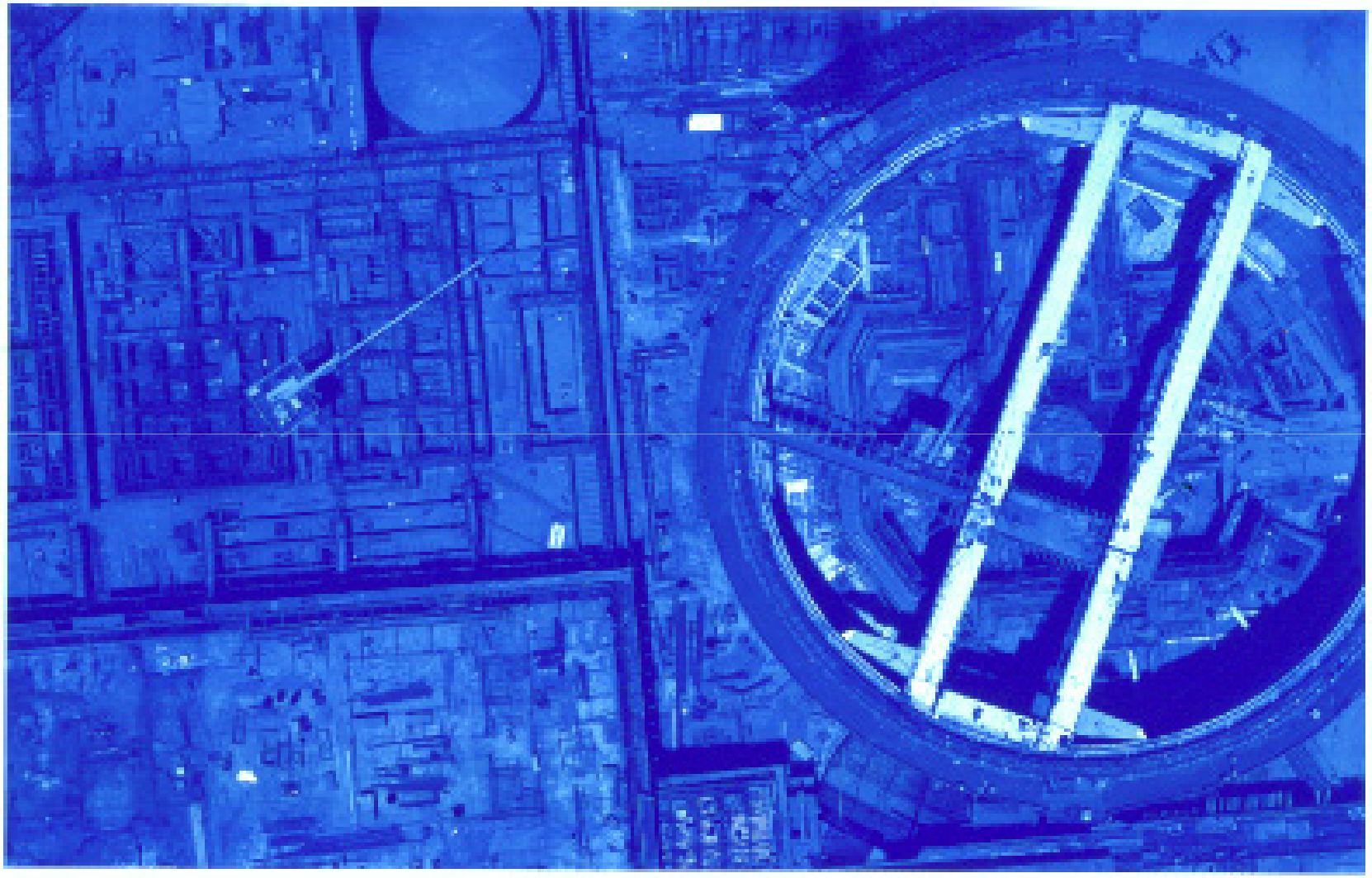
1988 - Processless Electron Recording Media



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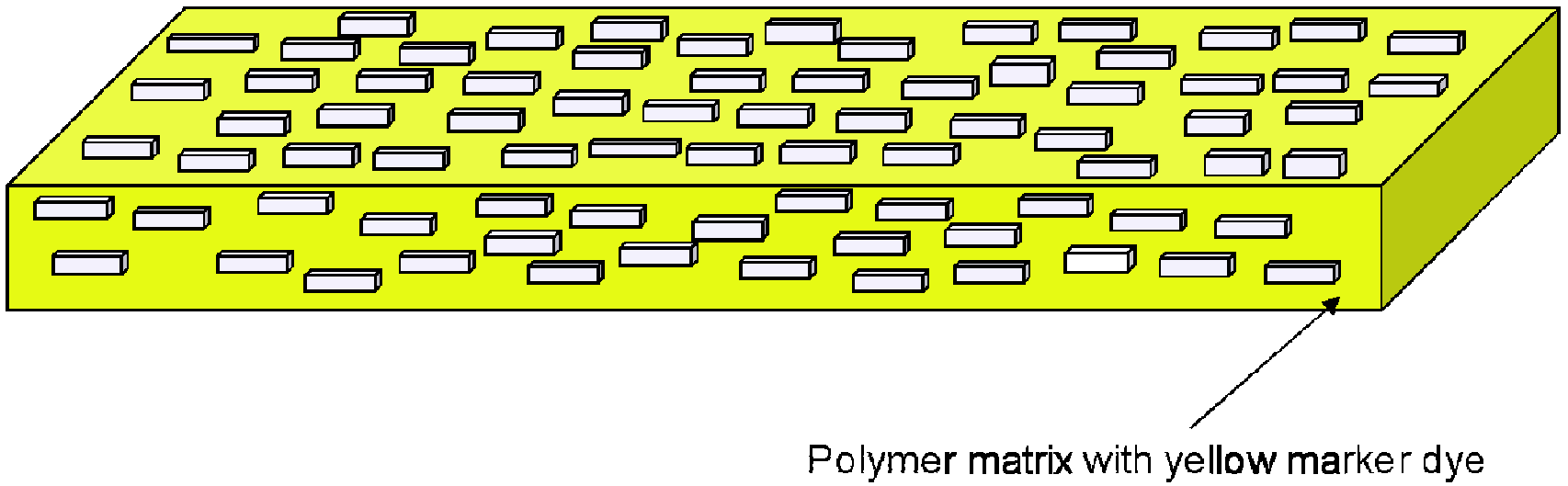
EBT2/EBT3 Dosimetry Film: Active Layer



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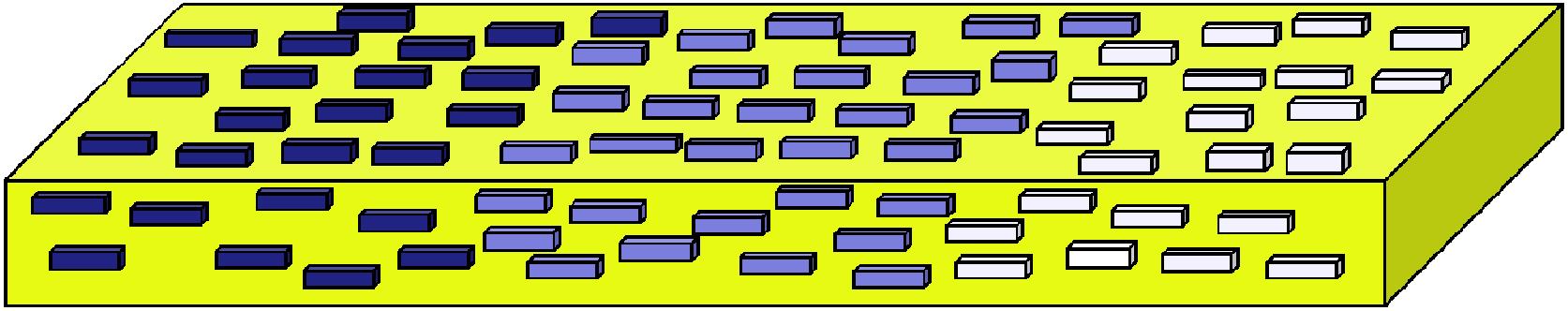
EBT2/EBT3 Dosimetry Film: Exposure



High exposure

Low exposure

Light transmission proportional to dose

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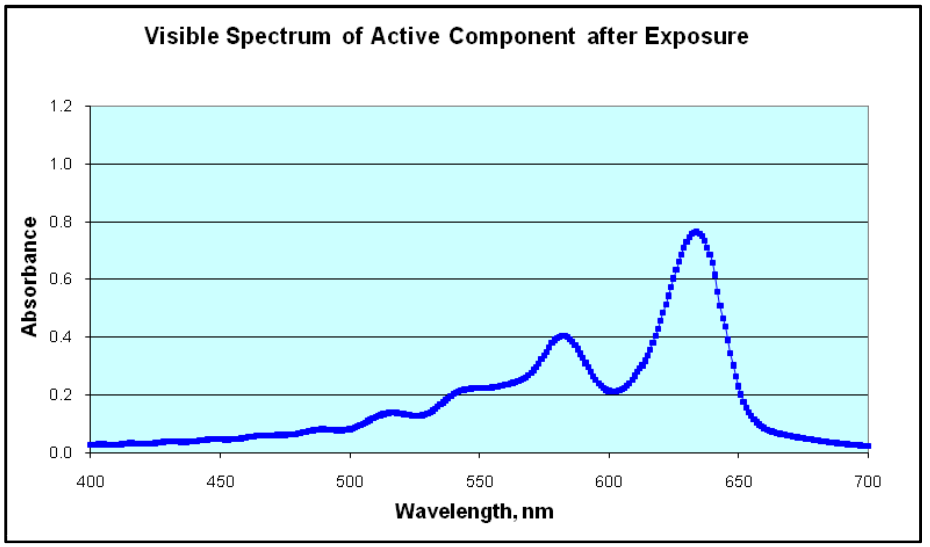
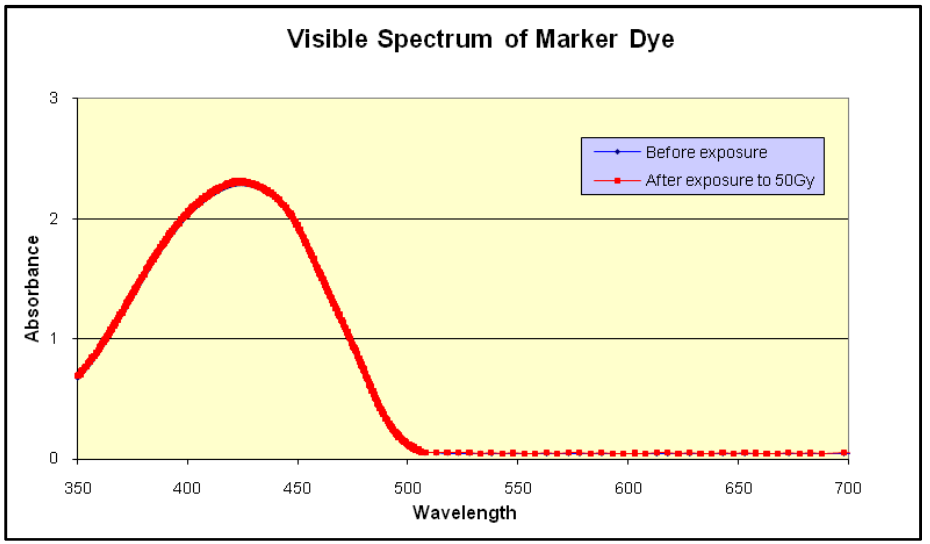
EBT2/EBT3 Films: Visible Absorbance Spectra

- Active component
  - Red/green wavelengths
  - Mainly dose information



- Marker dye
  - Blue wavelengths
  - Mainly thickness information



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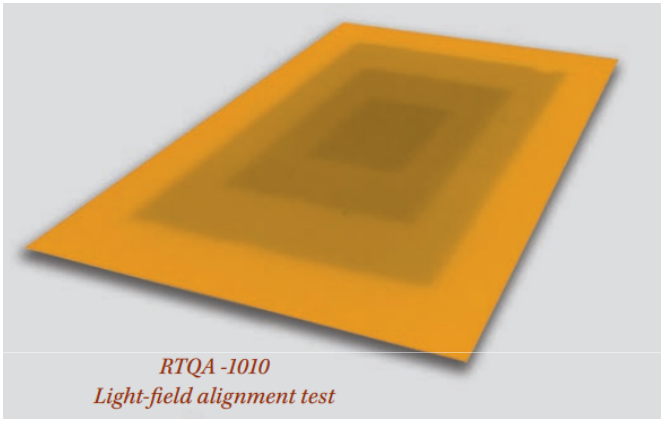
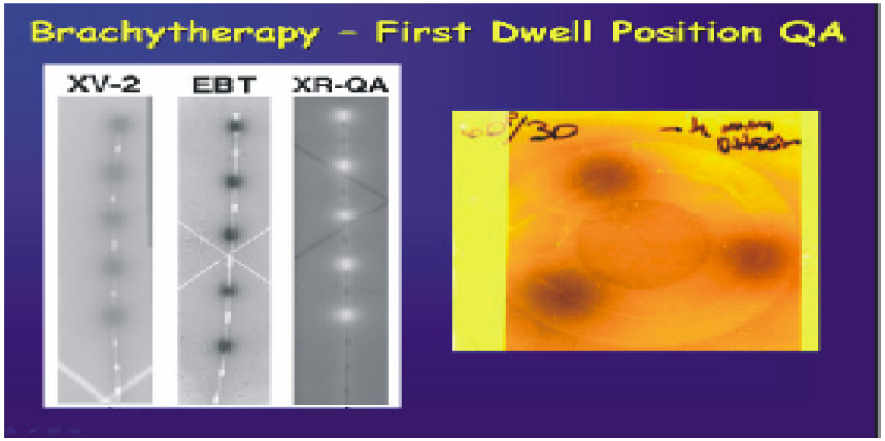
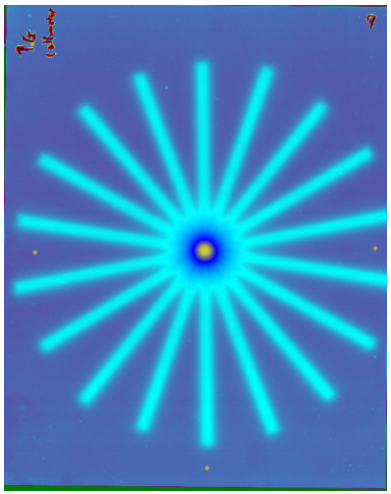
What for Beam Location?

- Radiotherapy (MV photons, electrons, protons)
  - RTQA2 - 2 cGy to 8 Gy
- Radiology (kV photons)
  - XRQA2 - 1 mGy to 20 cGy
  - XRCT2 - 1 mGy to 20 cGy
  - XRM2 - 1 mGy to 20 cGy



RTQA -1010
Light-field alignment test





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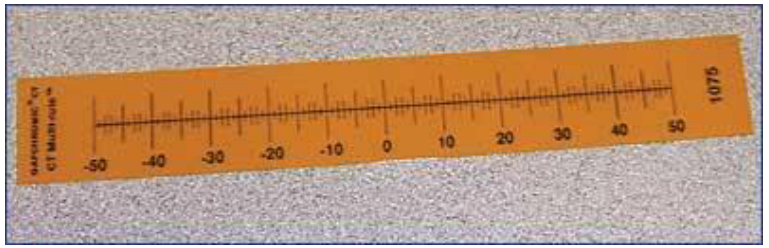
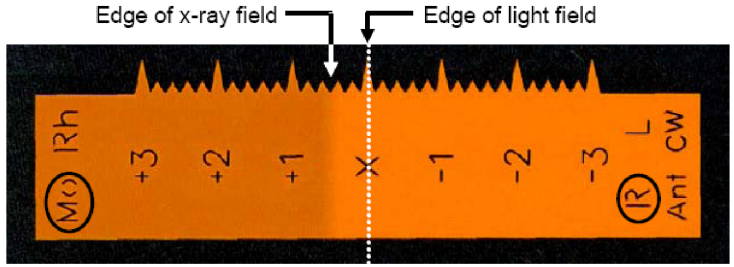
Product Offerings - Radiology

+ XR-CT



+ XR-M



X-ray field-to-Light field deviation = 5 mm in plane of XR-M film

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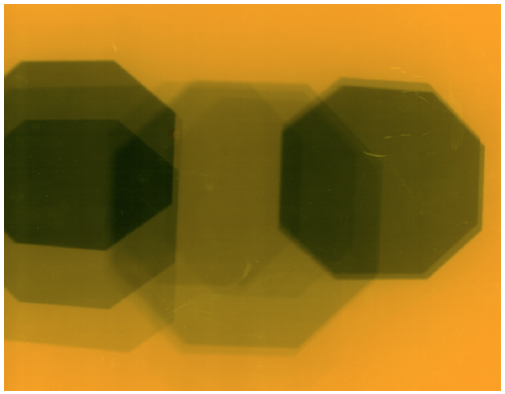
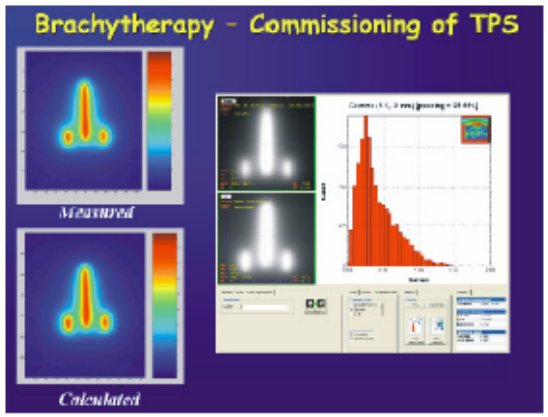
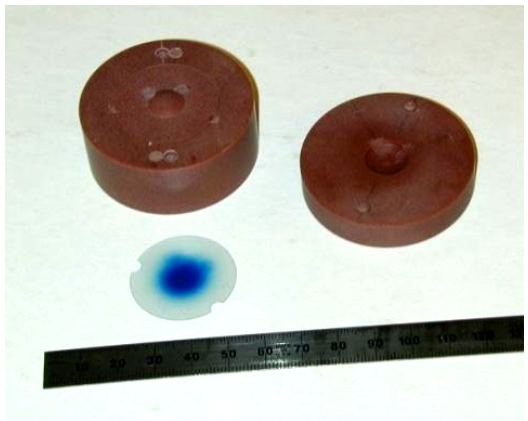
What for Dose Measurement?

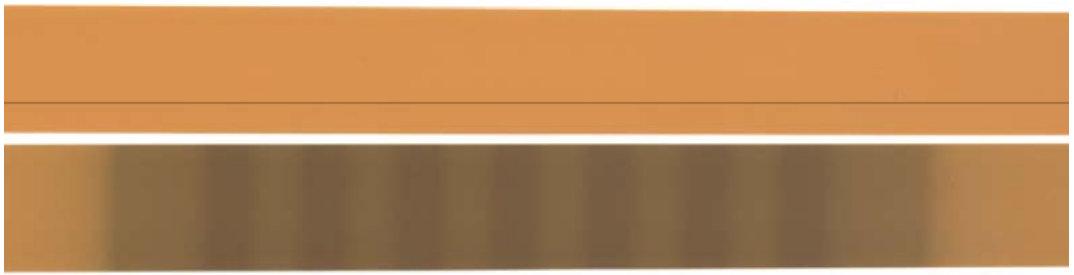
- Radiotherapy (MV photons/electrons/protons)
  - EBT2, EBT3 and EBT3+ - 1 cGy to >40 Gy
  - MD-V3 – 2 Gy to 100 Gy
  - HD-V2 - 10 Gy to 400 Gy
- Radiology (kV photons)
  - XR-RV3 - 5 cGy to 15 Gy
  - XRQA2 – 1 mGy to 20 cGy

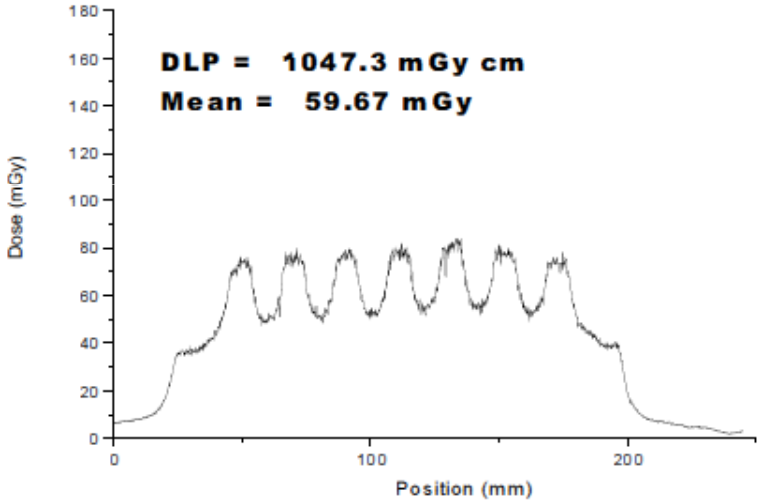






CT Dose measurement with XR-QA2 Films





Pelvis Phantom

120 kVp
Wedge L – 120 mm
200 mA – 313 mAs
PITCH 0.641

Queensway Carleton Hospital Januarv 2009

Toshiba Aquilion 64

Nagi Sharoubim, Engineer
Slobodan Devic, Ph.D., MCCPM

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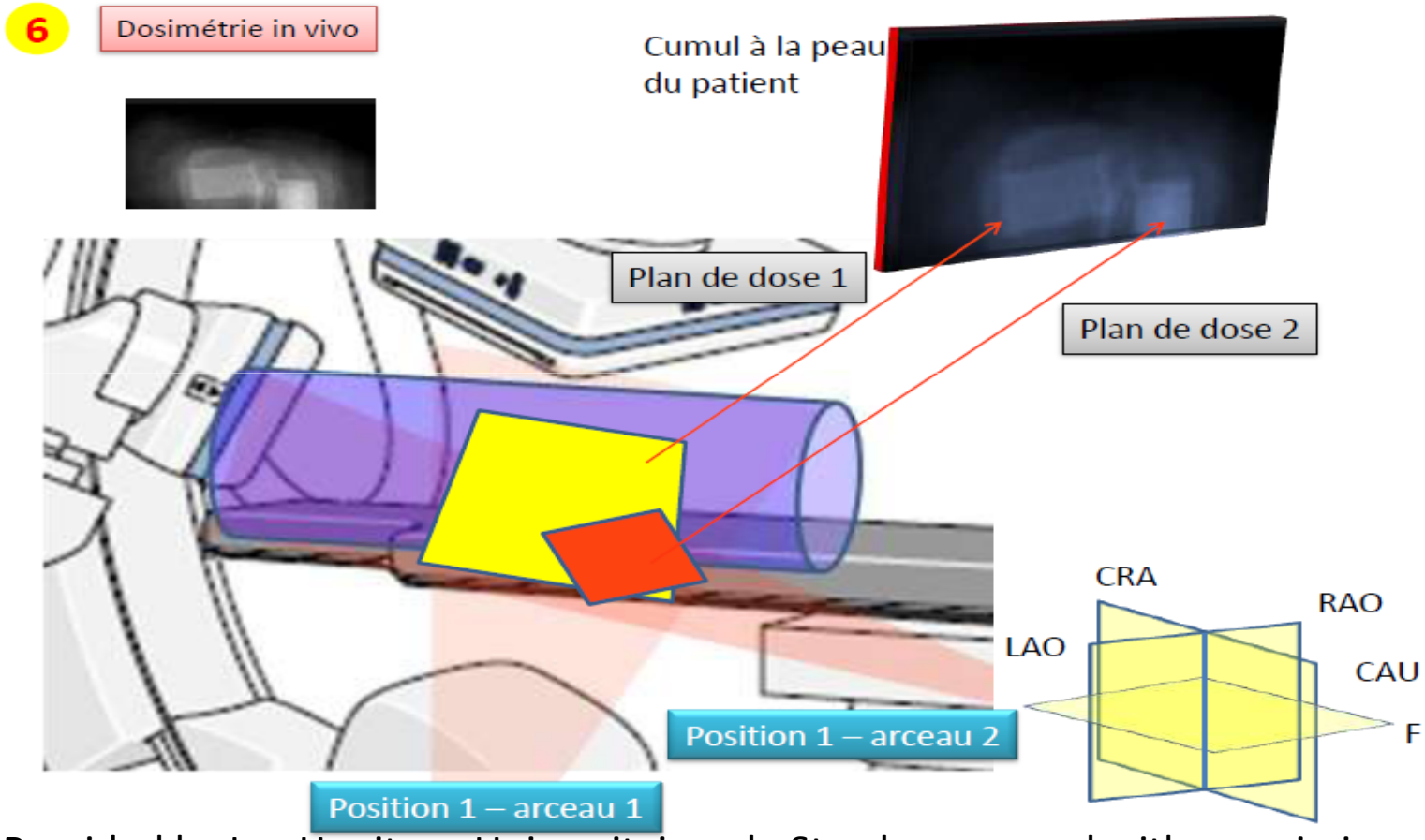
Peak skin dose monitoring with Gafchromic XR-R



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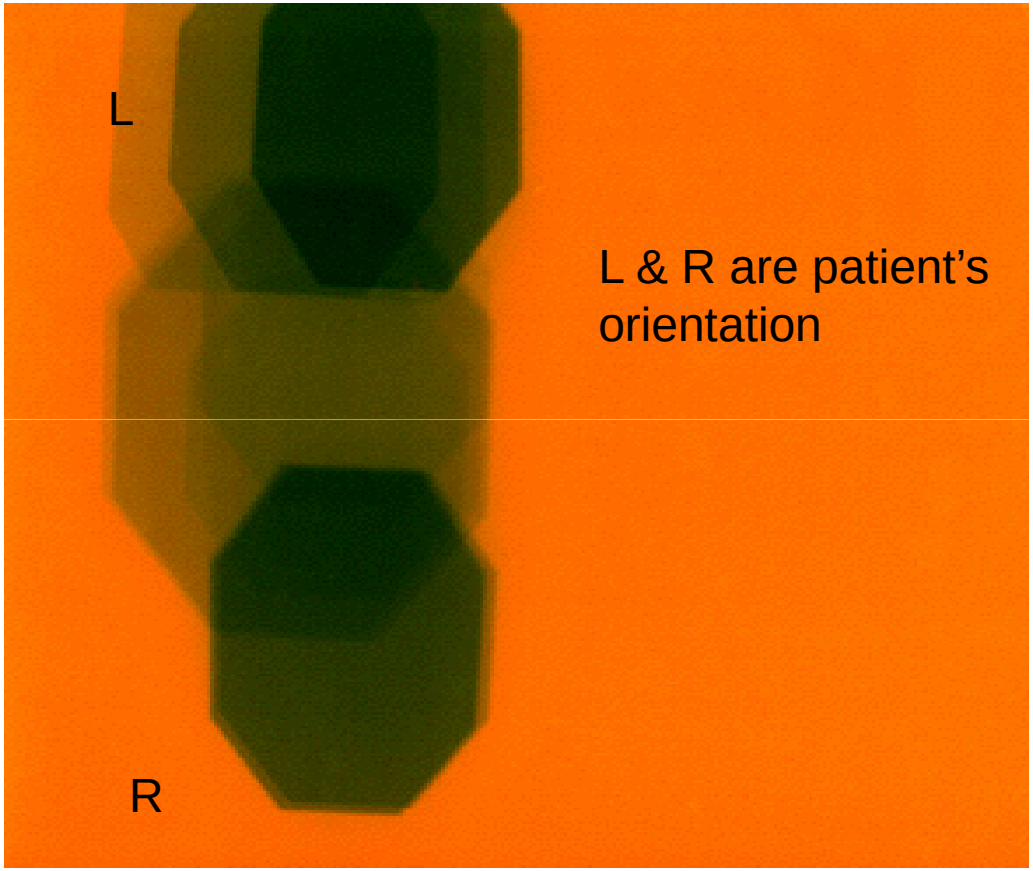
Dose Monitoring with Gafchromic XR-R



- **Immediate visualization** of patient exposure – magnitude and location
- Detailed **dose distribution**

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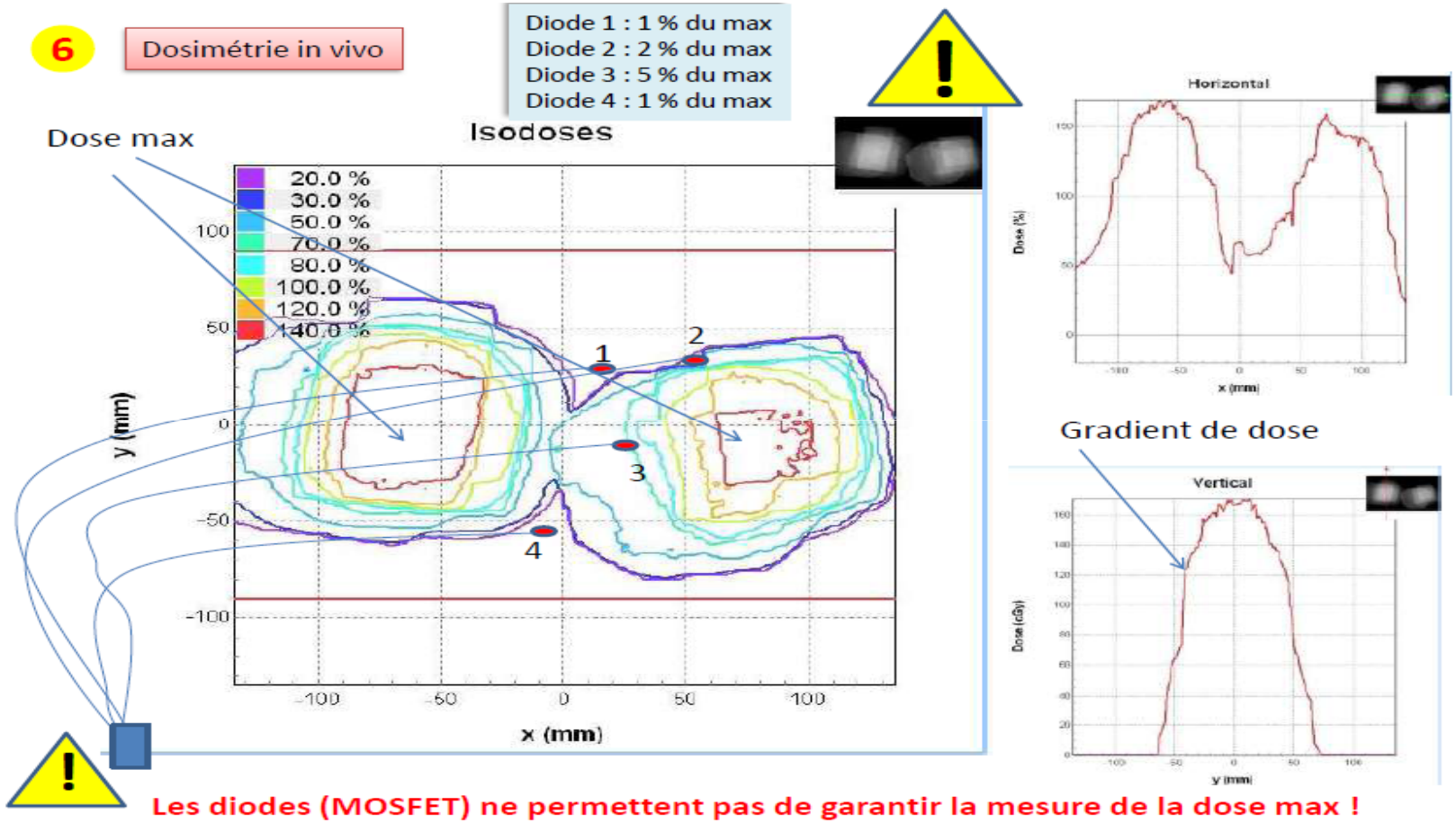
Comparison of Gafchromic XR-R vs. Diodes



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Radiochromic Dosimetry Film – The Advantages

- High spatial resolution
  - #1 choice for high dose gradients
  - Specially valuable for new conformal therapies
- Wide dynamic range – cGy region to >40 Gy
- Handle in light
- Cut to size
- Bend to shape
- Immerse in water

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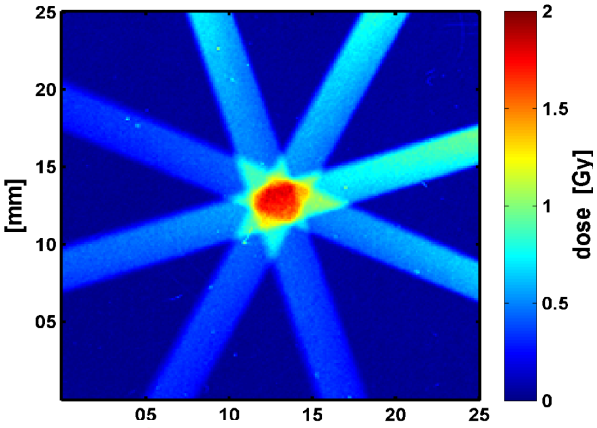
Emerging Modalities

- Trends
  - Small fields
  - High gradients
  - Less fractions
  - Higher dose per fraction
- High value on a dosimeter with:
  - High spatial resolution
  - Wide dynamic range



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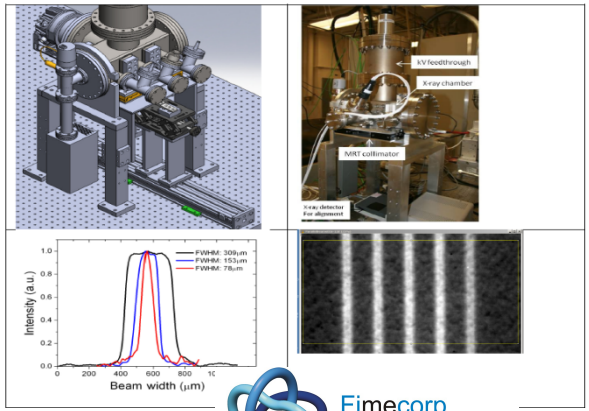

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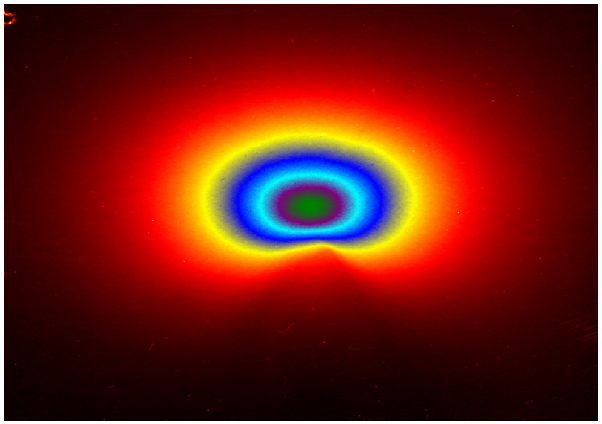

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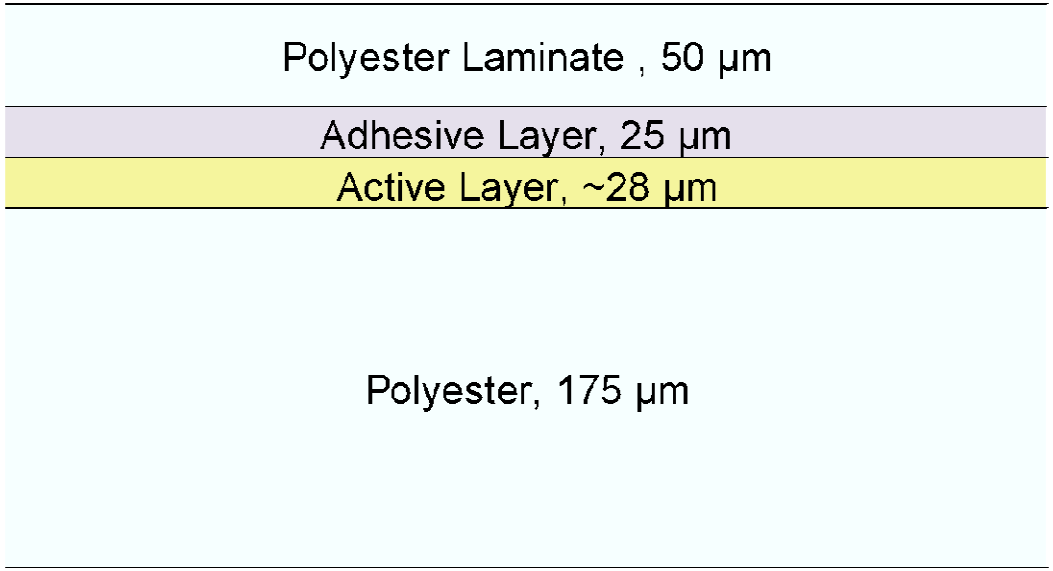
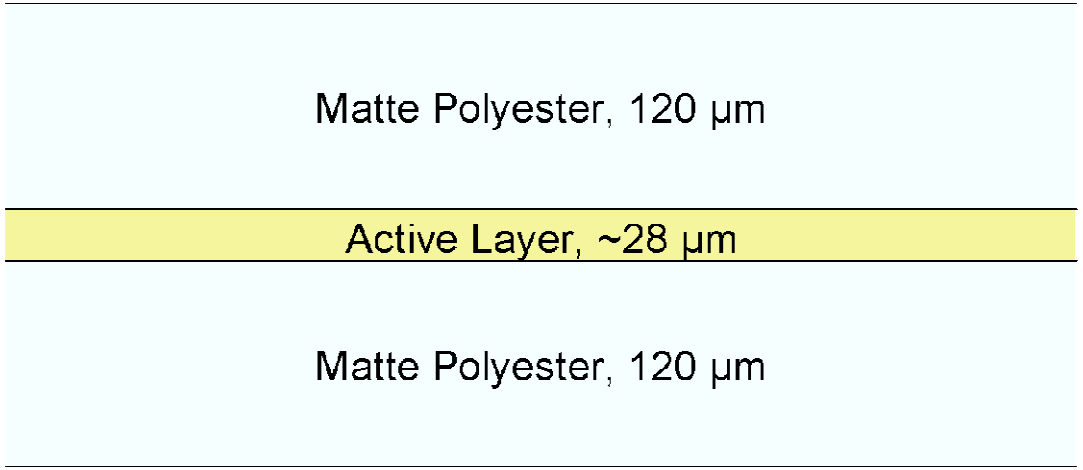
Configuration of EBT2, EBT3 and EBT3+



EBT2



EBT3 and EBT3+

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Composition and Energy Dependence

GafChromic EBT2 Film – since October 2012 (lot A102312)								
Layer	**Nominal thickness, µm**	**Density, g/cm²**	**COMPOSITION (ATOM%)**					**Effective Z**
			H	**Li**	**C**	**O**	**Al**	
Smooth polyester film base	50	1.35	36.4%	0.0%	45.5%	18.2%	0.0%	6.64
Acrylic adhesive	20	1.2	57.1%	0.0%	33.3%	9.5%	0.0%	6.26
Active (assumes 7.5% moisture)	28	1.2	56.8%	0.6%	27.6%	13.3%	1.6%	7.26
Smooth polyester film base	175	1.35	36.4%	0.0%	45.5%	18.2%	0.0%	6.64

GafChromic EBT3 Film Types – since October 2012 (lot A101012)								
Layer	**Nominal thickness, µm**	**Density, g/cm²**	**COMPOSITION (ATOM%)**					**Effective Z**
			H	**Li**	**C**	**O**	**Al**	
Matte polyester film base	125	1.35	36.4%	0.0%	45.5%	18.2%	0.0%	6.64
Active (assumes 7.5% moisture)	28	1.2	56.8%	0.6%	27.6%	13.3%	1.6%	7.26
Matte polyester film base	125	1.35	36.4%	0.0%	45.5%	18.2%	0.0%	6.64

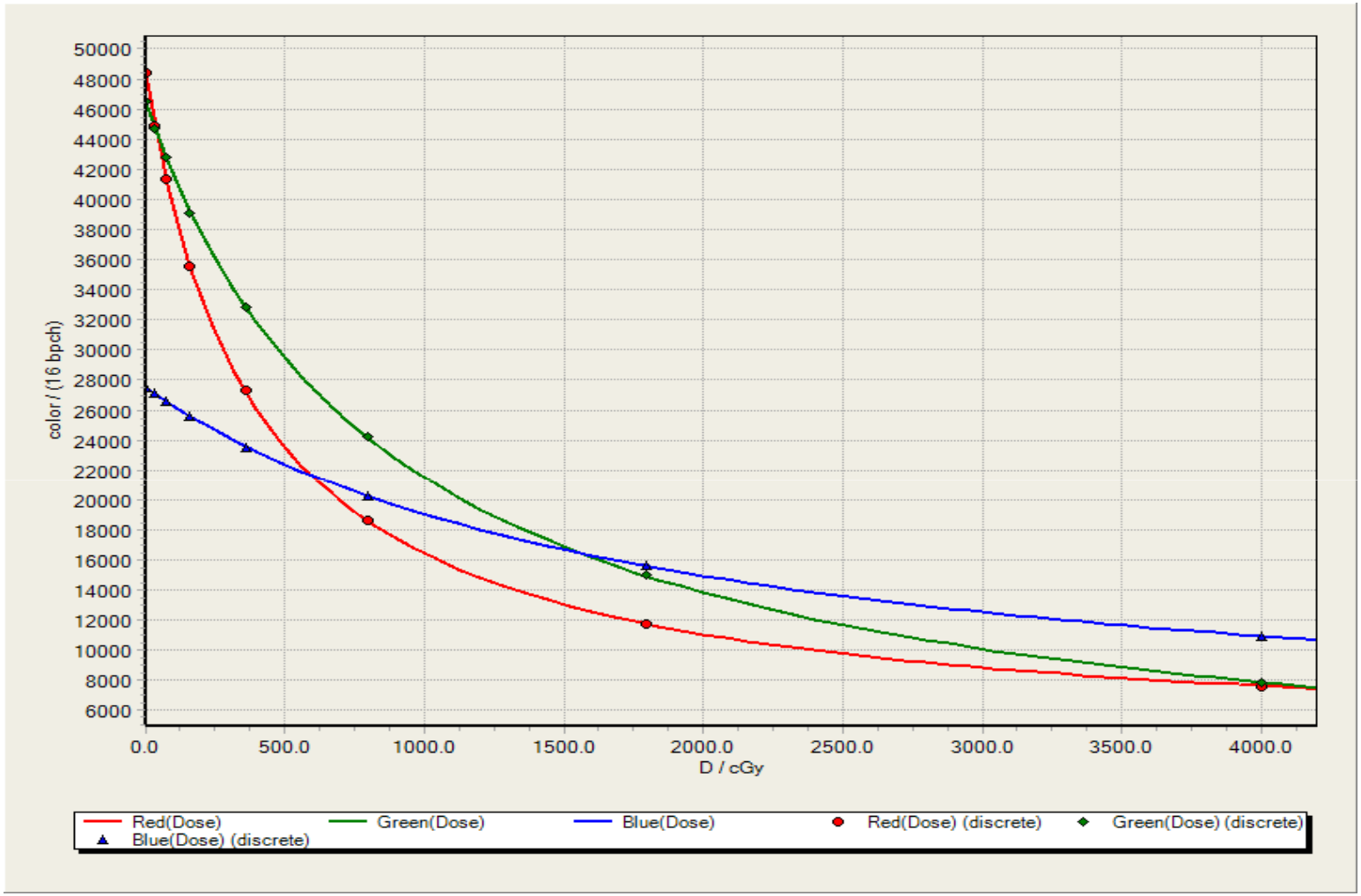
Energy independent MV to 100 keV

6%±4% under-response at 40keV

20%±4% under-response at 20keV

Bekerat et al., Medical Physics, Feb. 2014: 41(2): 022101

EBT2, EBT3 and EBT3+ Dynamic Range



High spatial resolution – to 25 µm

Wide dynamic range – cGy to >40 Gy

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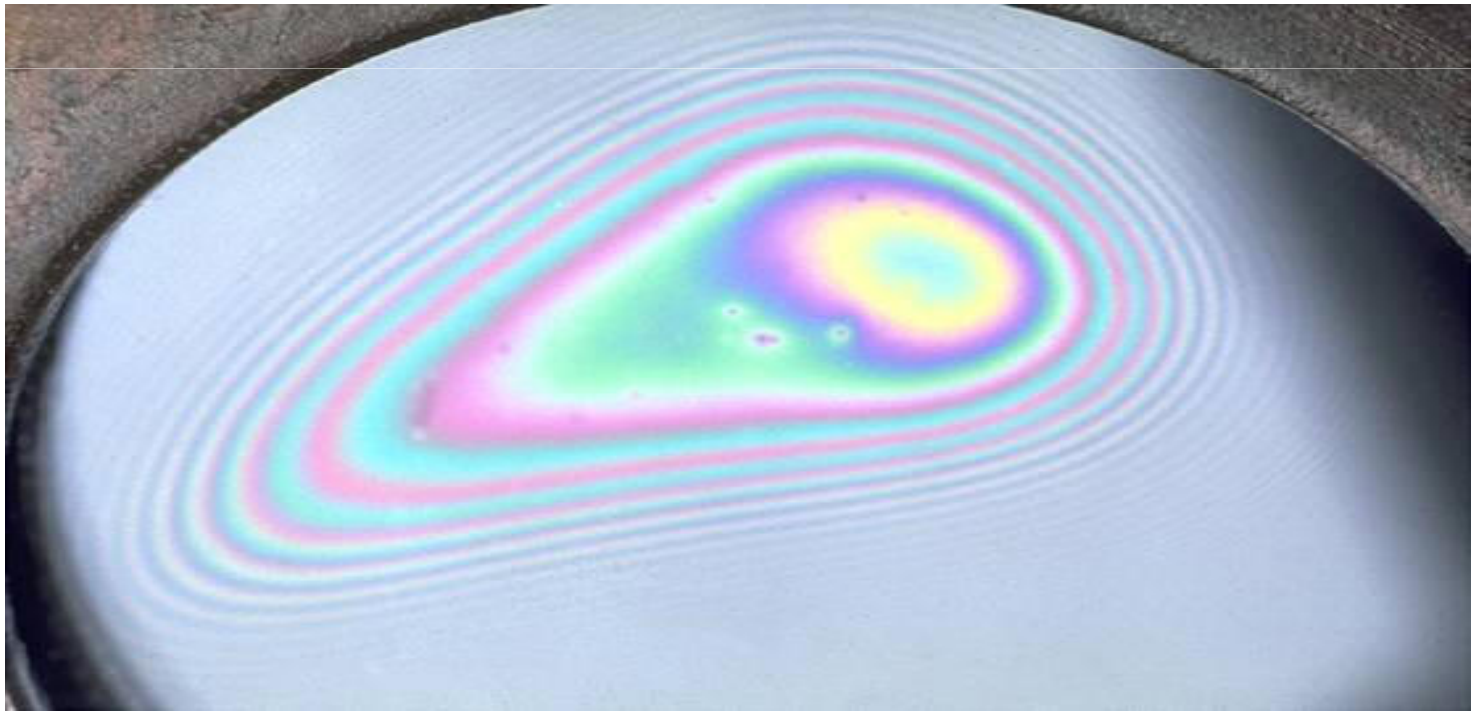
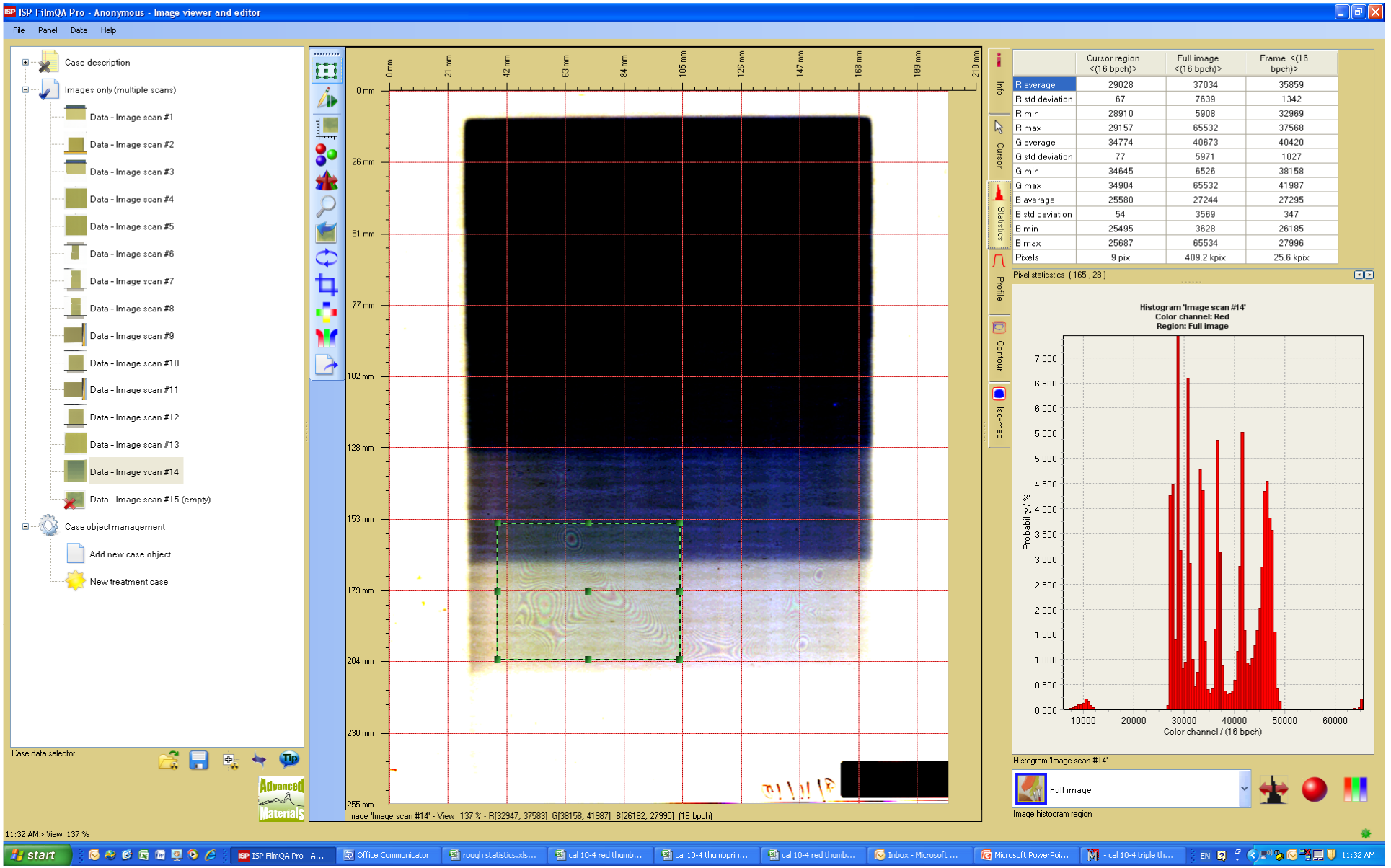
Newton’s Rings Pattern

- Constructive/destructive optical interference bands in the gap between two closely spaced surfaces
  - Monochromatic light yields light and dark bands
  - White light yields colored bands

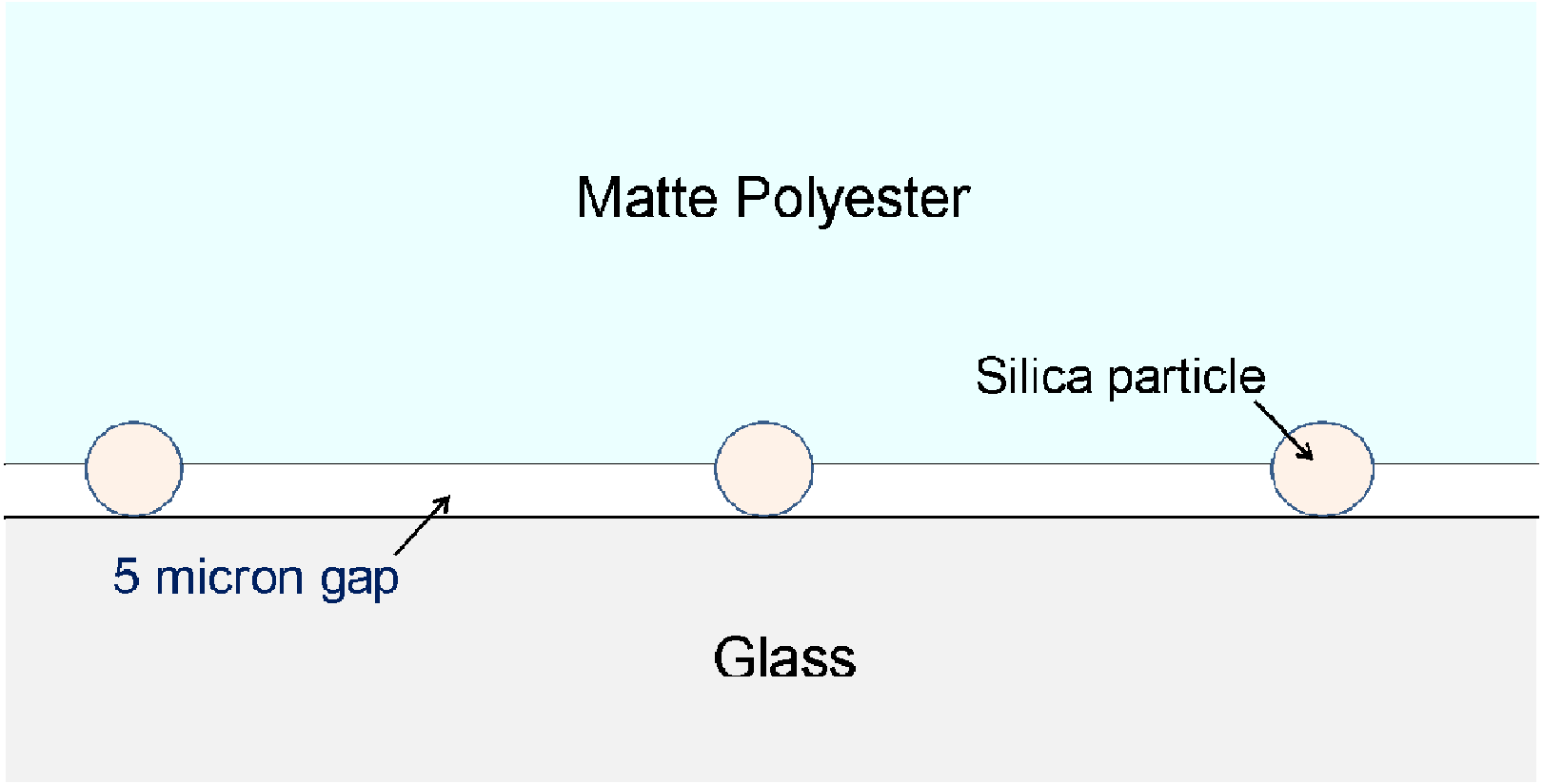
.



Newton’s Rings – EBT2 Film Image



EBT3: Matte Polyester Stops Newton's Rings



Gap >> λ_{light}

What should you know about film dosimetry?

- **Know the things that work together!!!**
  - EBT2/EBT3
  - Multi-channel dosimetry
  - The “One-scan” protocols
  - FilmQAPro 3.0

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Don’t be obstinate

- Forget single channel dosimetry
  - All response errors convert to dose errors
  - The errors are invisible to you
- Use multi-channel dosimetry
  - Compensates for film/scanner artifacts
  - Consistency map makes errors visible
- Use the “One-scan” protocol
  - Eliminates scan-to-scan variability
  - Reduce post-exposure wait to minutes

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Radiochromic Film Dosimetry:
The Basics

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How is Radiochromic Film Measured?

- Color reference chart
- Densitometer
- Scanner
  - An rgb color scanner
  - 16 bit/channel resolution essential for dose measurement
- Epson flatbed scanners:
  - 10000XL with transparency adapter – A3 format
  - V700, V750, 1680 and 4990 – A4 format

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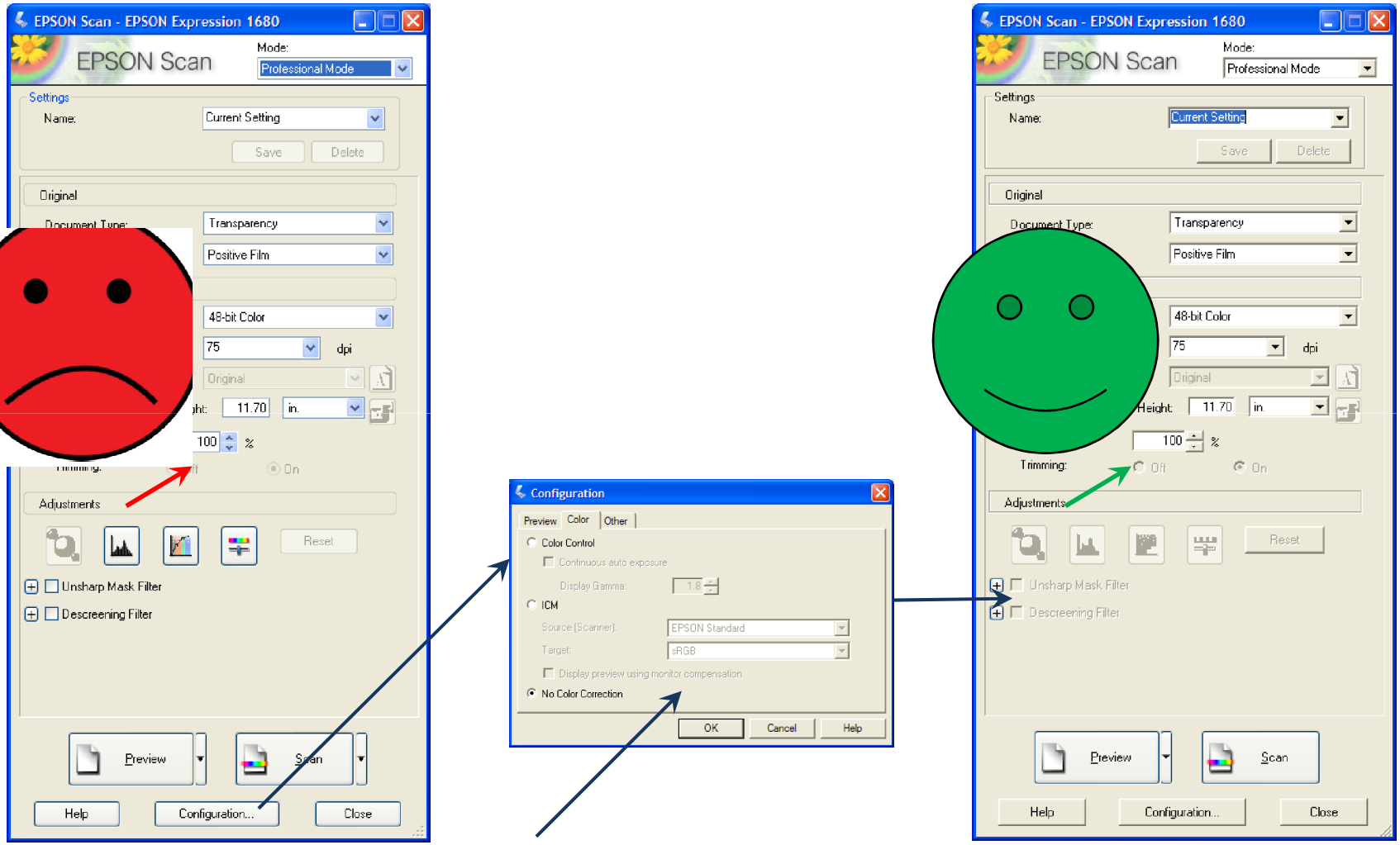
Disable the Color Correction Features



Check “No Color Correction”

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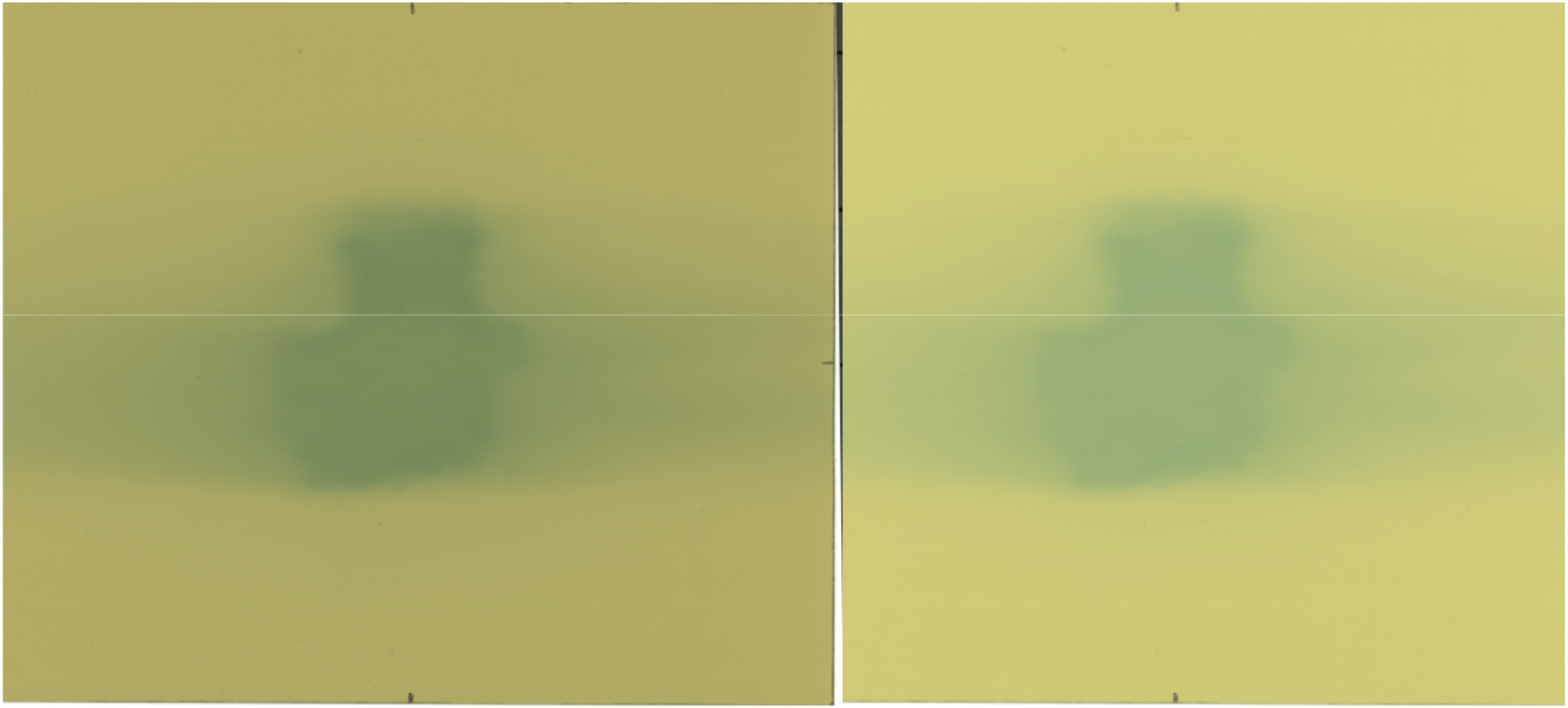
Image Color Correction



No color correction

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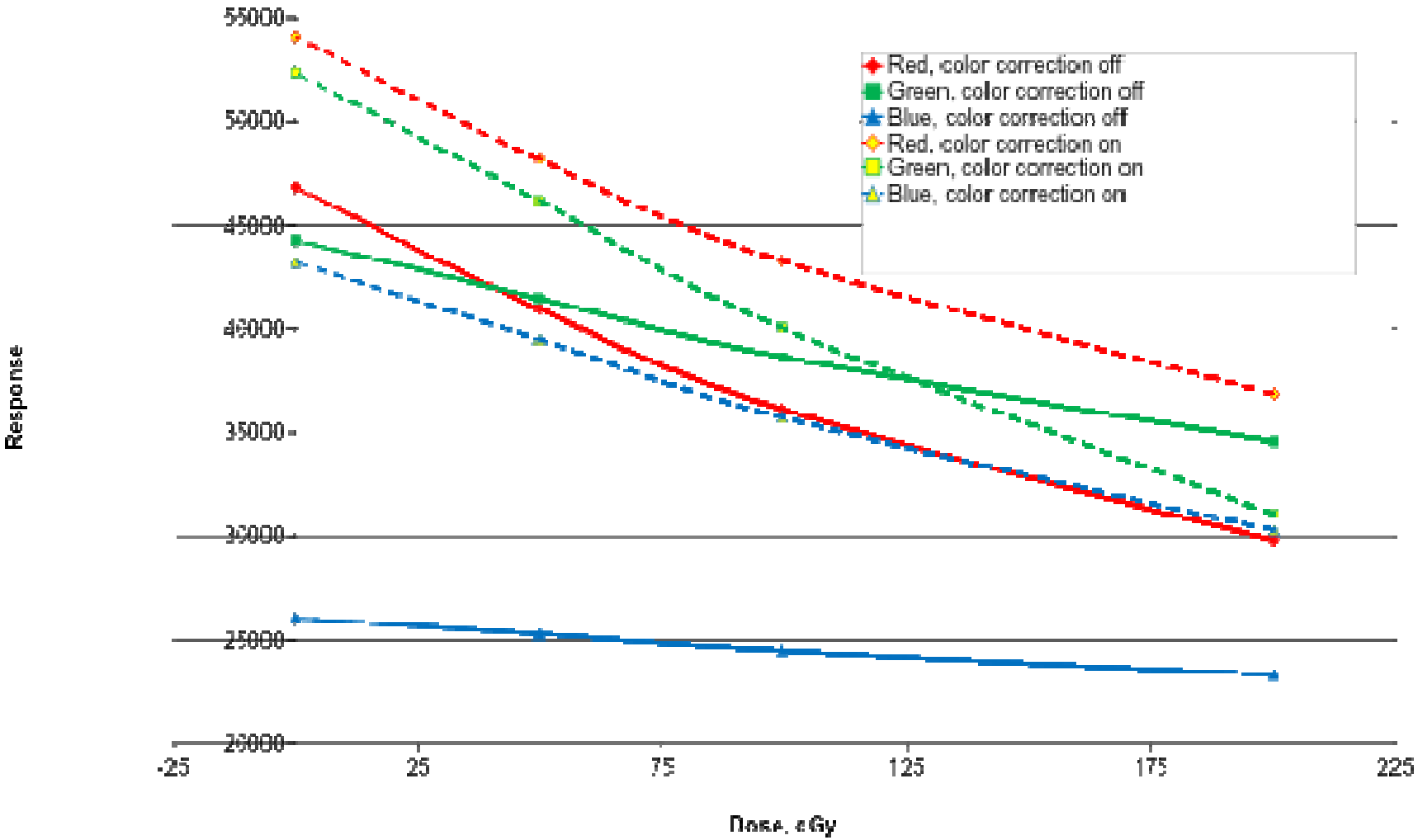
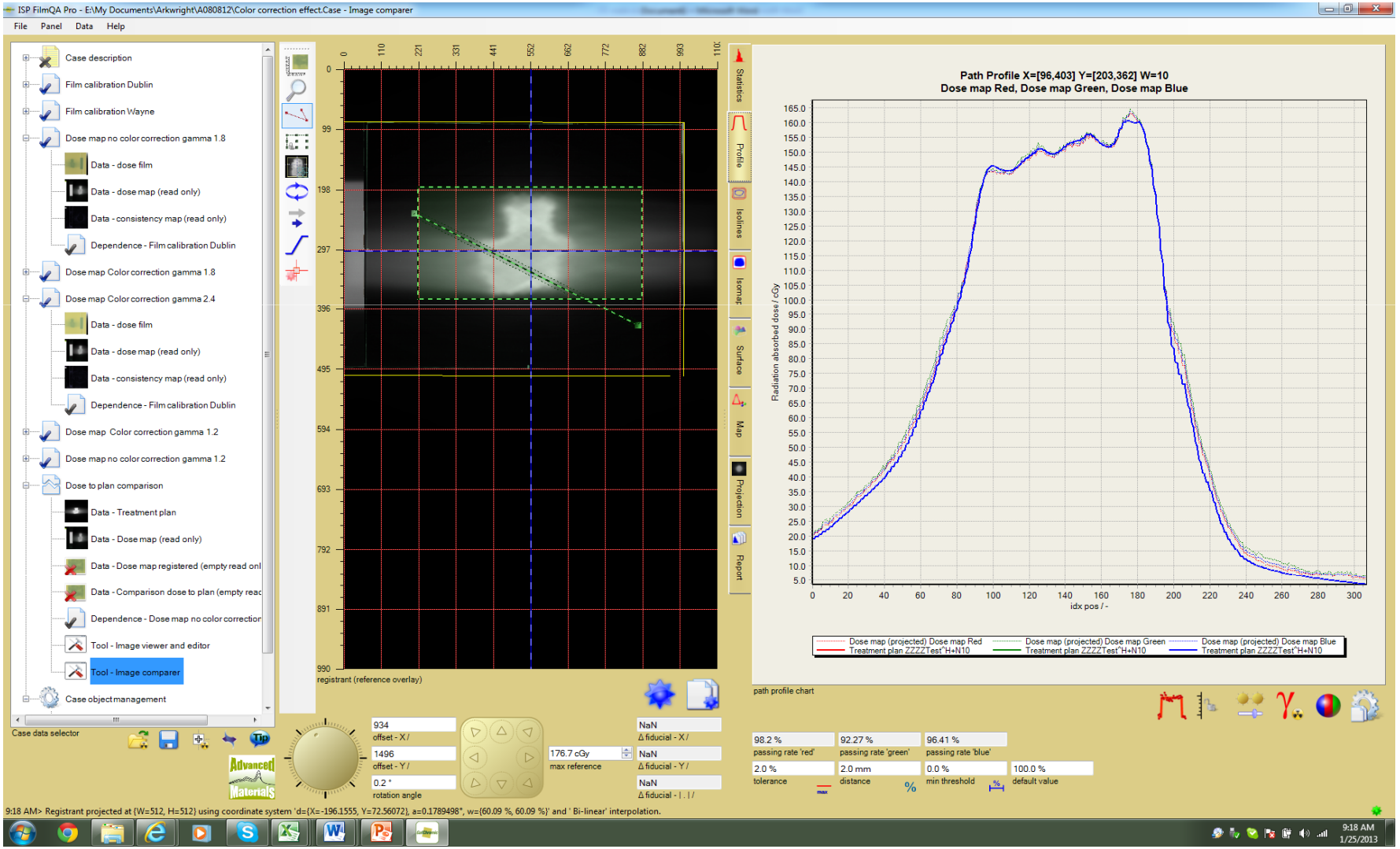
Color correction active

Calibration – Effect of Color Correction



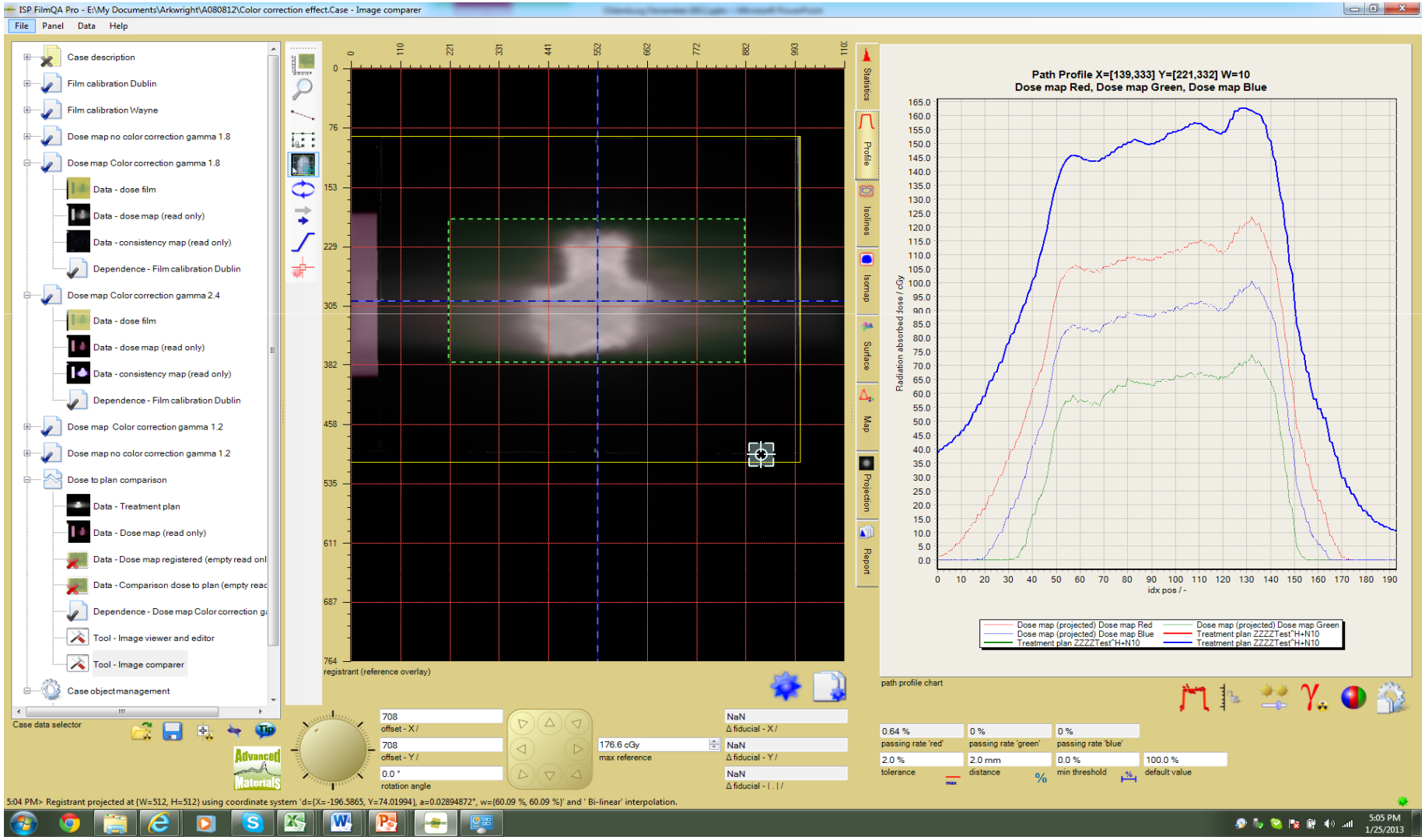
Dosimetry and Color Correction

Color correction turned off for calibration **and** measurement

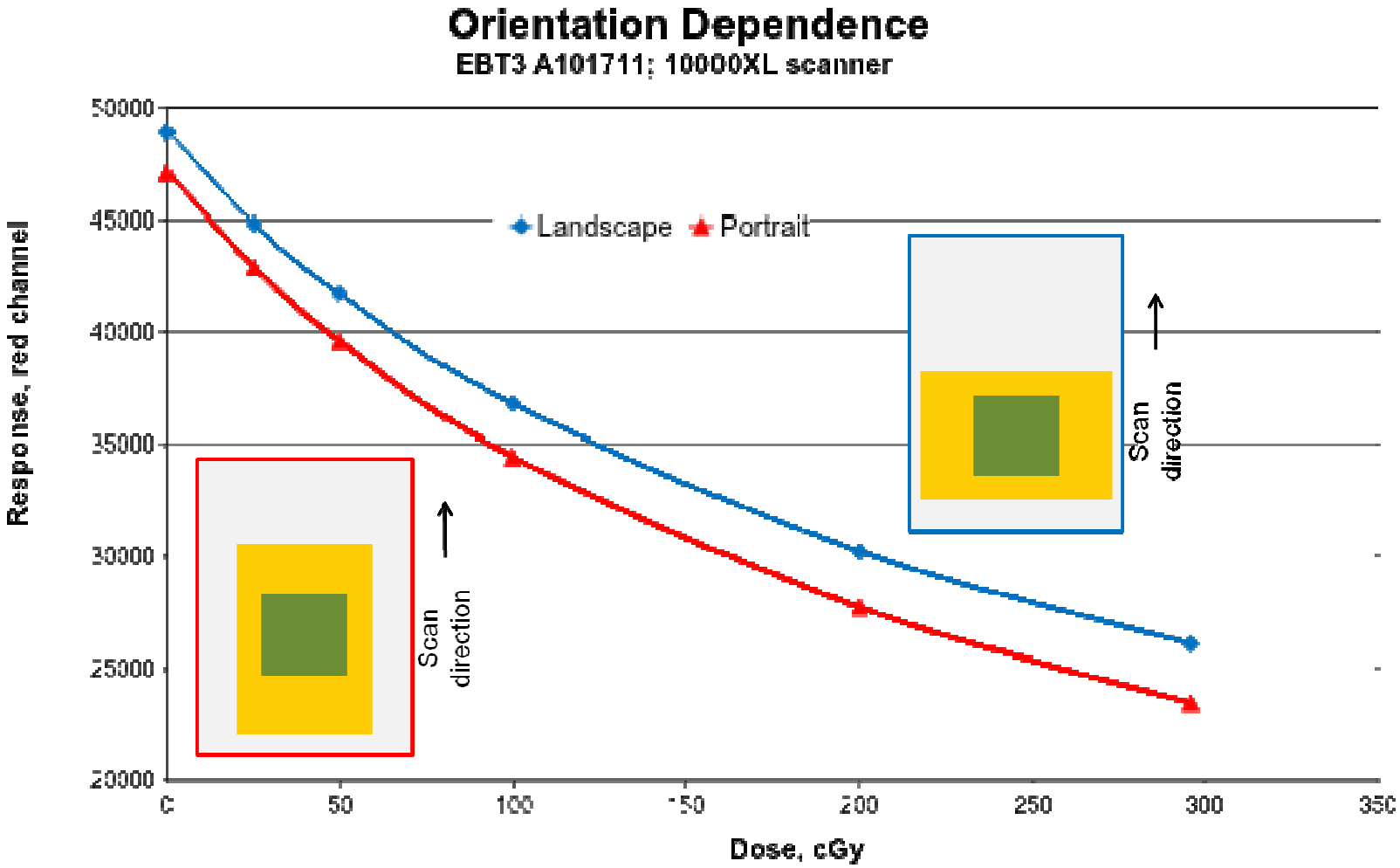


Dosimetry and Color Correction

Color correction off for calibration and on for measurement



Orientation Dependence



- **Either orientation is usable**
- **But don't mix orientations!**

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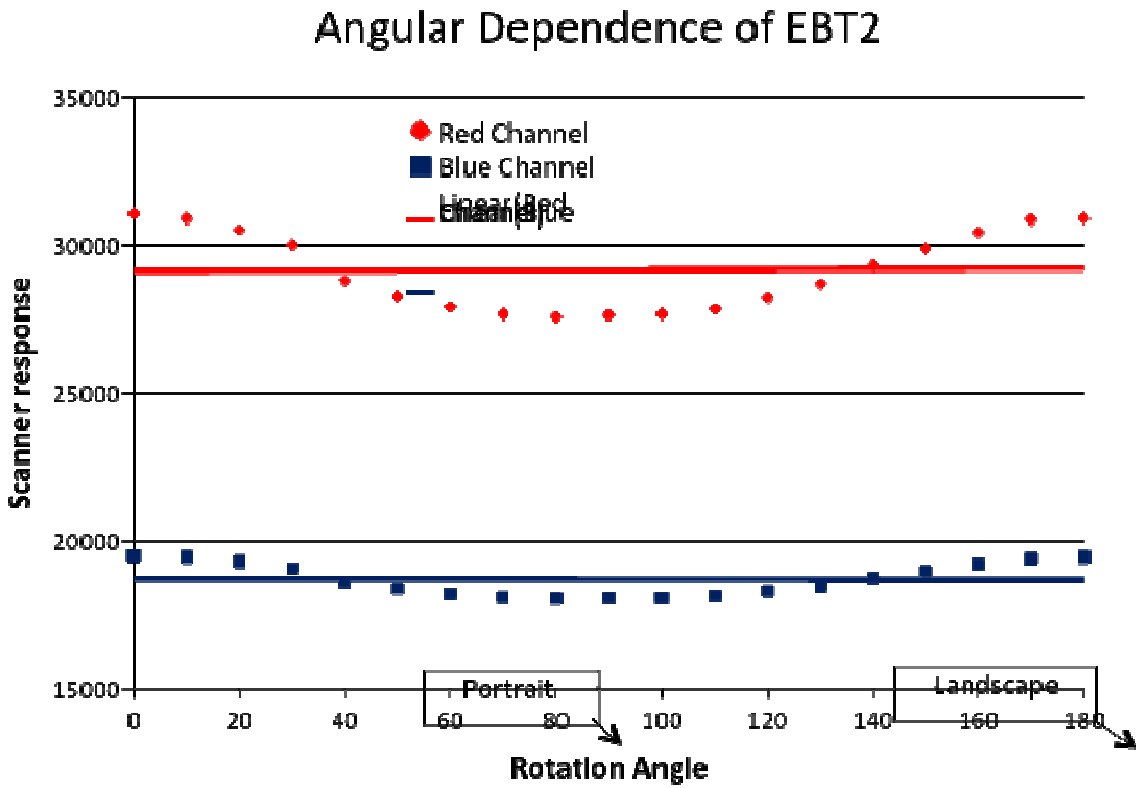
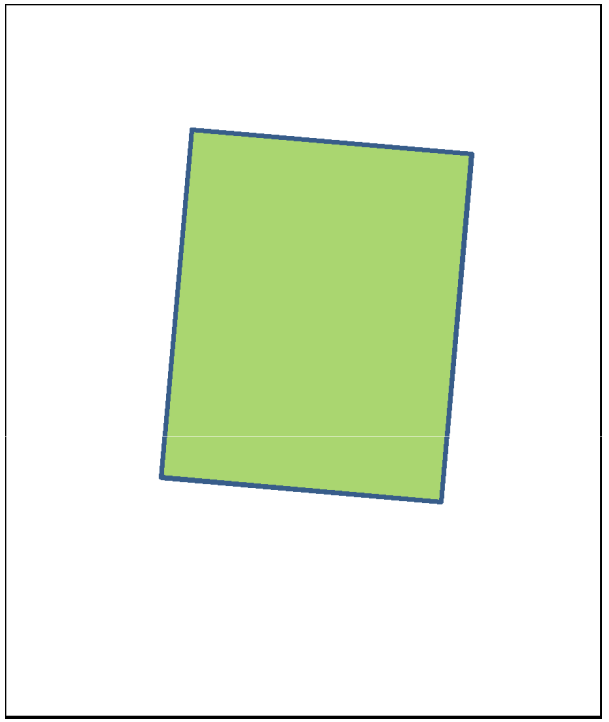
Orientation Dependence





Response error is ~0.05% per degree
Dose error ~0.15% per degree

5° misalignment on scanner

Conclusion: Misalignment is unlikely to cause significant error

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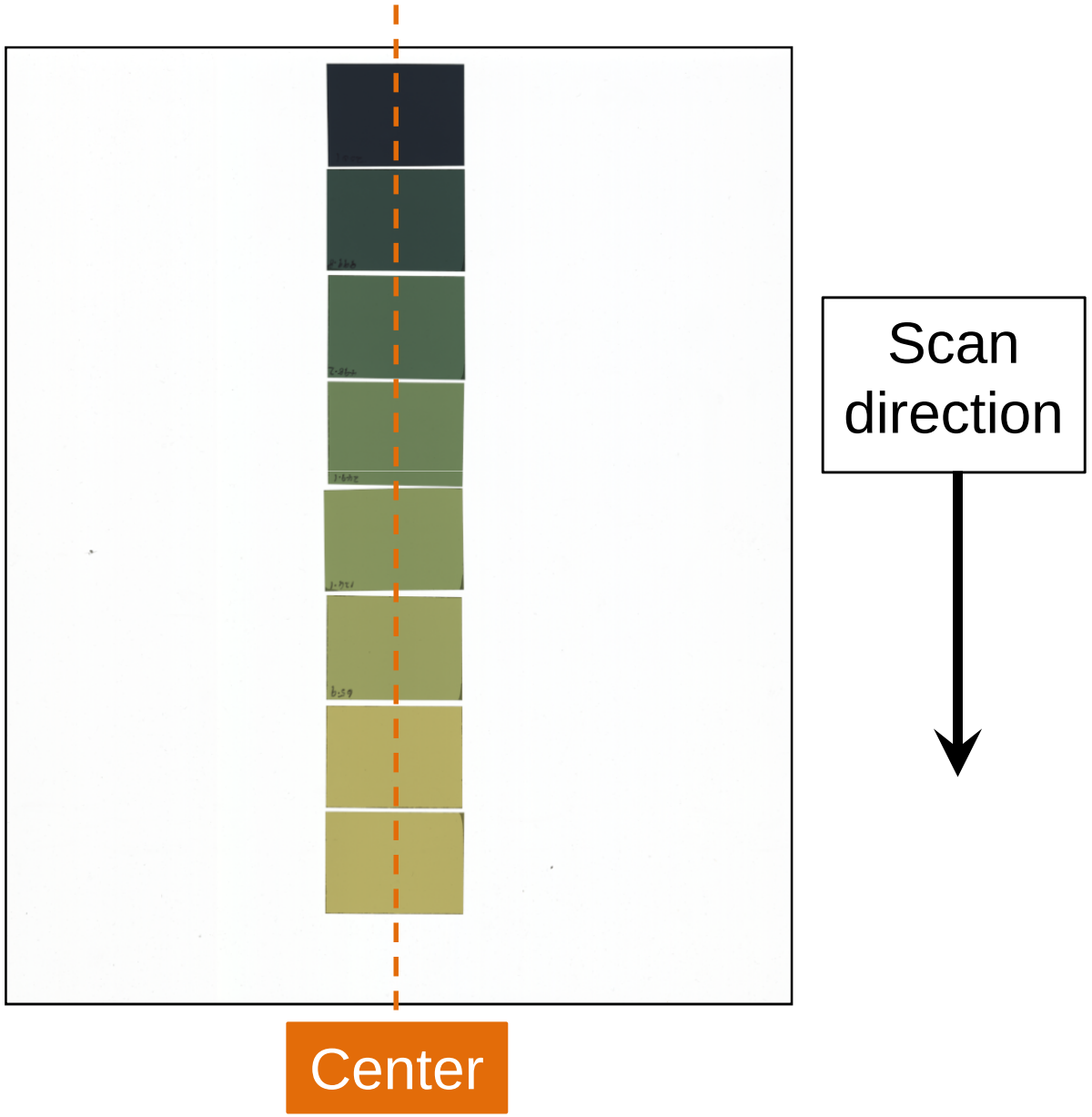
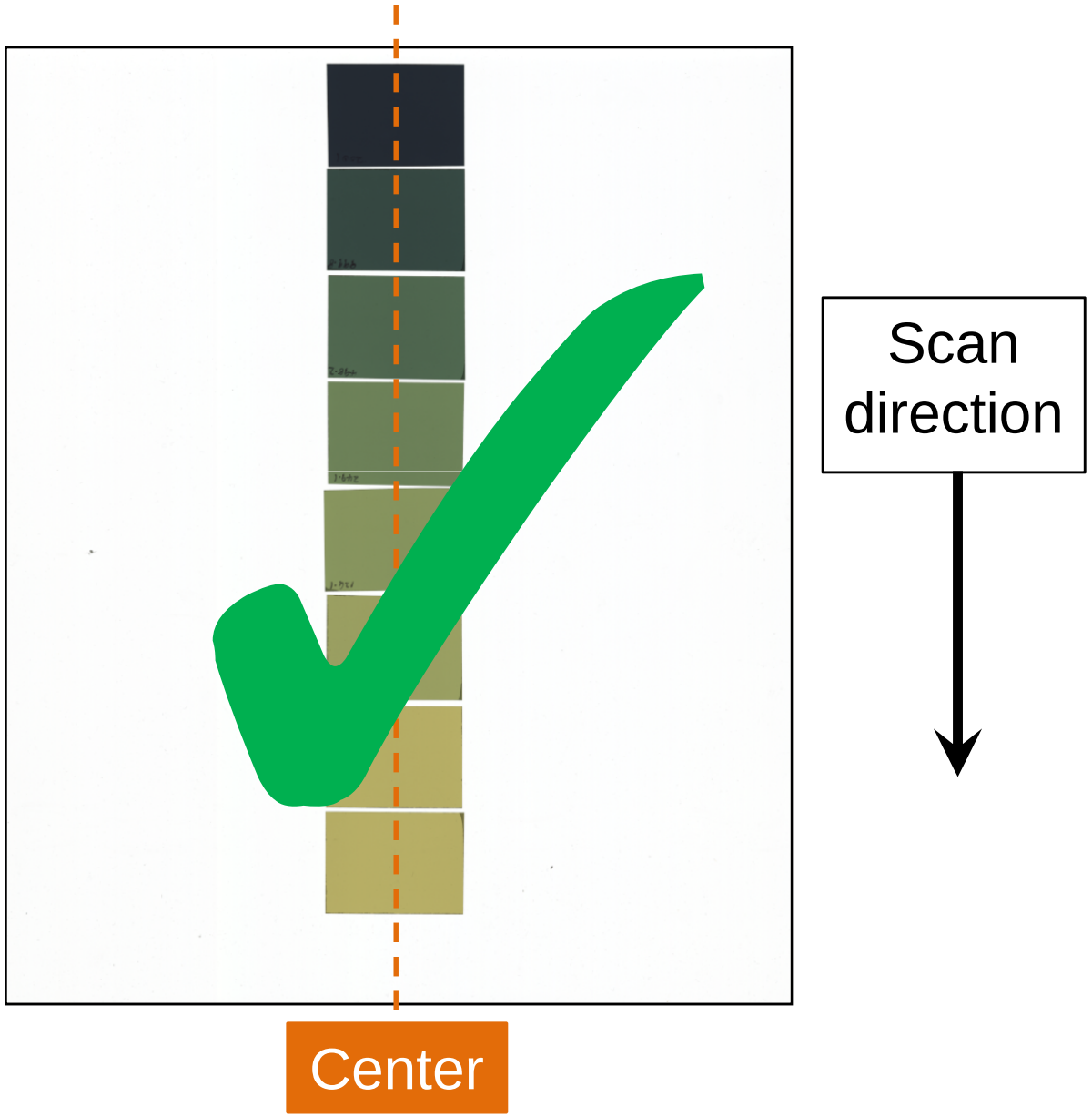
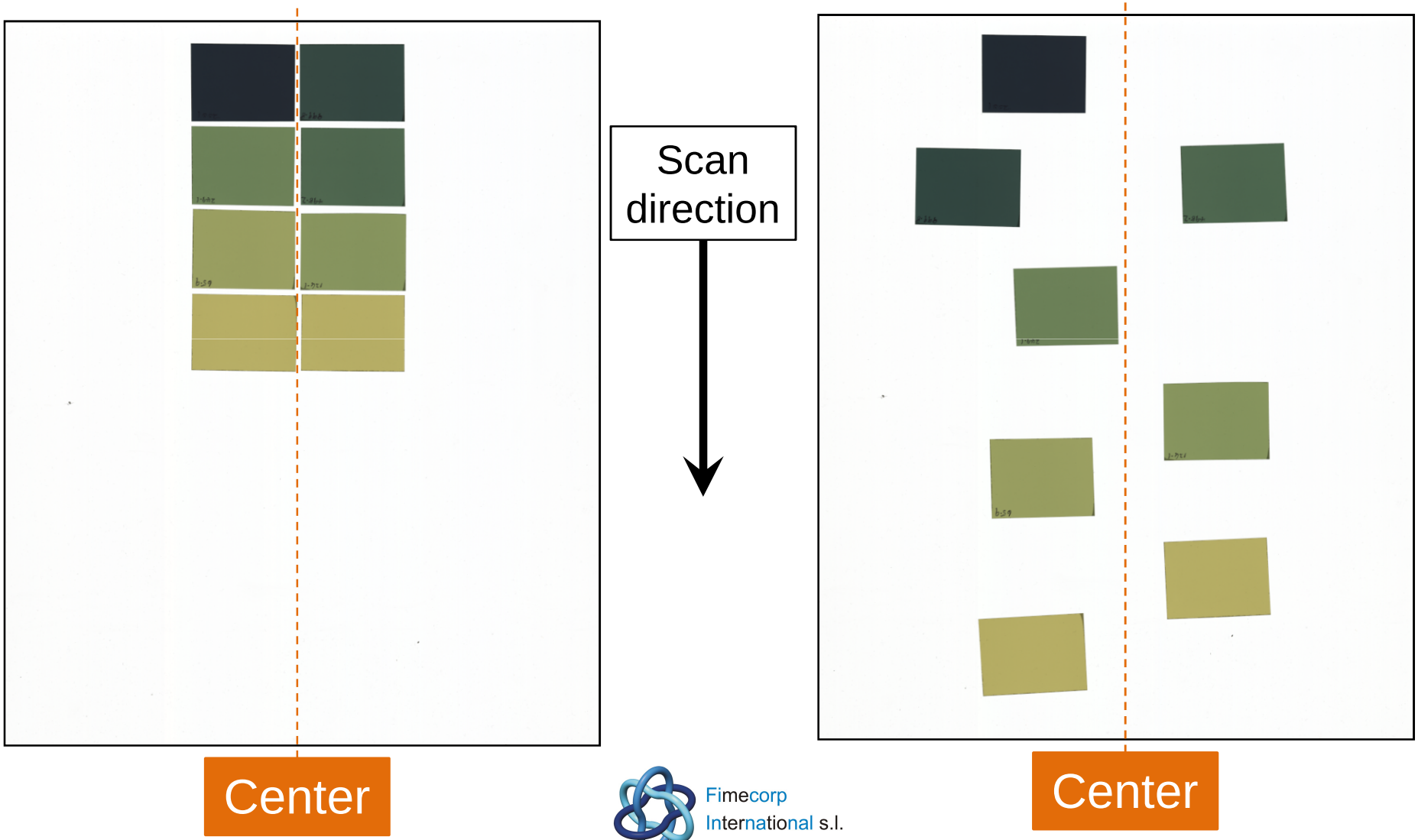
Central Placement for Scanning



Correct Placement for Scanning



Incorrect Placement for Scanning



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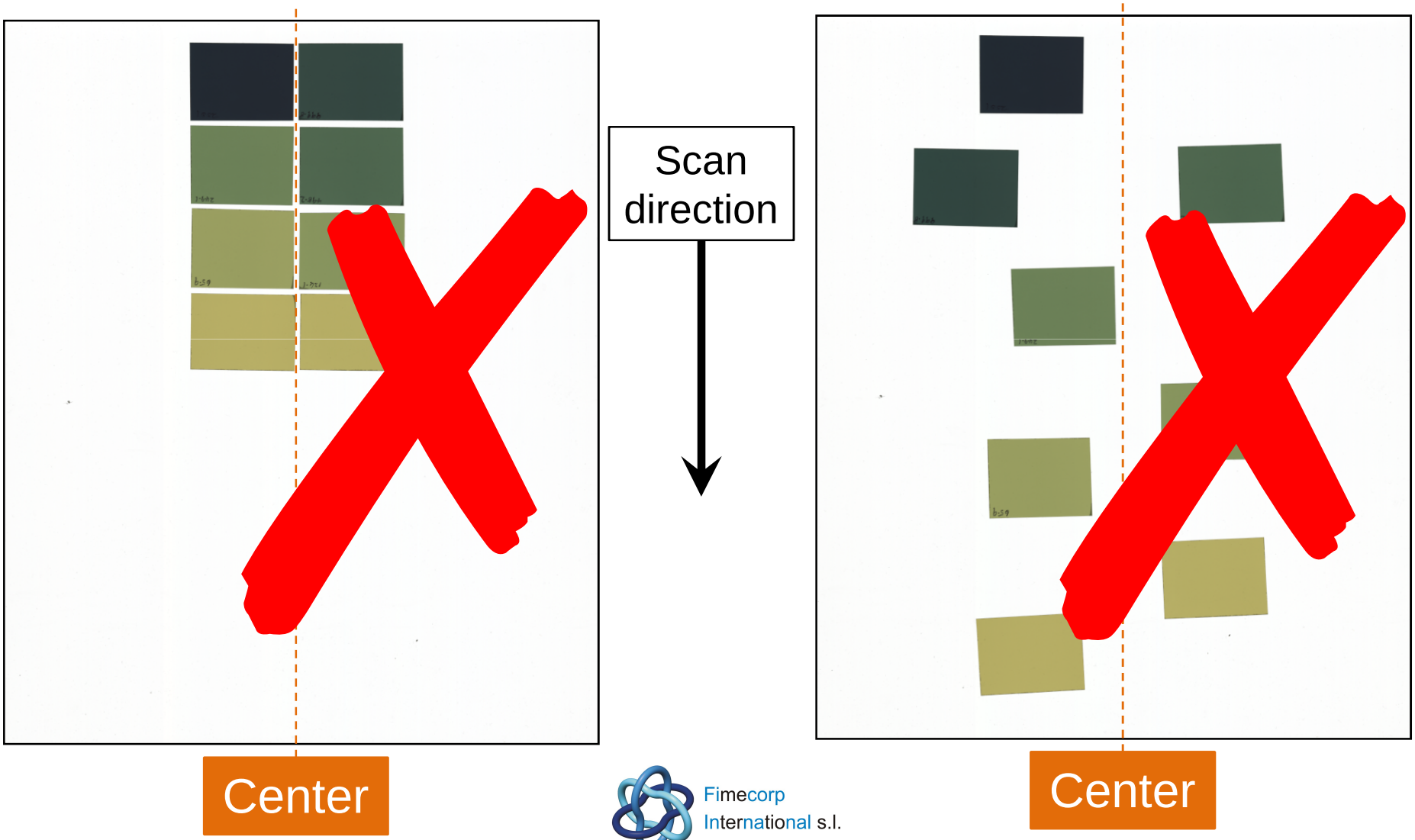
Incorrect Placement for Scanning



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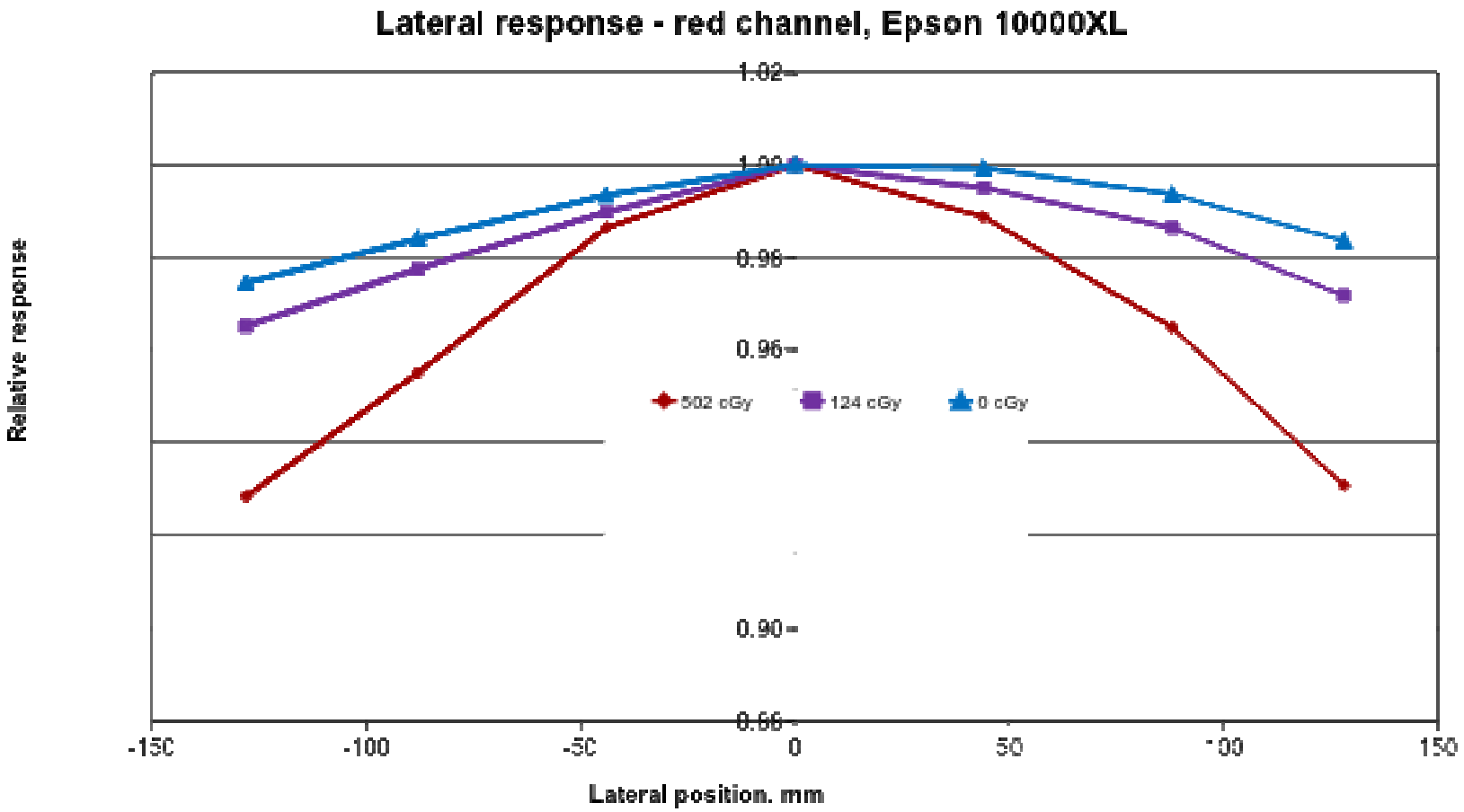
Lateral Position Artifact



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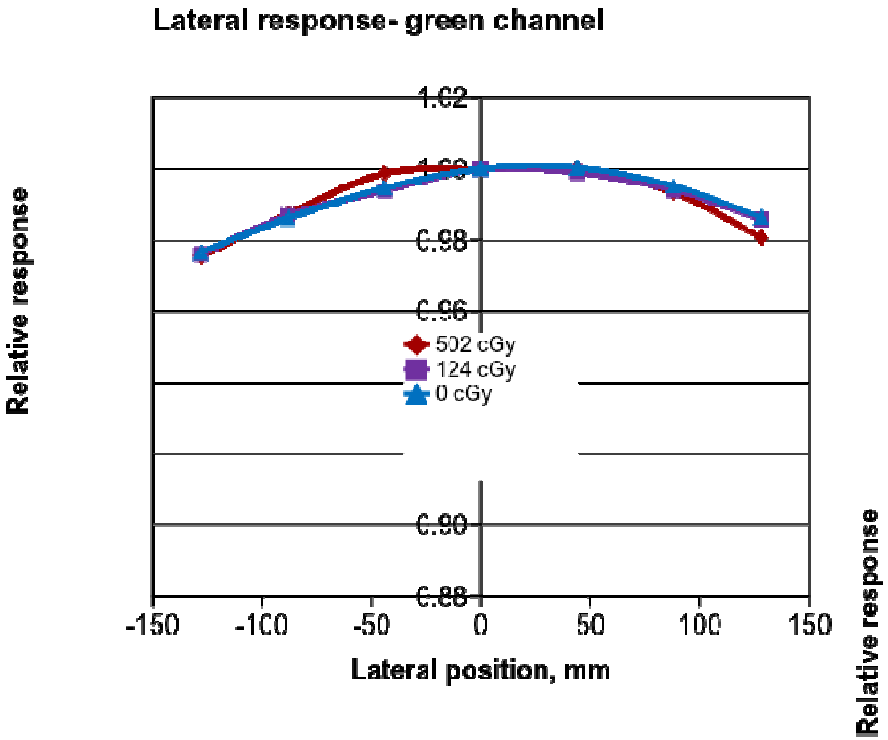
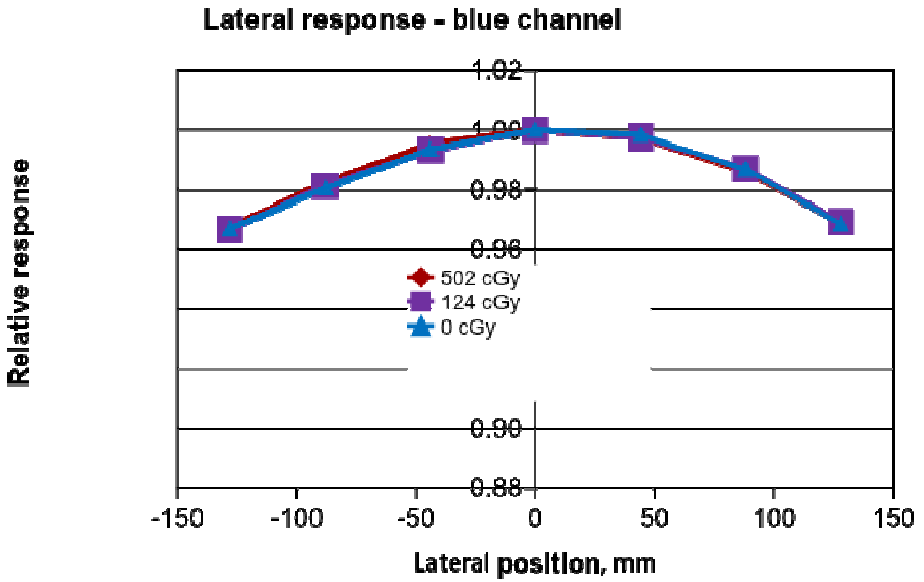
Lateral Position Artifact





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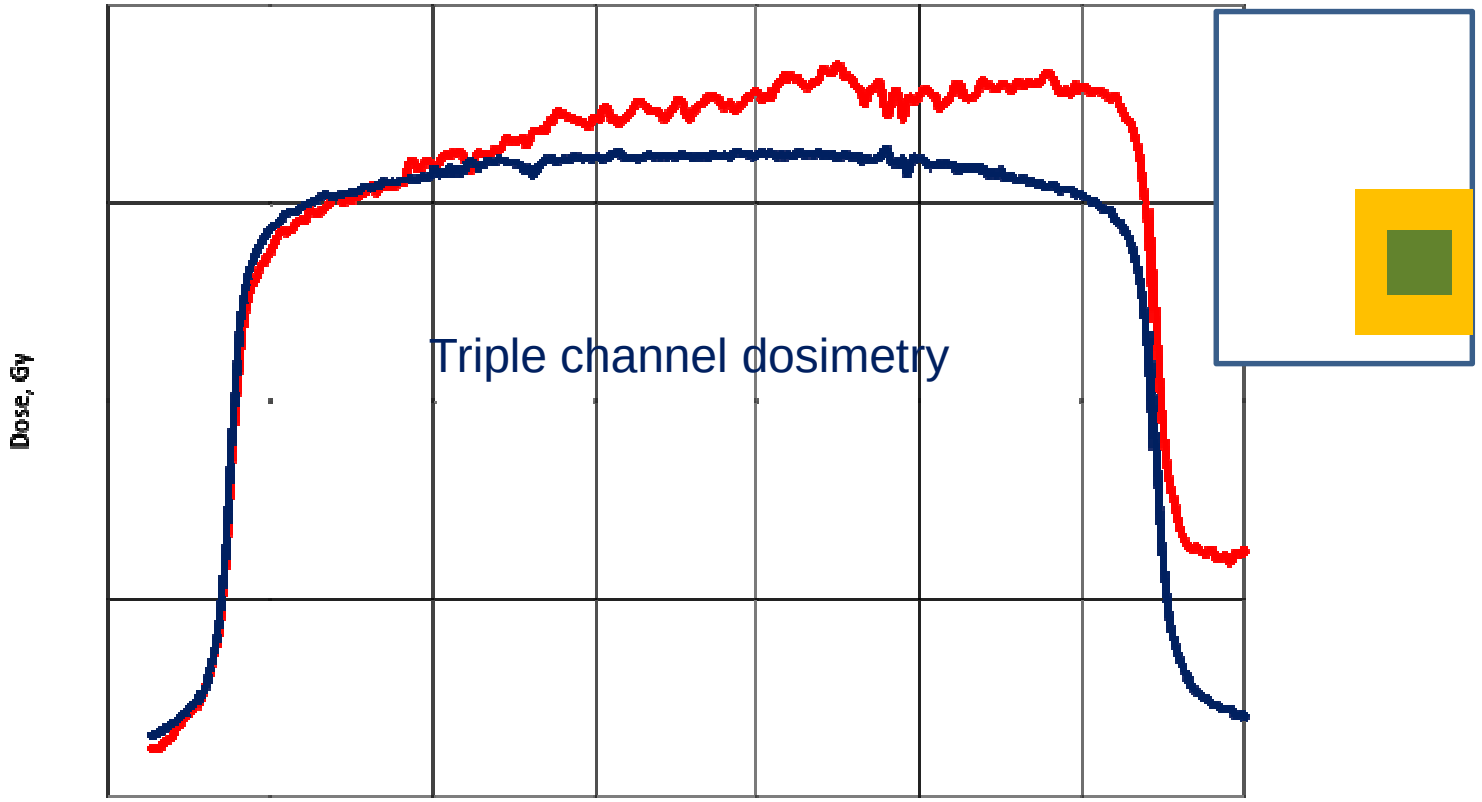
Correcting the Lateral Artifact

Red channel dosimetry



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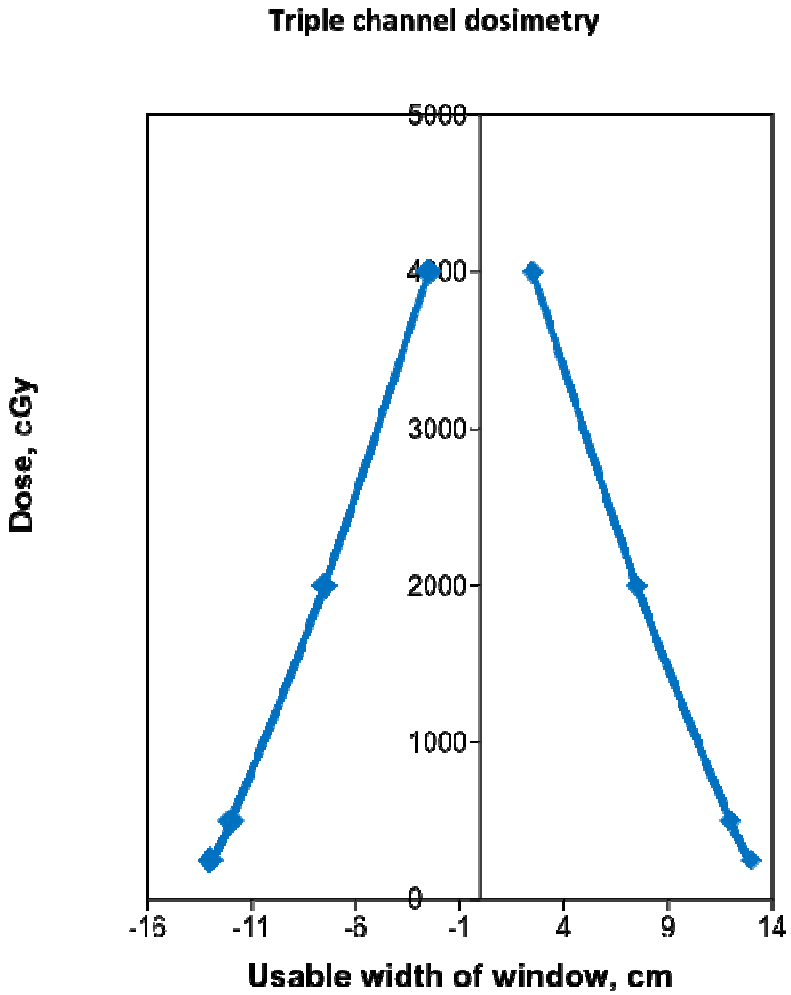
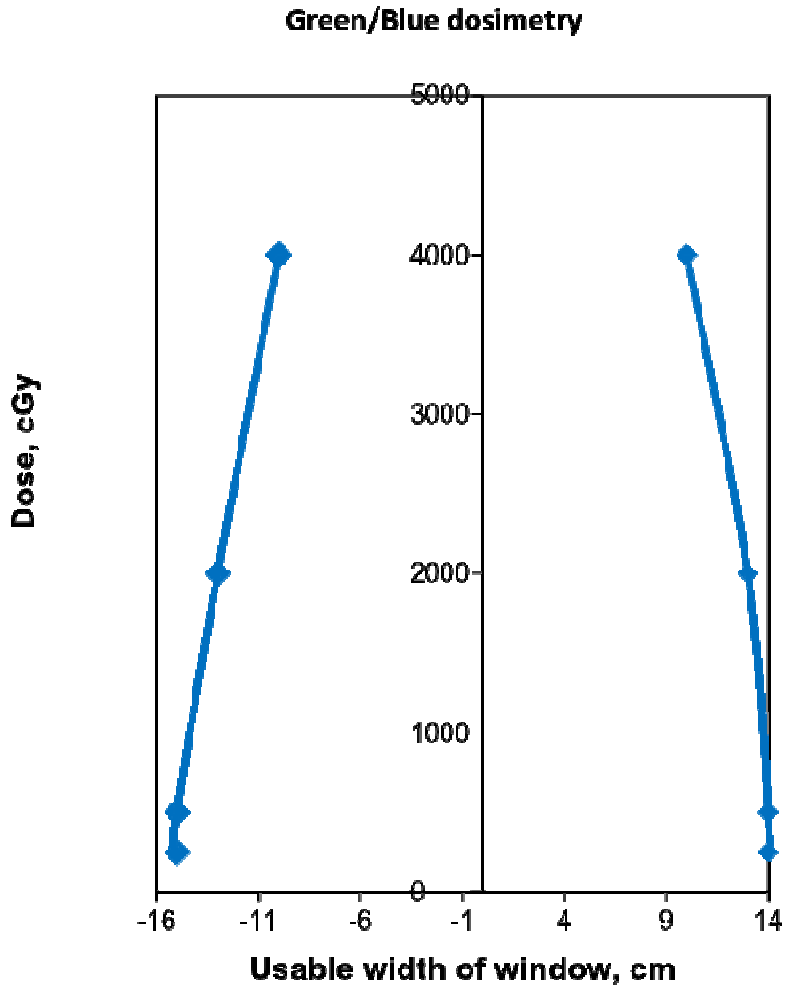
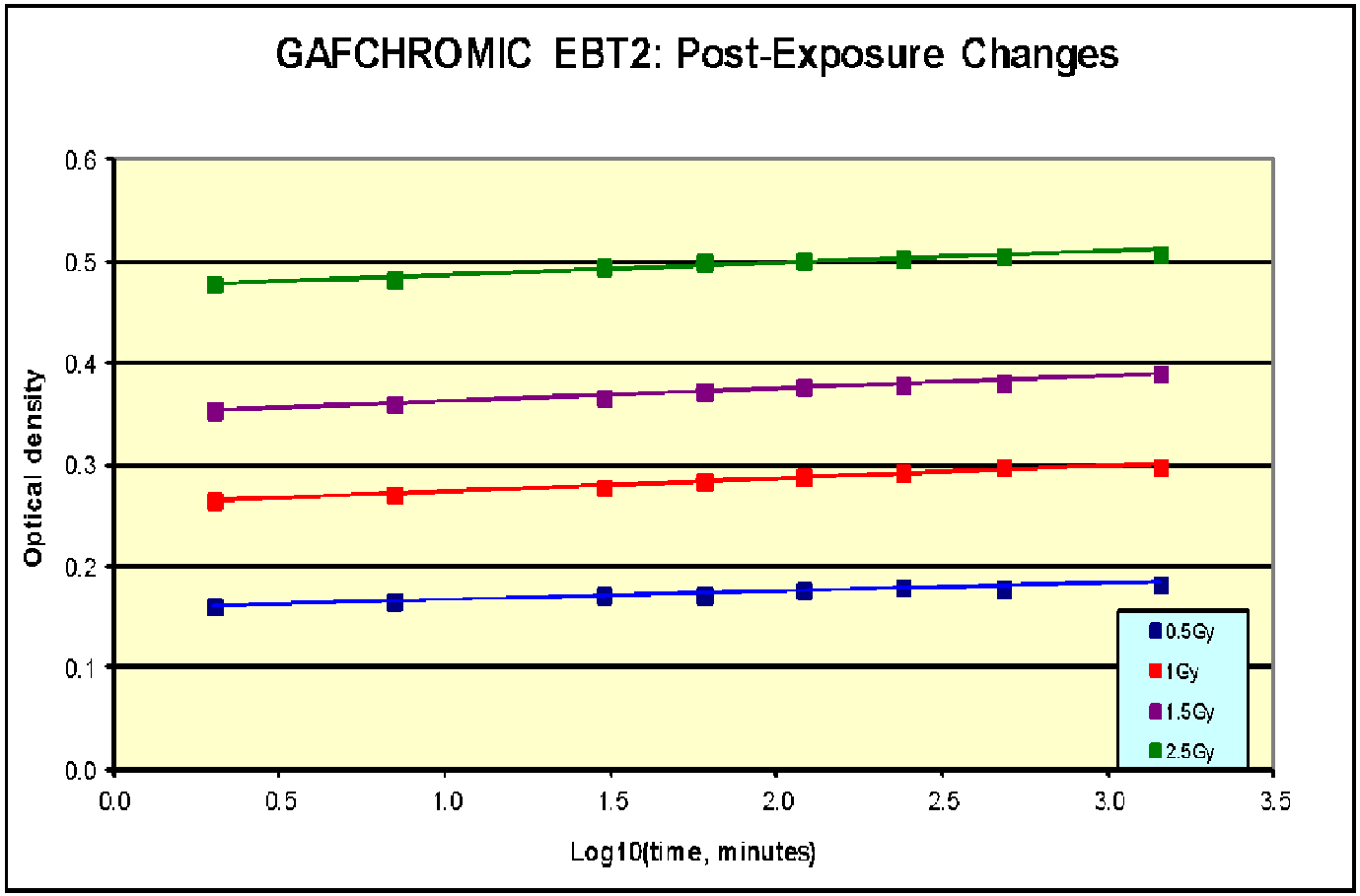
Usable Scan Window, Epson 10000XL





Post-exposure Change



- Wait for the rate of change to diminish

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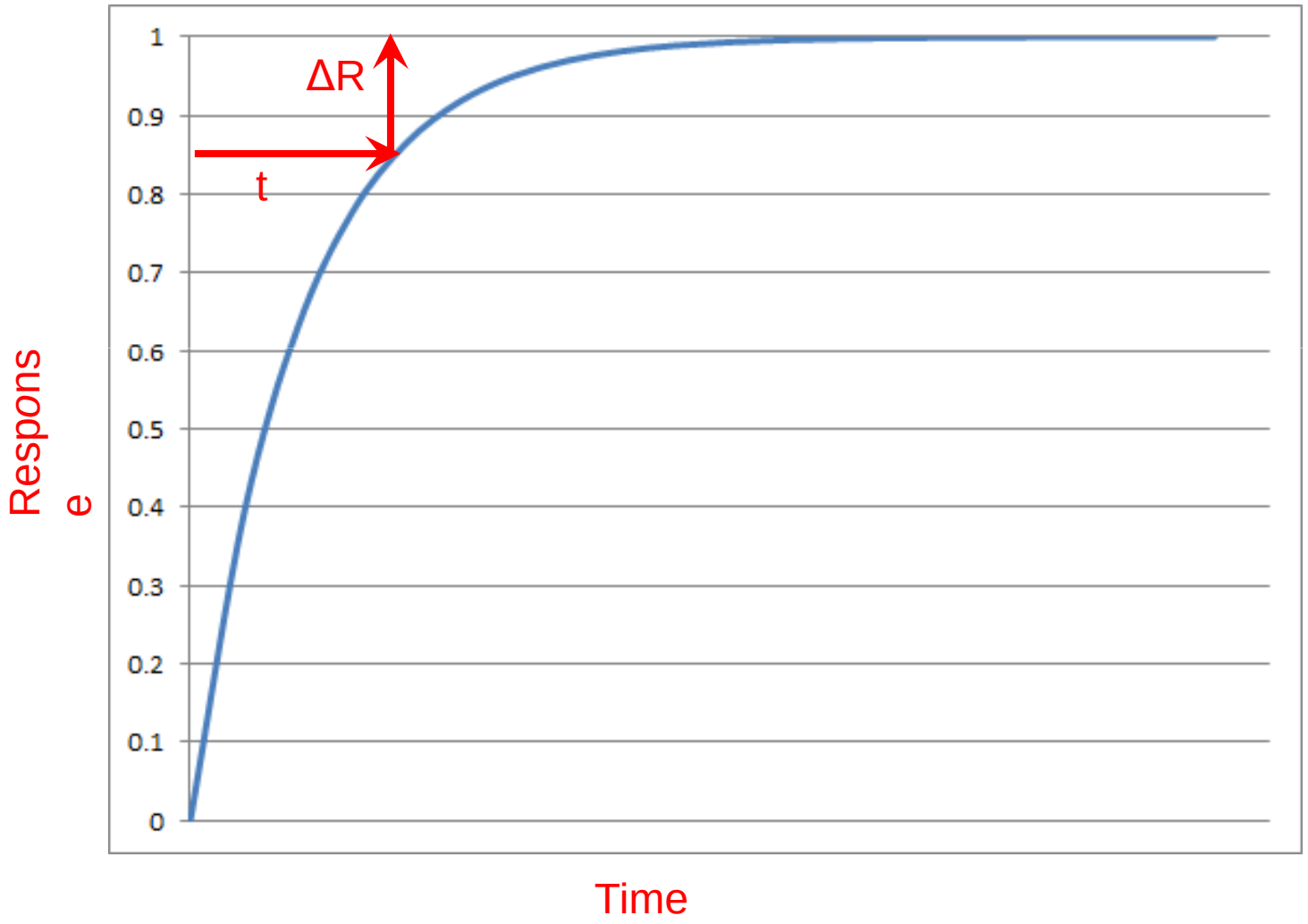
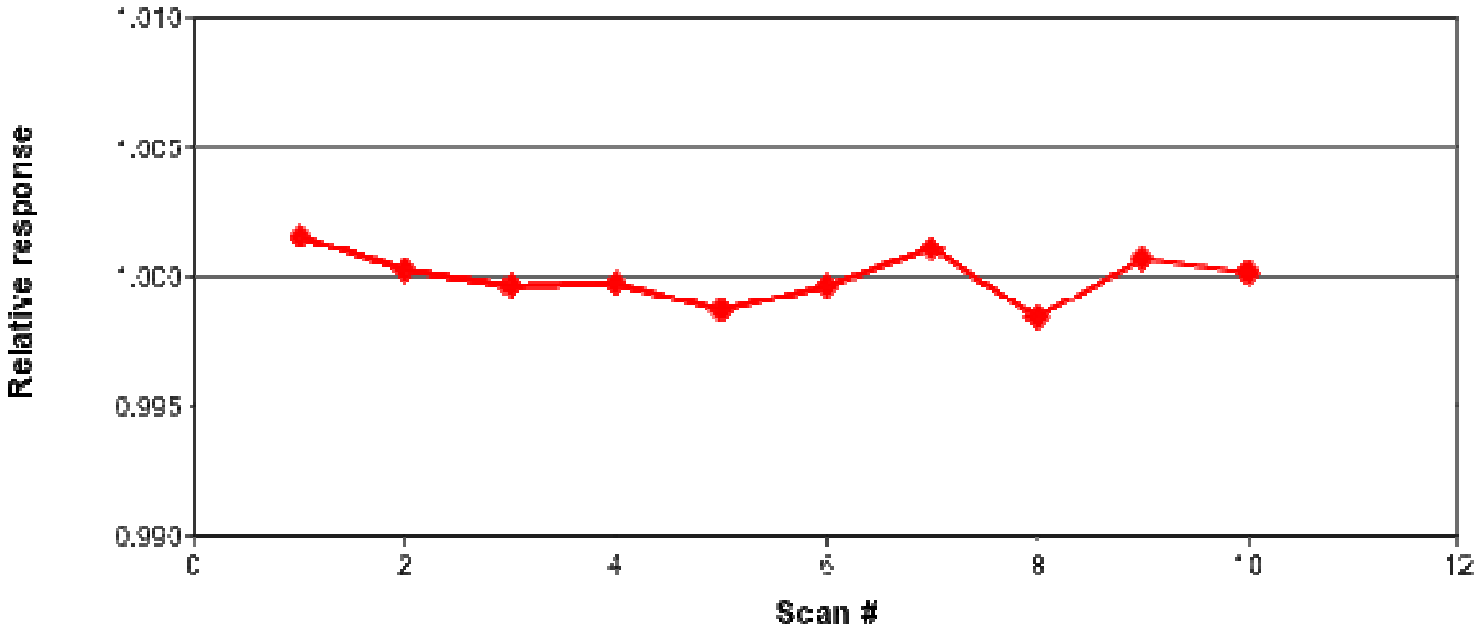
Dealing with Post-exposure Change



Typical Scan-to-scan Consistency Epson 10000XL



Standard deviation is ~0.15% of response value

“Rule of thumb” - 1% in response ≈3% in dose

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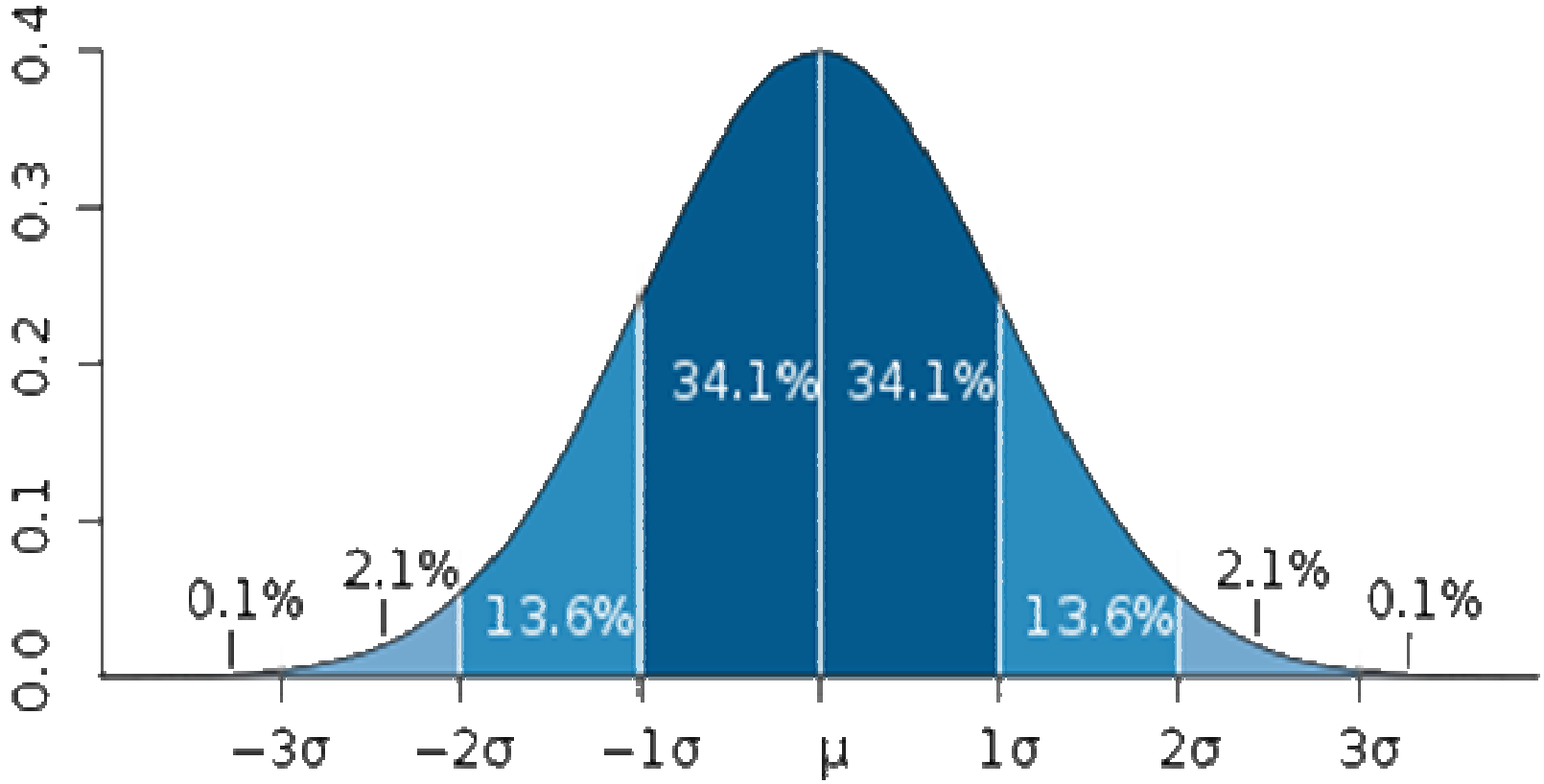
Scan-to-scan variability



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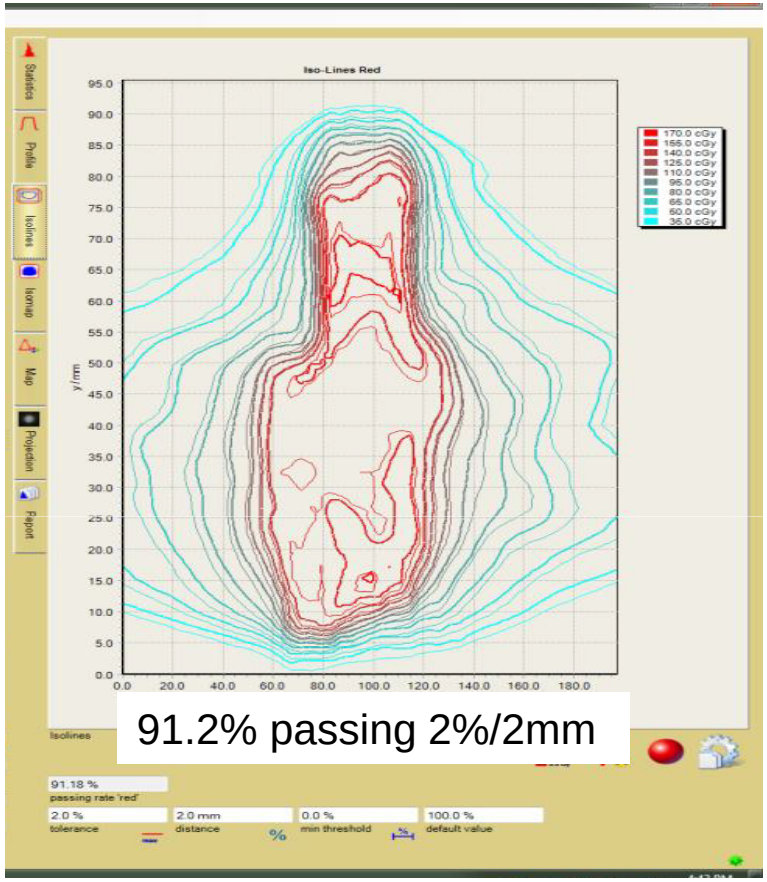
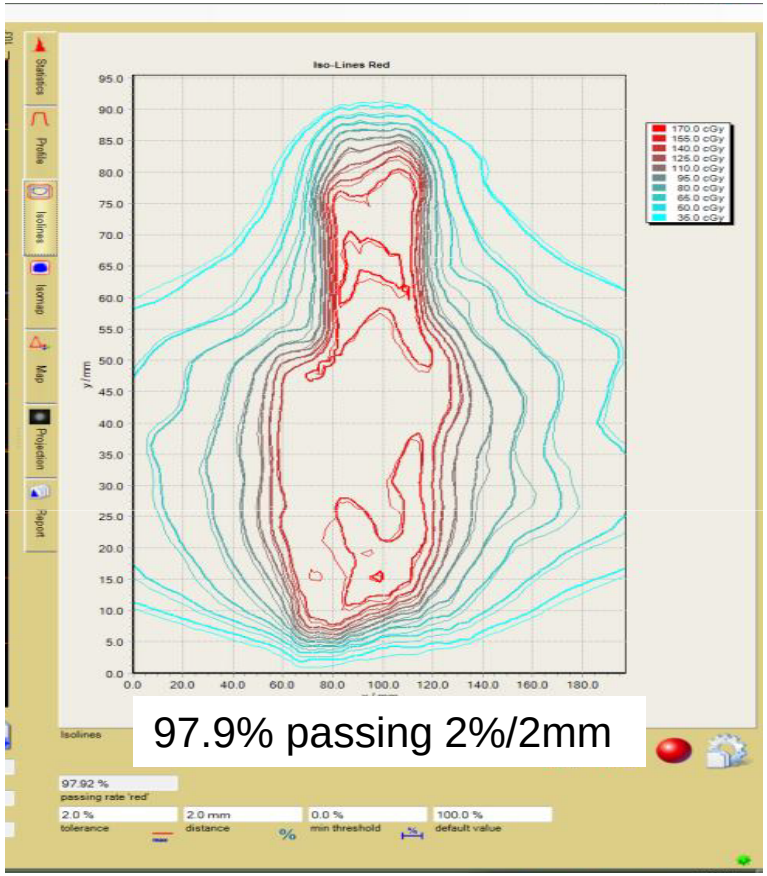
Scan-to-scan Variability



First scan



Re-scan

Use the “One-scan” protocol to eliminate scan-to-scan variability

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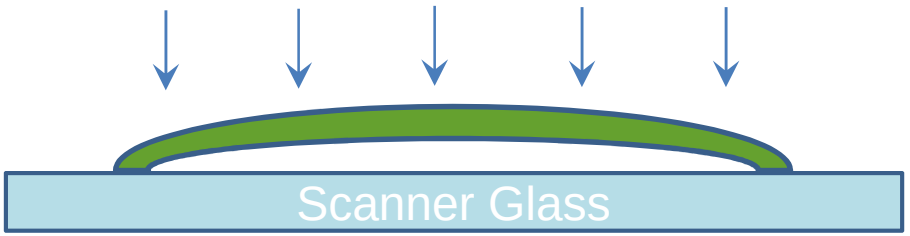
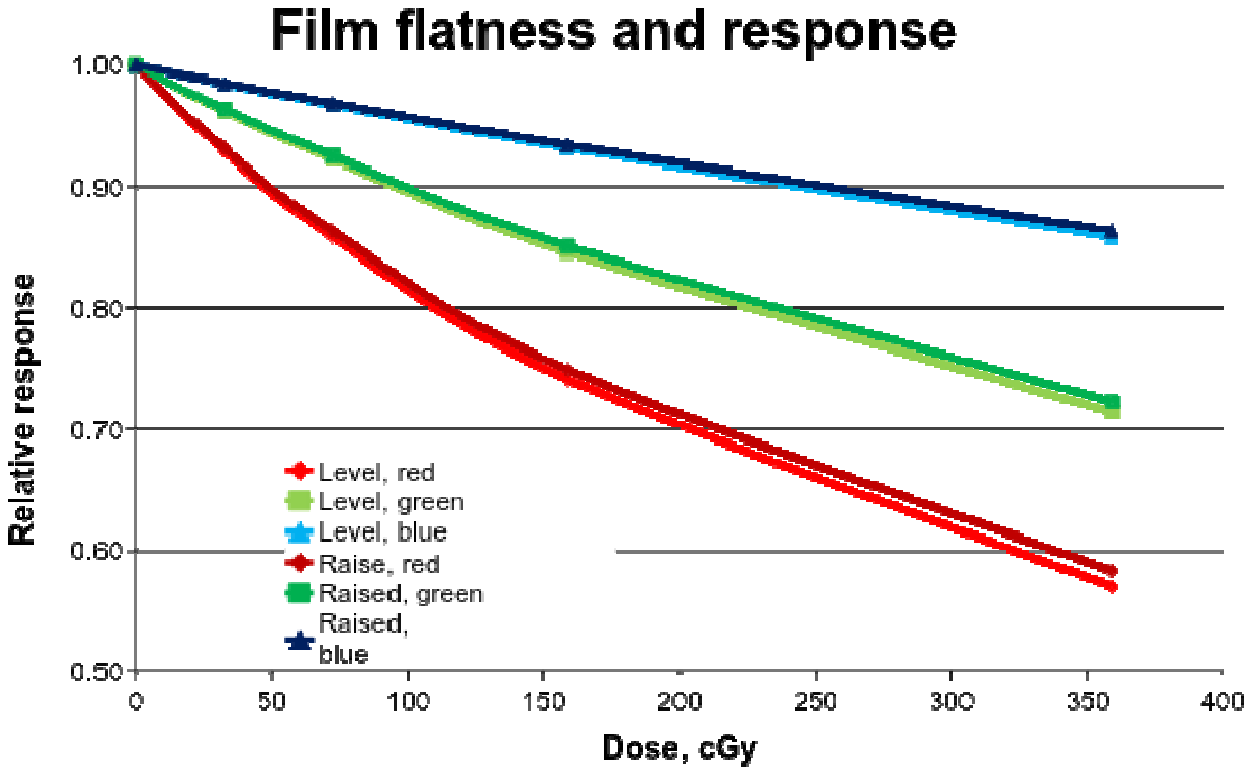
Film Flatness - the Callier Effect





Transmission changes with the distance to a diffuse light source

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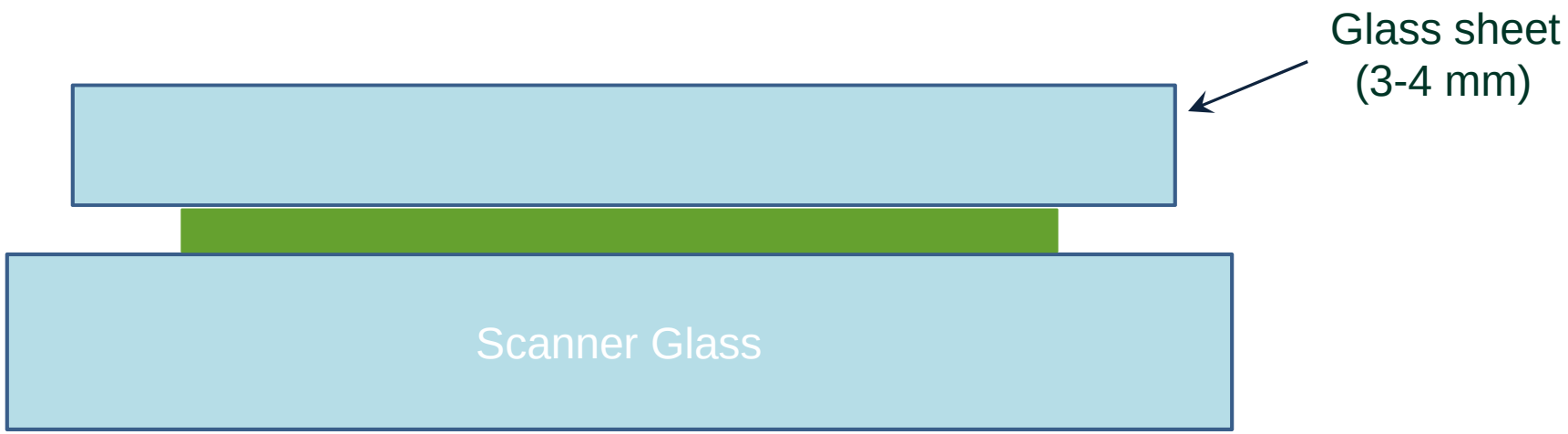
Make the Film Lie Flat



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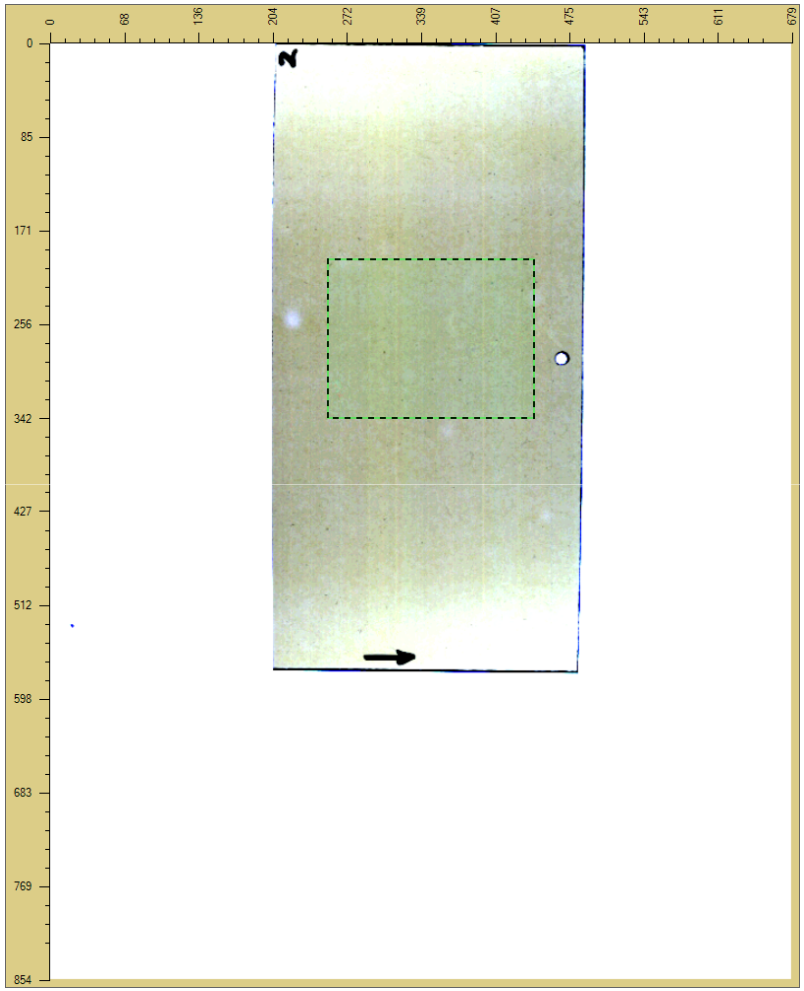
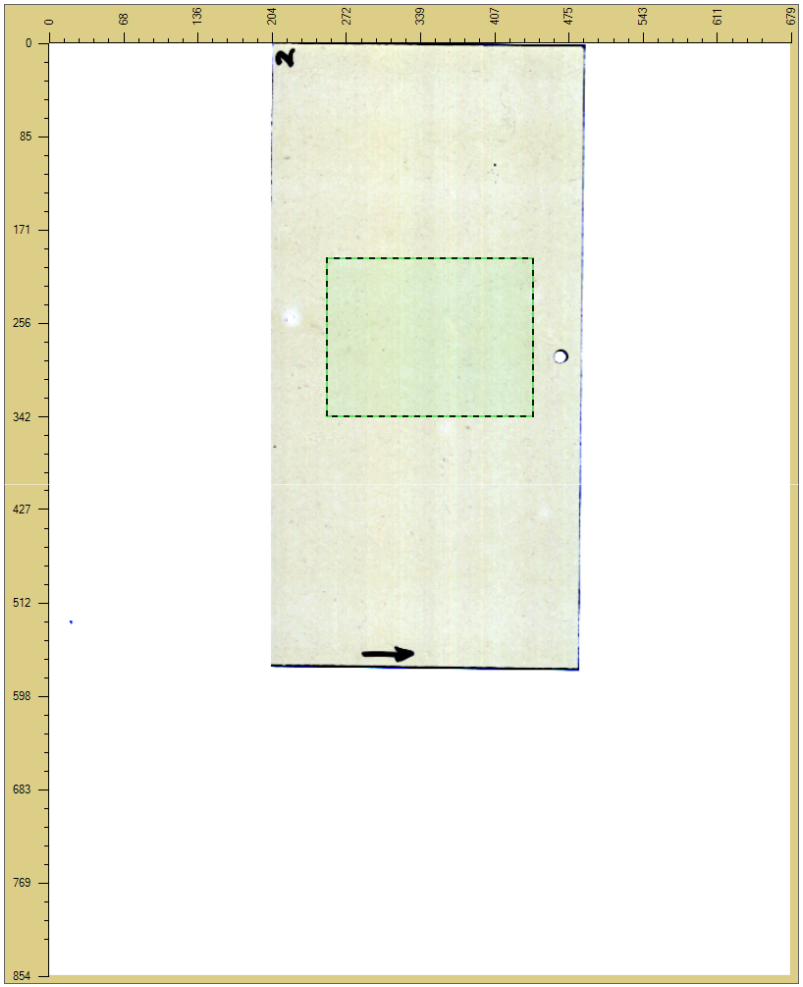
Film flatness and response uniformity





Scanner Glass

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Scanner Glass

The ‘One-scan’ Dosimetry Protocol“An Efficient Protocol for Radiochromic Film Dosimetry Combining Calibration and Measurement in a Single Scan” D. Lewis, A. Micke, X. Yu and M. F. Chan, Medical Physics 39(10) p6339-50, October 2012

David F. Lewis
Advanced Materials Group

March, 2014

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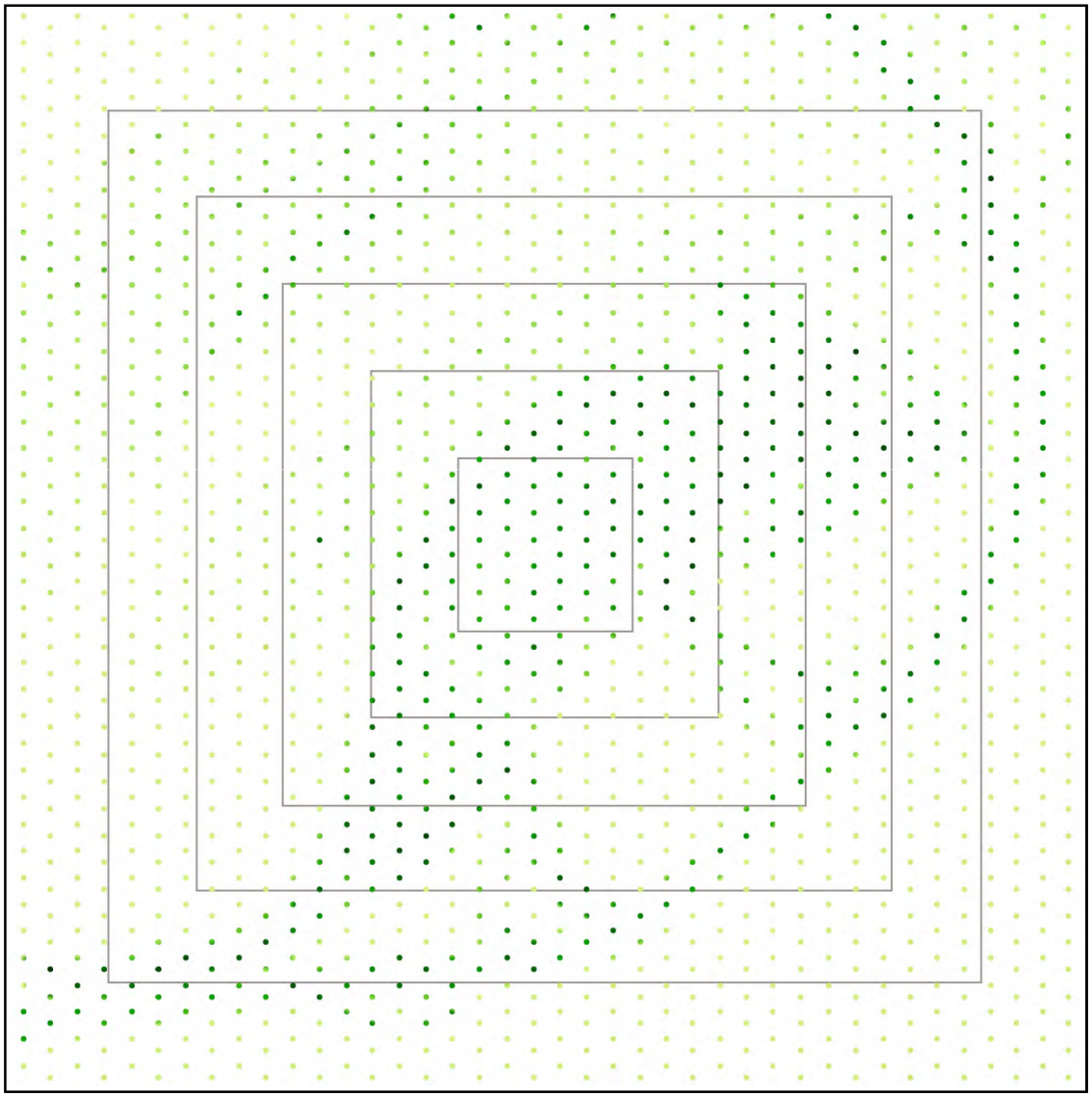
What does an array see?



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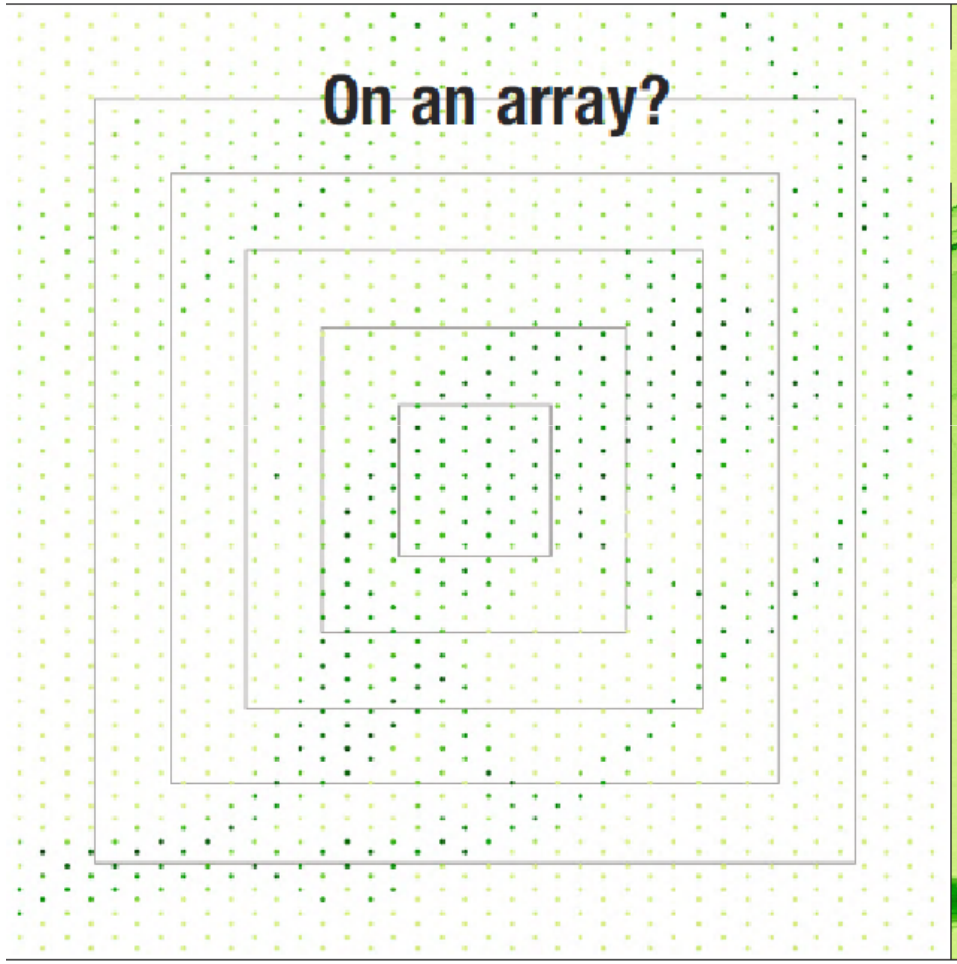
How do you capture a chameleon?



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Radiochromic Film – The Advantages

- **High spatial resolution**
- **Shoot from any angle**
- **Near water-equivalent**
- **Nearly energy independent**
- **Get the whole picture**
  - **Film provides millions of measurements**
  - **Arrays miss >99% of the area**
- **Shoot film from any angle**
  - **Shoot the whole plan on one film**
  - **Just like the patient gets it**

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Film Dosimetry – The Past

Film is a hassle.

- **Post-exposure waiting**
- Film artifacts
- Scanner artifacts
- Dos and don’ts

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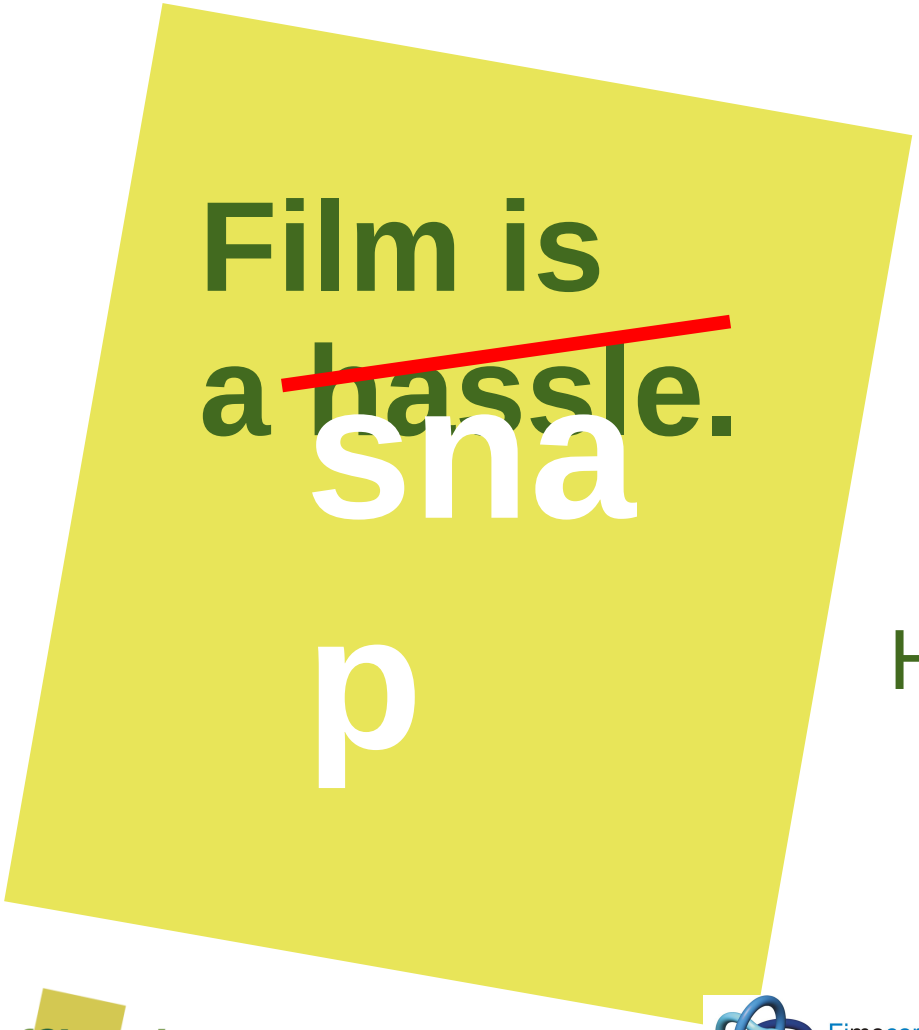
Film Dosimetry – The Present



How did we do that?

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Here's What Changed

- Simplified calibration
  - **"One-scan" calibration protocol**
  - Fitting functions that "behave" like film
  - Less films and all scanned together
- Combined measurement with calibration
  - **"One-scan" measurement protocol**
  - Every patient film scanned with reference films
  - Eliminates inter-scan variability
- Reduced post-exposure waiting to minutes

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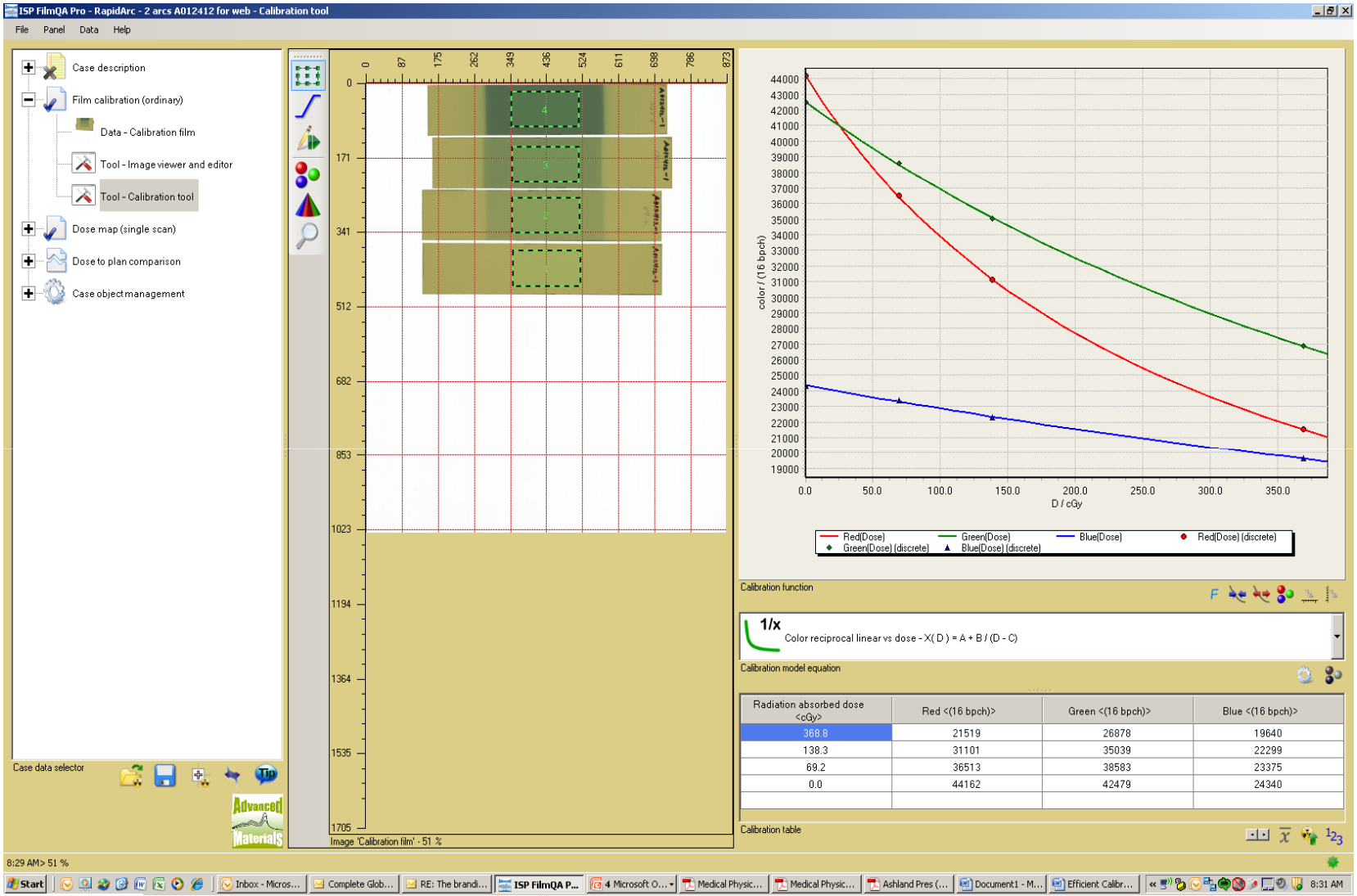
‘One-scan’ Calibration



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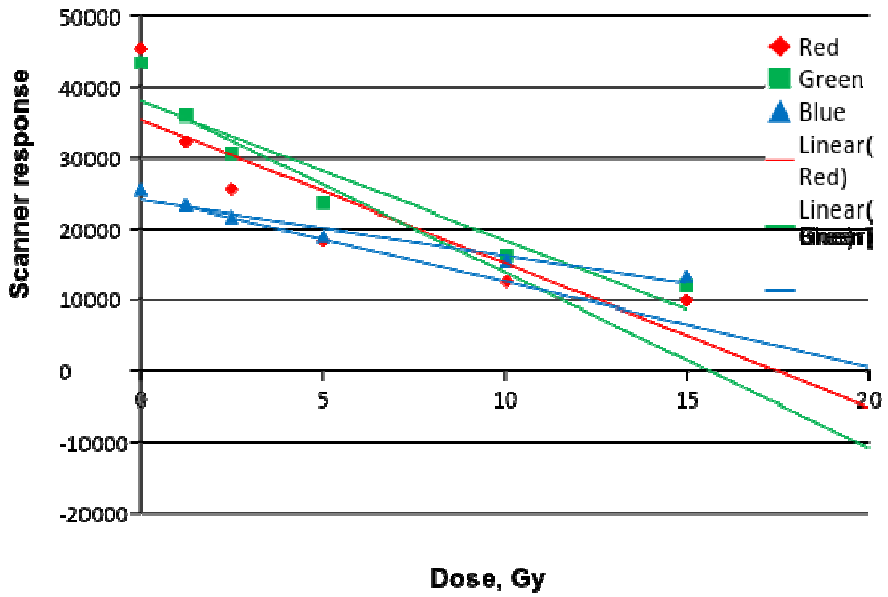
Correlating Calibration Data

Polynomial Functions

$X(D) = a_1.D^n + a_2.D^{n-1} + ... a_n.D + C$

D = dose, X(D) = response



Not consistent with core properties of film ✗

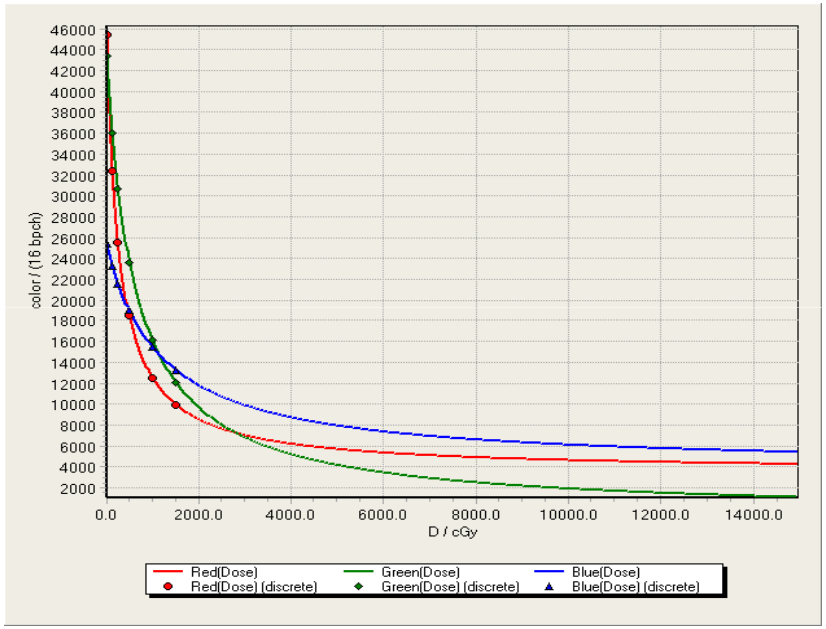
Function often oscillates between values ✗

Cannot be inverted ✗

Rational Functions

X(D)= a + b/(D-c)

D = dose; X(D) = response



"Behaves" like film ✓

Easily inverted - D = c + b/(X(D)-a) ✓

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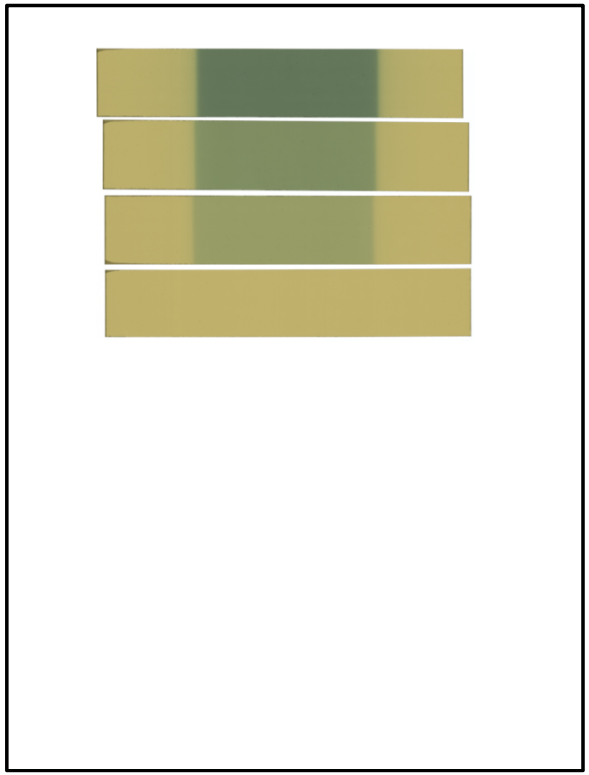
Just ‘One-scan’ for Calibration



4 strips: ~ 4x20 cm^2
10x10 cm^2 field for exposure

Don’t waste your time with too many calibration exposures

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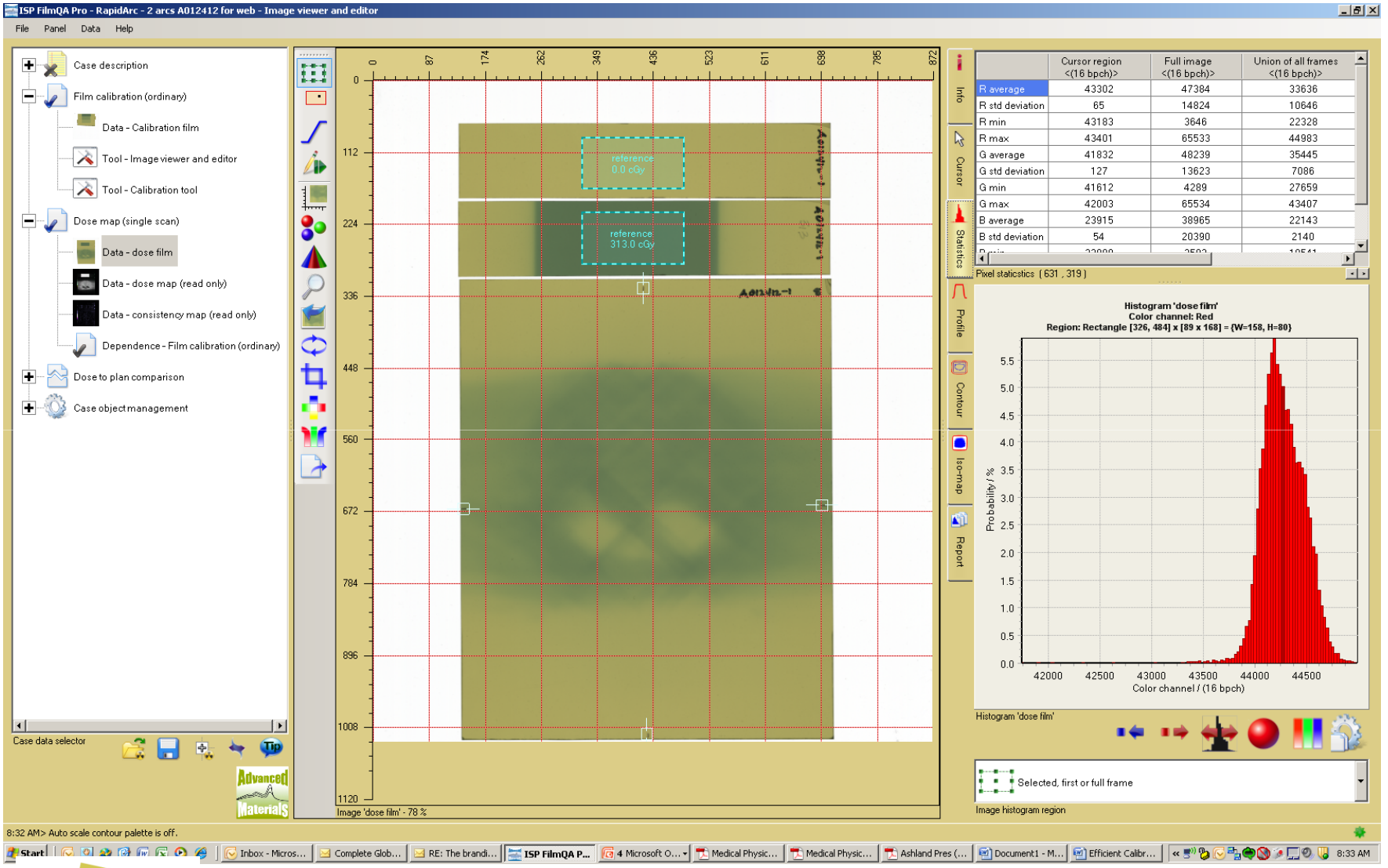
‘One-Scan’ for Measurement



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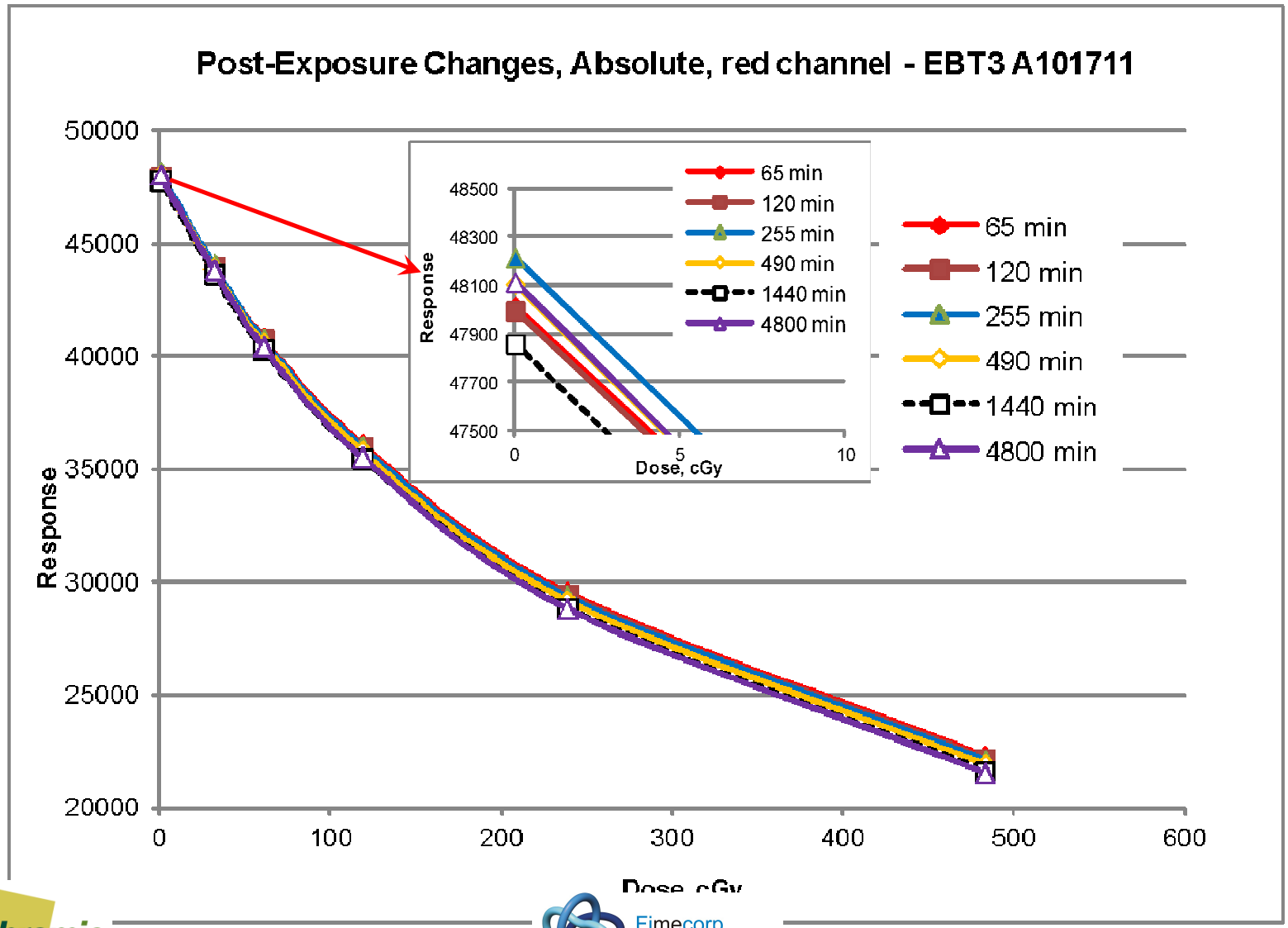
Post-Exposure Change



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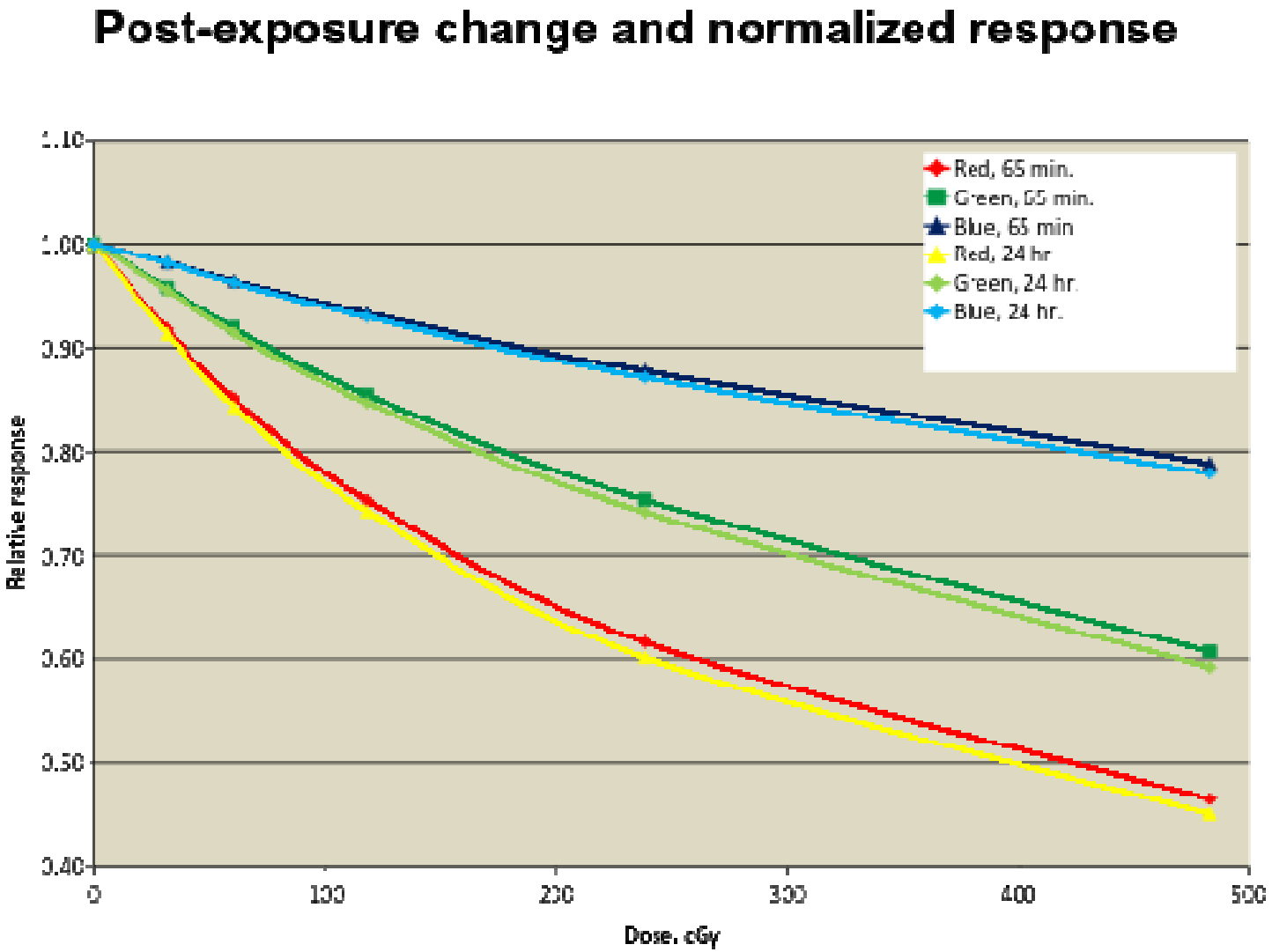
Response Normalized to Unexposed Film



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Scale the Normalized Responses

- Net response, X_{net}, - color C, dose D, time-after-exposure t:

$$X_{net}(C,D,t) = X(C,D,t) - X(C,zero,t)$$
$$= X(C,D,t) - 1$$

- For all doses:

$$X_{net}(C,t_1) = X_{net}(C,t_2) * K(C,t_1,t_2) \text{ where K is a constant}$$

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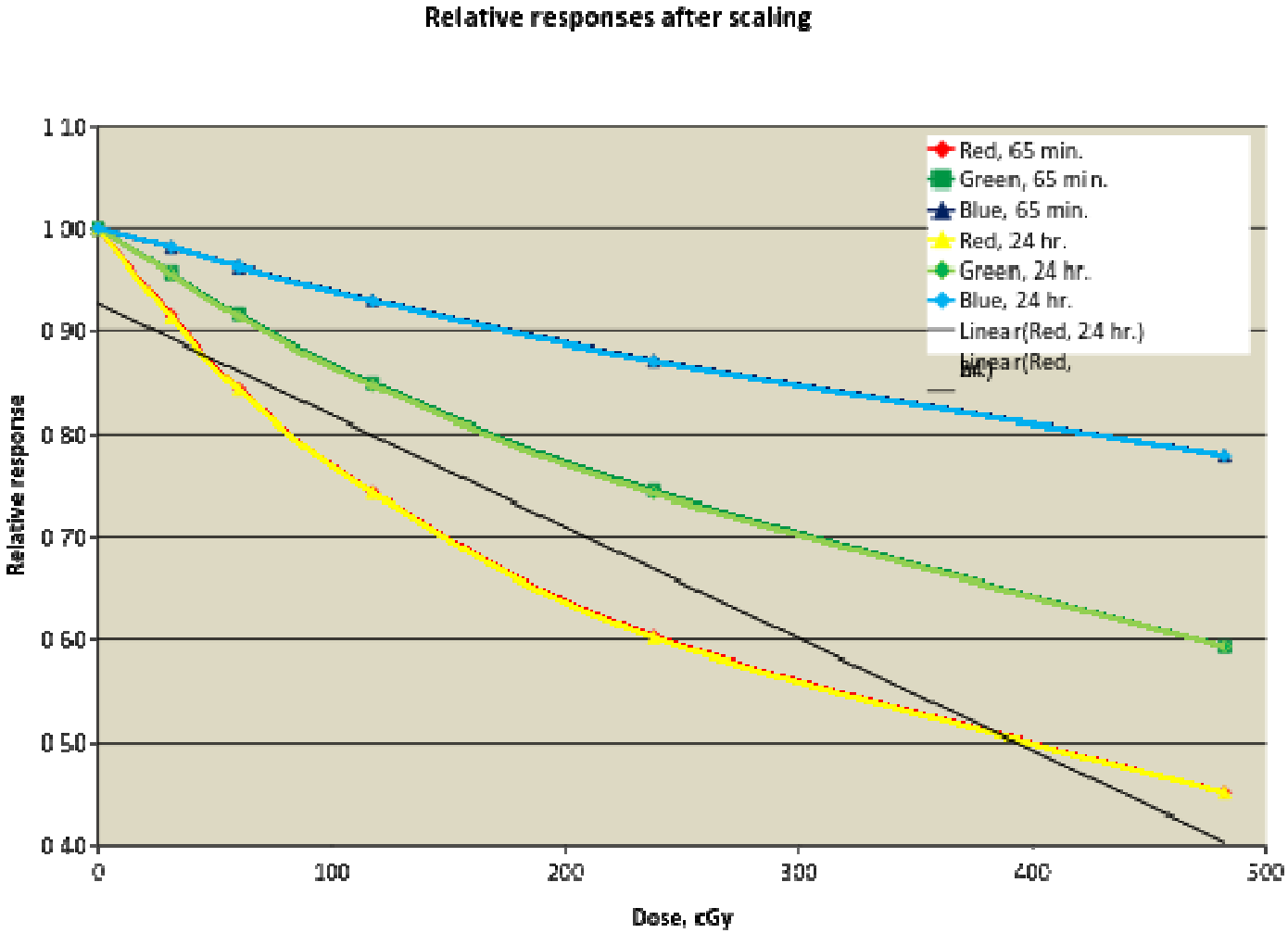
After Normalization and Scaling



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Similar Equivalences

- Different scanners (same type)
- Different models - Epson 10000XL, V700, 1680
- Different scan temperatures
- Different photon energies
- Different orientations – landscape and portrait

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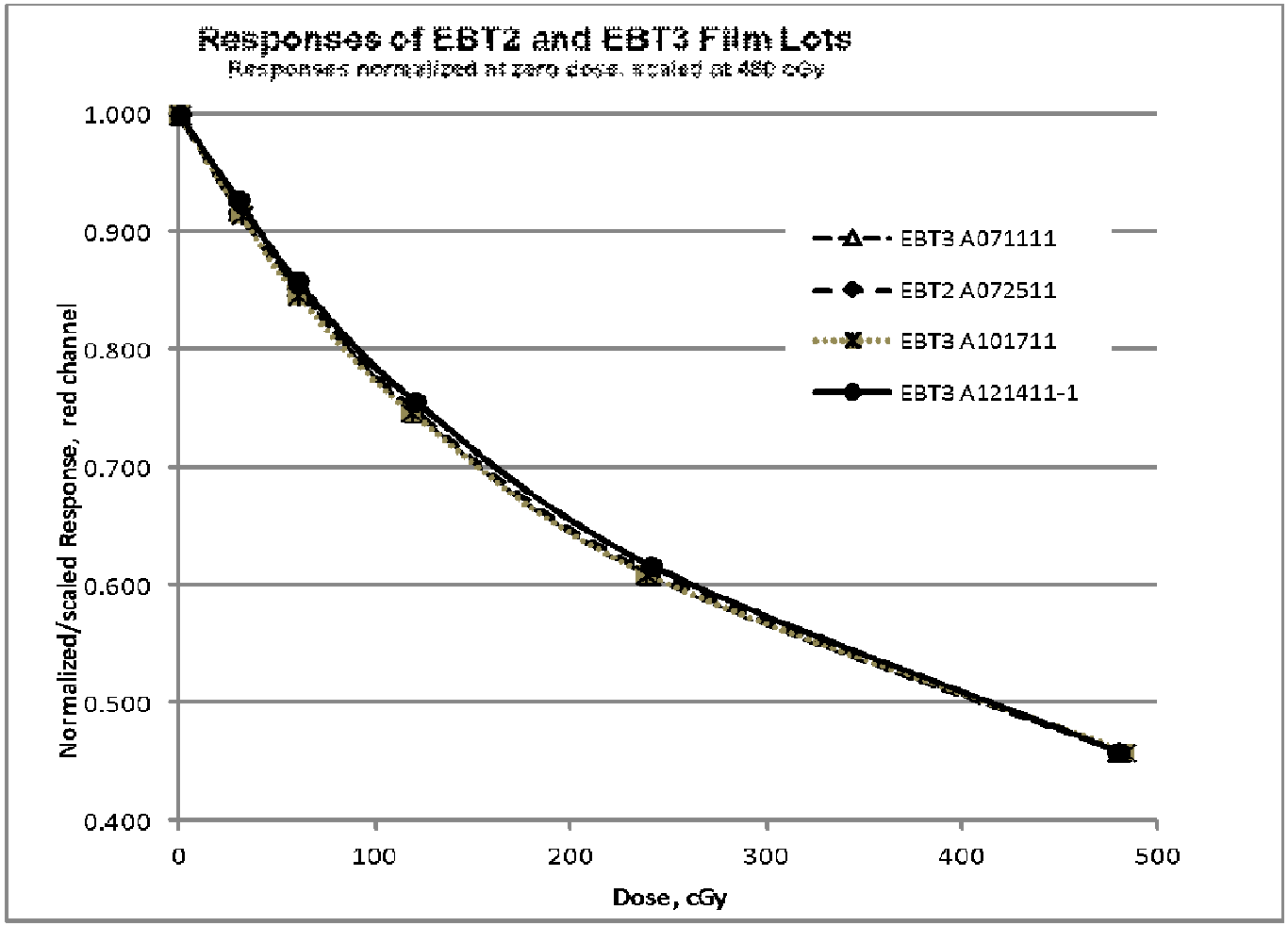
Lot-to-lot: Curves Have Different Shape



Requires three-point re-scaling, i.e. re-calibration

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Dosimetry with Two-point Re-scaling

- Set up and expose the measurement film
- Expose a reference film (same lot) ~80-100% D_{max}
- Scan measurement film, reference film and an unexposed reference film together
- Use the reference films to re-scale calibration

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Benefit of Re-Scaling

- Permits scanning a few minutes after exposure
- Eliminates scan-to-scan variability
  - Repeatability
    - Scan-to-scan response occasionally varies >0.5%
    - 0.5% change in response maps to about 1.5% in dose
  - Temperature
    - About 0.1% response change per °C
    - Maps to about 0.3% in dose per °C

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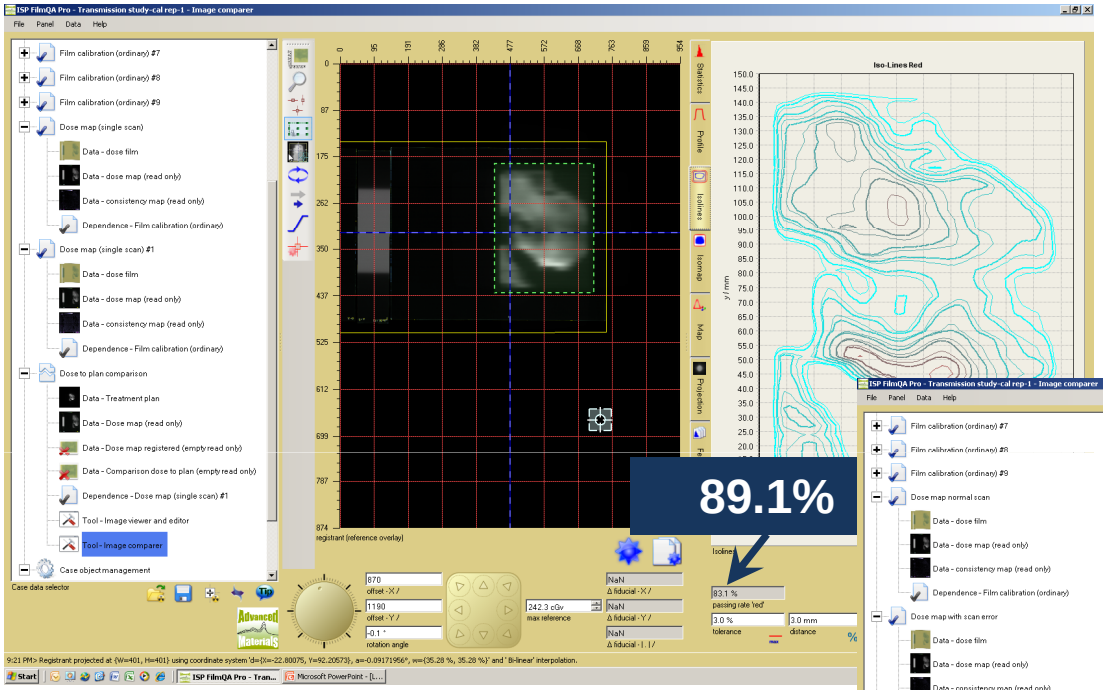
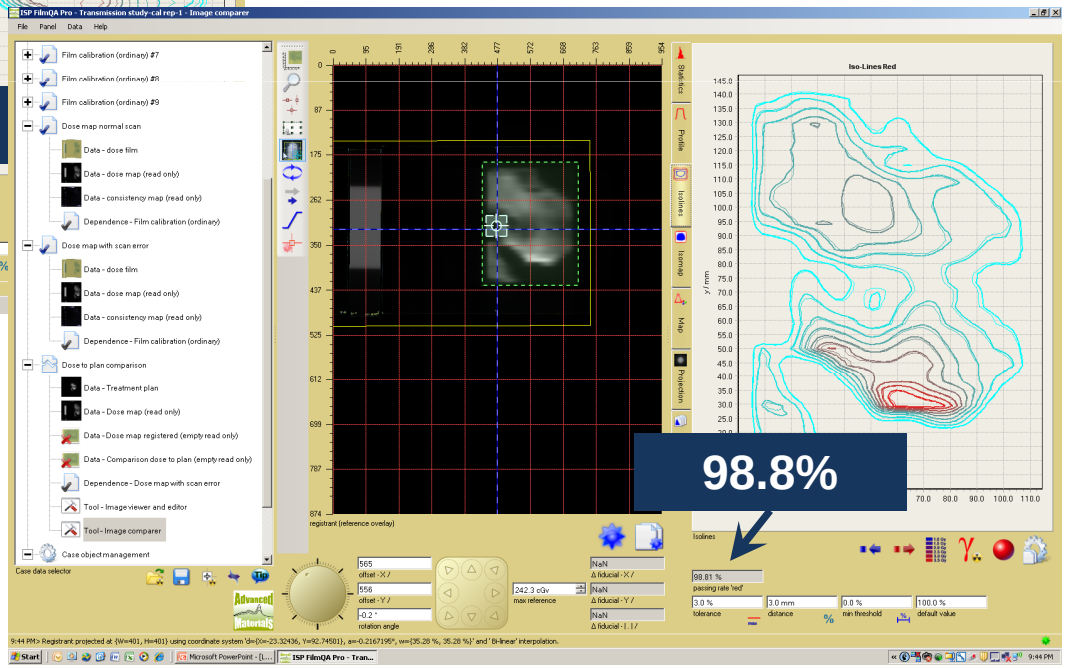
Response Variability may Impact Results

Without reference films



With reference films



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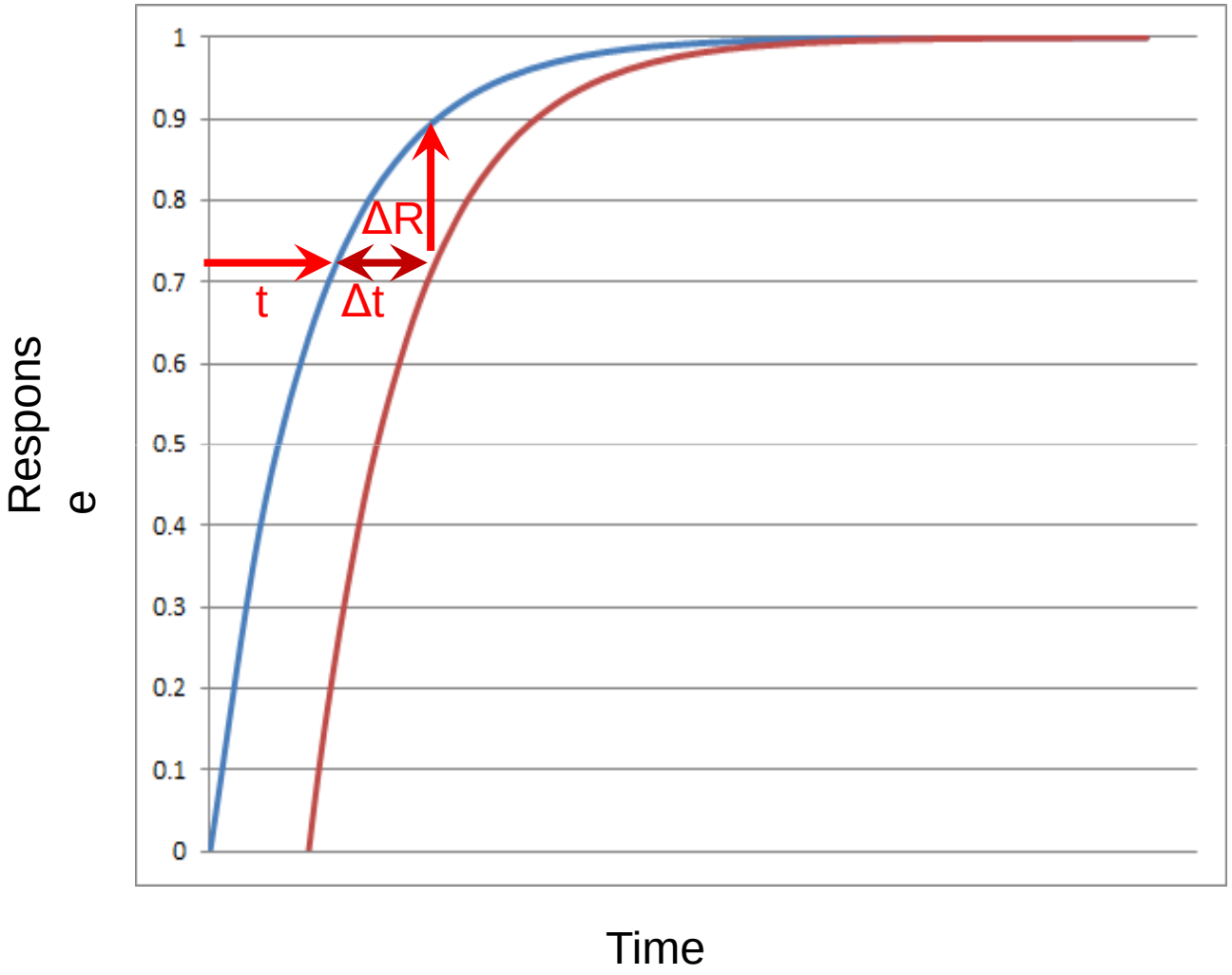
Accommodate post-exposure change - Use relative aging



When t >2.Δt the dose error <1%

“One-scan” Results

Time after exposure, minutes	Calculated dose, cGy (calibration at 2hr. post-exposure; scaling at 0 and 482.3 cGy)					
	Step 1	Step2	Step 3	Step4	Step 5	Step 6
60	0.4	30.9	61.4	118.6	233.7	482.3
120	0.4	30.9	61.3	118.5	233.7	482.3
255	0.5	31.1	61.7	118.7	233.8	482.3
490	0.4	31.0	61.5	118.3	233.6	482.3
1440	0.5	30.9	61.3	116.8	233.4	482.3
4800	0.5	30.9	61.3	116.8	233.2	482.3

- Calibration films scanned at various times after exposure
- Use a calibration function for film scanned at 2 hours
- Calculate dose maps using two-point re-scaling

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‘One-scan’ Protocol - Summary

- Scan patient and reference films together
  - Avoid inter-scan variability
  - Adapt measurements to calibration
- Dose accuracy better than 1%
  - Sharper assessment of treatment plan
- Post-exposure timing rules relaxed
  - Measure in minutes not hours
  - No concern whether an old calibration is still valid
- Minimizes number of films, exposures and scans

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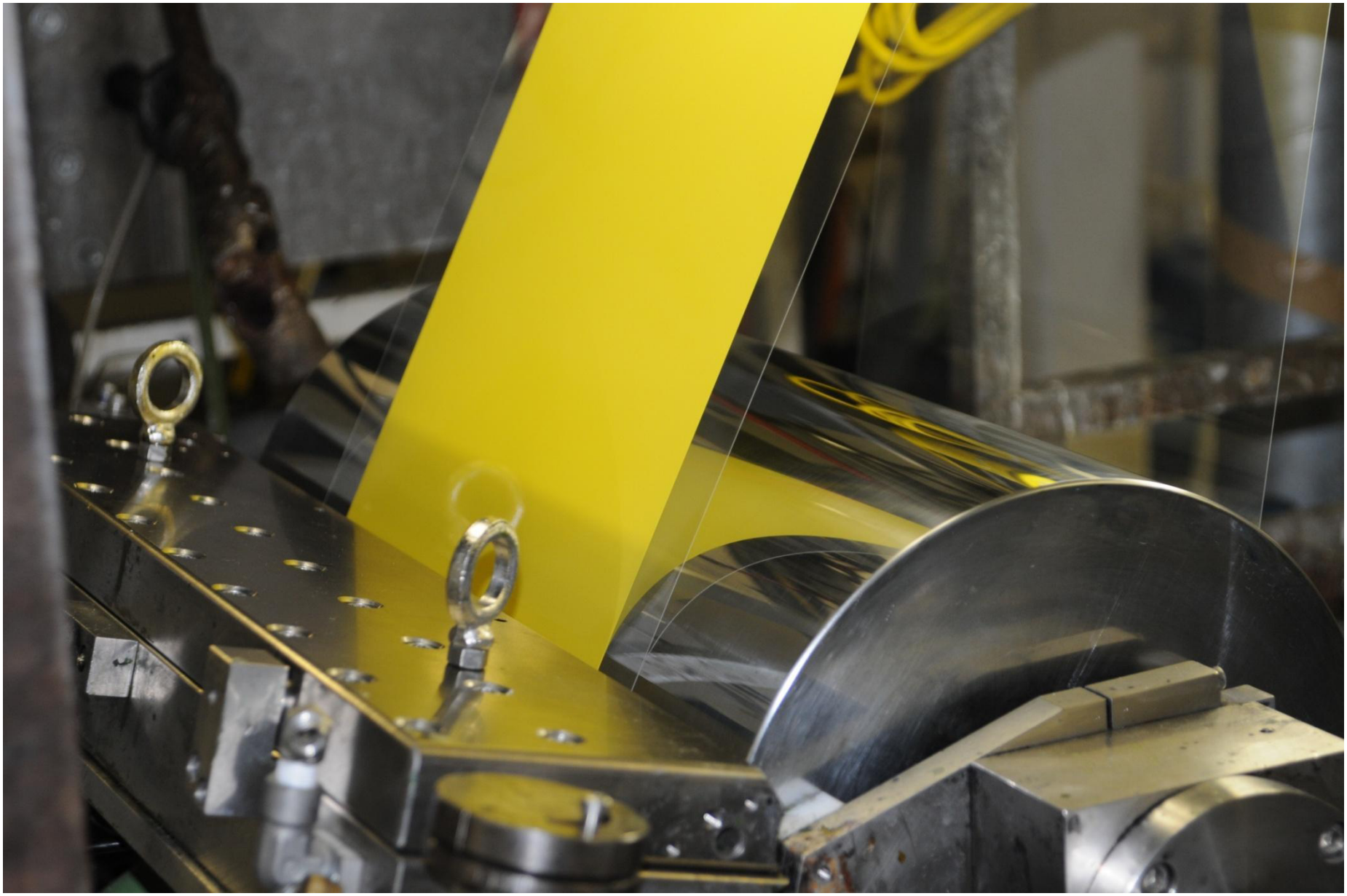
Coating Radiochromic Films



So tell me, why is that film yellow?

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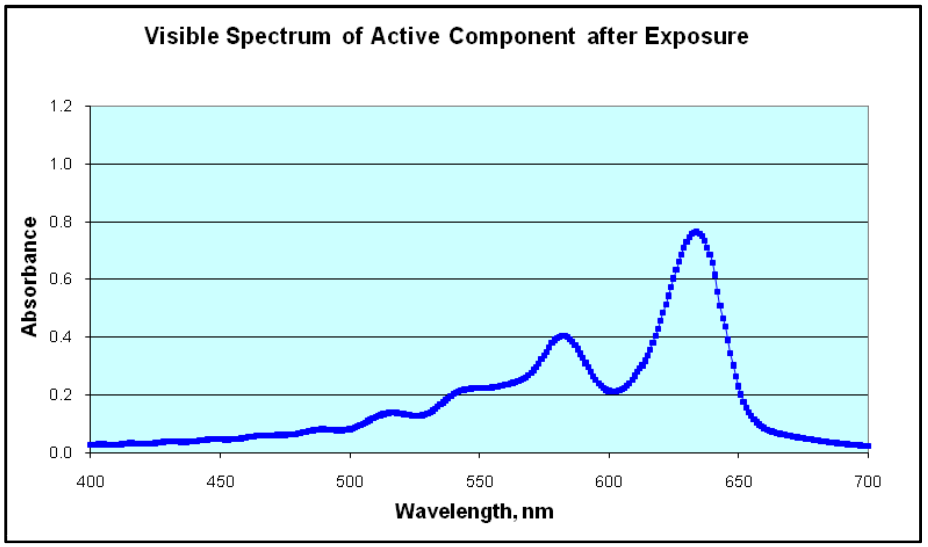
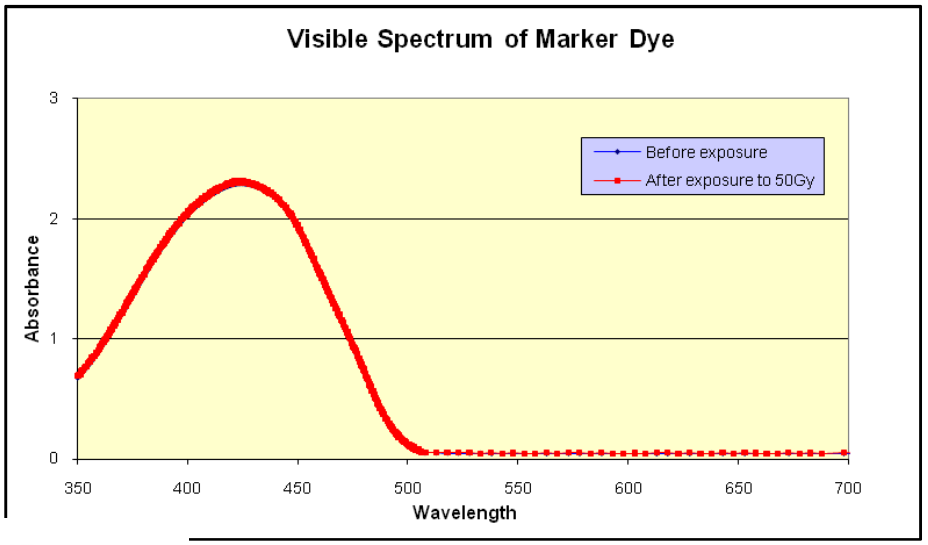
Visible Spectra – EBT2, EBT3 and EBT3+

- Active component
  - Red/green wavelengths
  - Mainly dose information



- Marker dye
  - Blue wavelengths
  - Mainly thickness information



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With multi-channel dosimetry and FilmQAPro 3.0 software

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The future is film

The Calibration Function

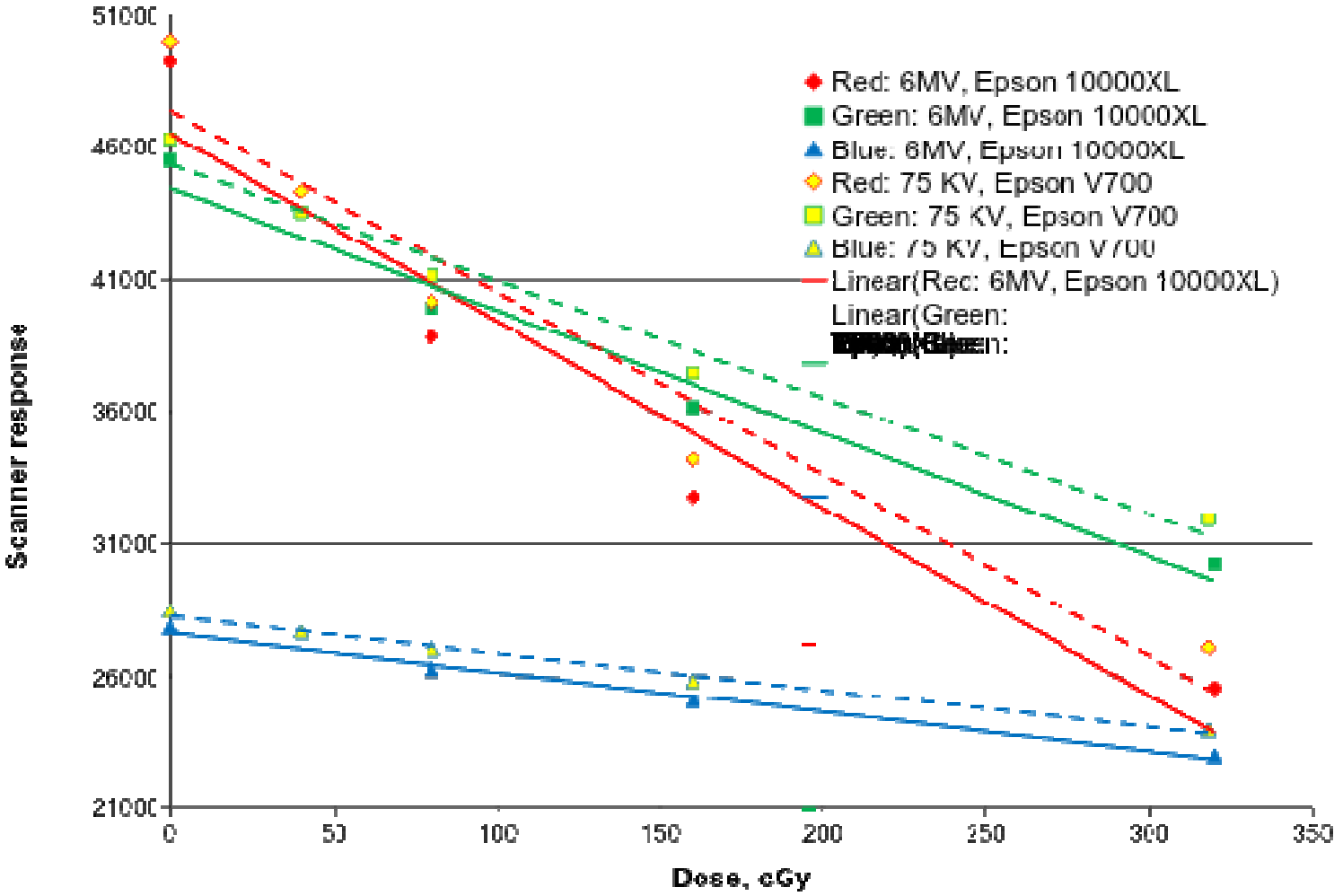
- Make your own measurements

or explore a new direction

- Use a public calibration function
  - Same film lot
  - Epson scanner
  - “One-scan” measurement protocol and reference films

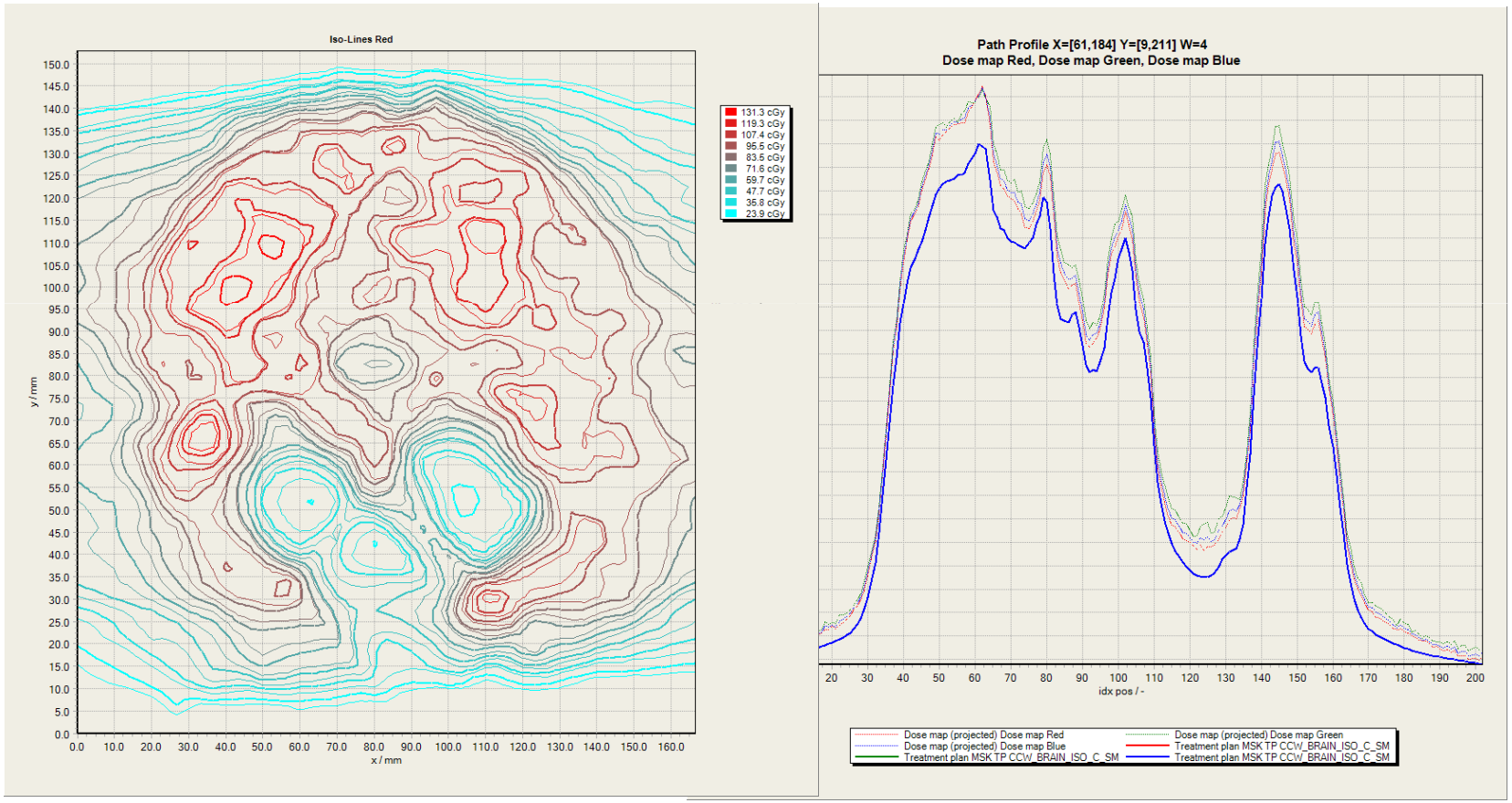
- Public calibration function
  - Acquired on any Epson scanner
  - Need not use the same radiation source
  - Need not be for the same post-exposure time

Calibration under Different Conditions



Dose calculation without reference films

Public calibration function: 75 KV photons scanned on Epson V700
Your measurements: 6MV photons scanned on Epson 10000XL



Gamma test (2%/2mm): 36% agreement measurement-to-plan

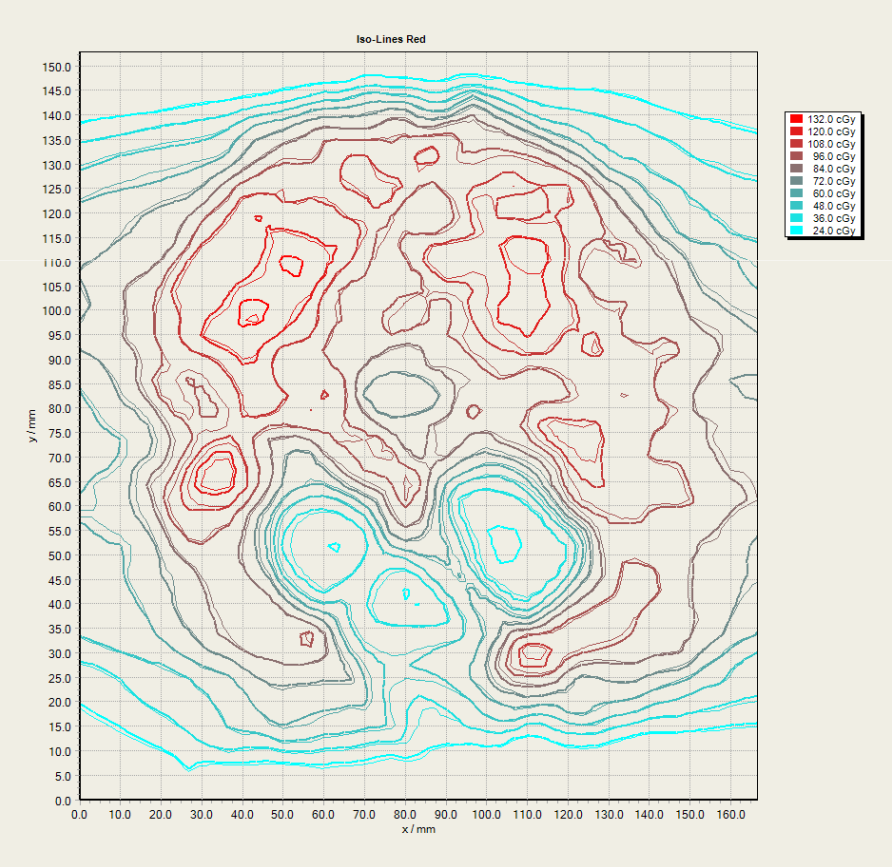
Public function with reference films

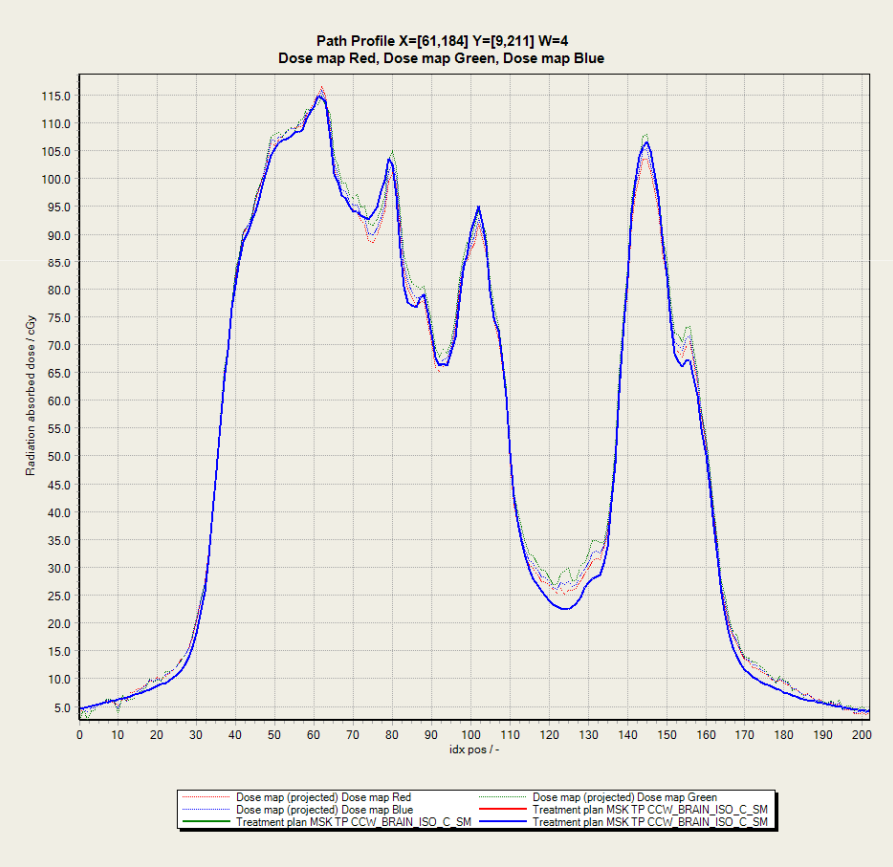
Public calibration function: 75 KV photons scanned on Epson V700

Your measurements: 6MV photons scanned on Epson 10000XL

and

Your reference film: 6MV photons scanned on Epson 10000XL

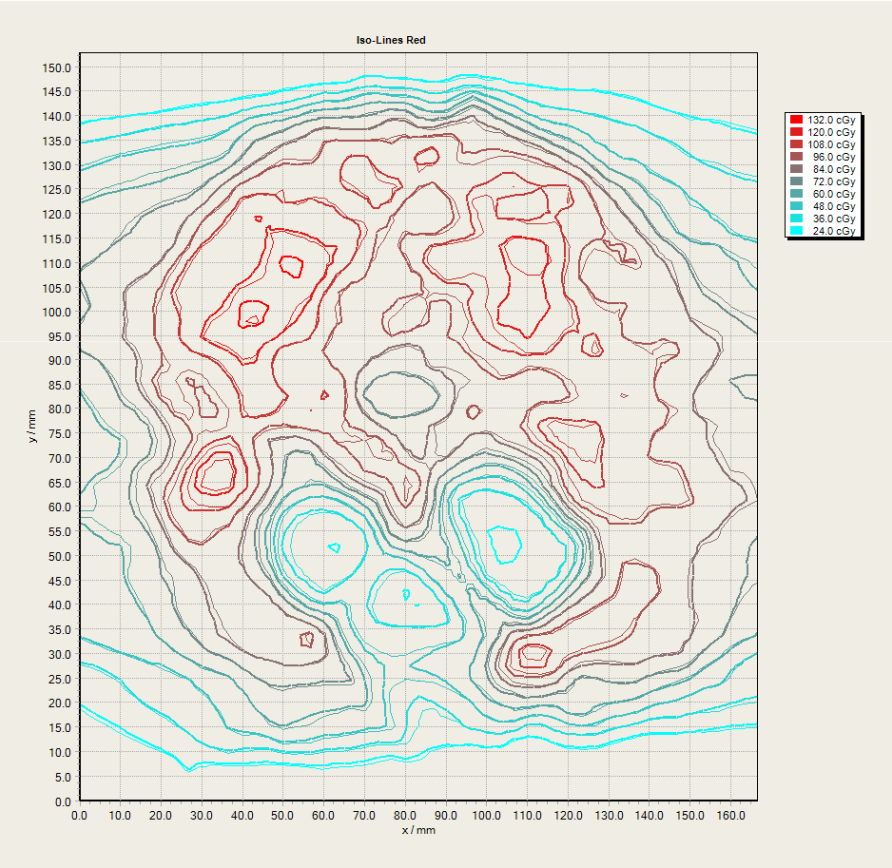


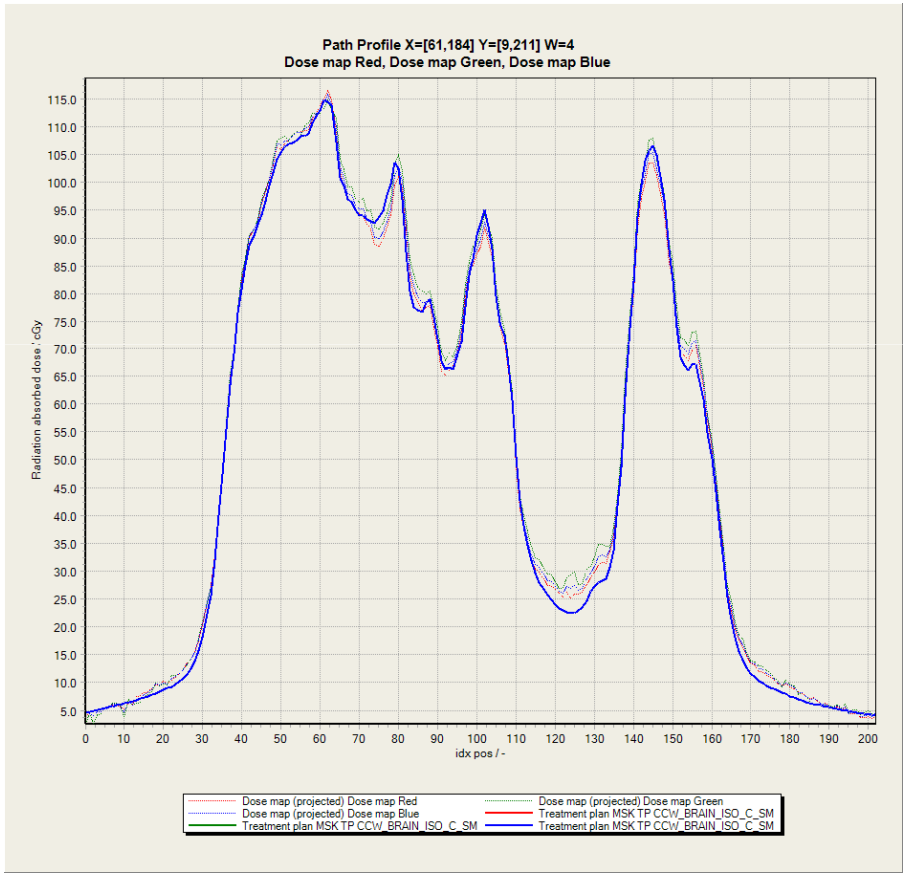


Gamma test (2%/2mm): 96.6% agreement

Customized calibration using reference films

Your calibration function: 6MV KV photons scanned on Epson 10000XL
Your measurements: 6MV photons scanned on Epson 10000XL





Gamma test (2%/2mm): 96.7% agreement

Quantitative Results – IMRT Plan vs. Time

Time after exposure		Gamma % passing for 2%@2mm		
Calibration	Patient film and reference	Red	Green	Blue
2 hr	30 min.	97.9	97.0	97.6
2 hr	60 min.	97.6	96.2	97.3
2 hr	4 hr	97.7	96.3	97.3
2 hr	24 hr	97.9	97.0	97.8
2 hr	72 hr	97.9	97.6	97.9

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