

A Guide to Radiochromic Film Dosimetry with EBT2 and EBT3

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Advanced Materials Group
Ashland Specialty Ingredients

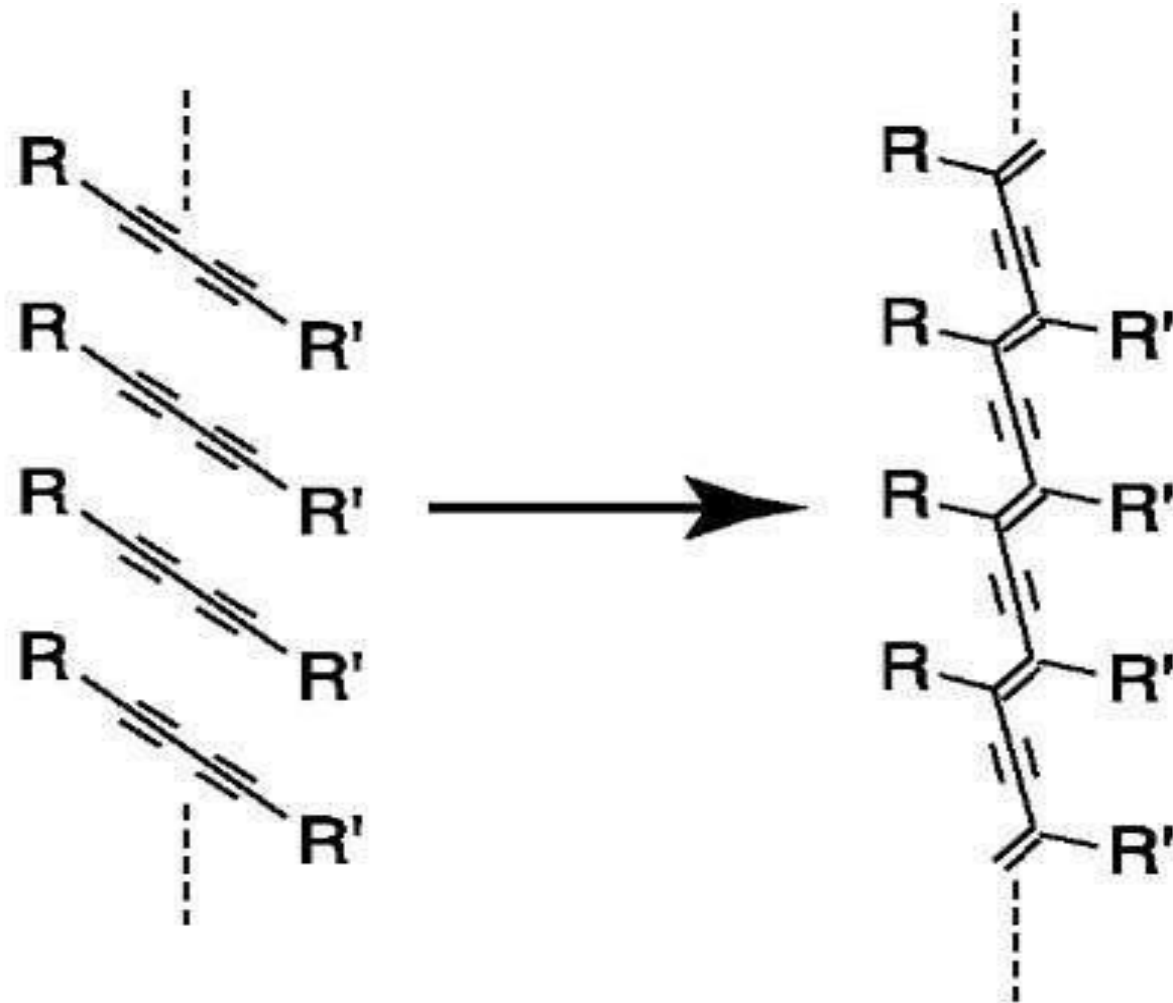
Spain, April 2014



What is Radiochromic Film?

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

Core Technology

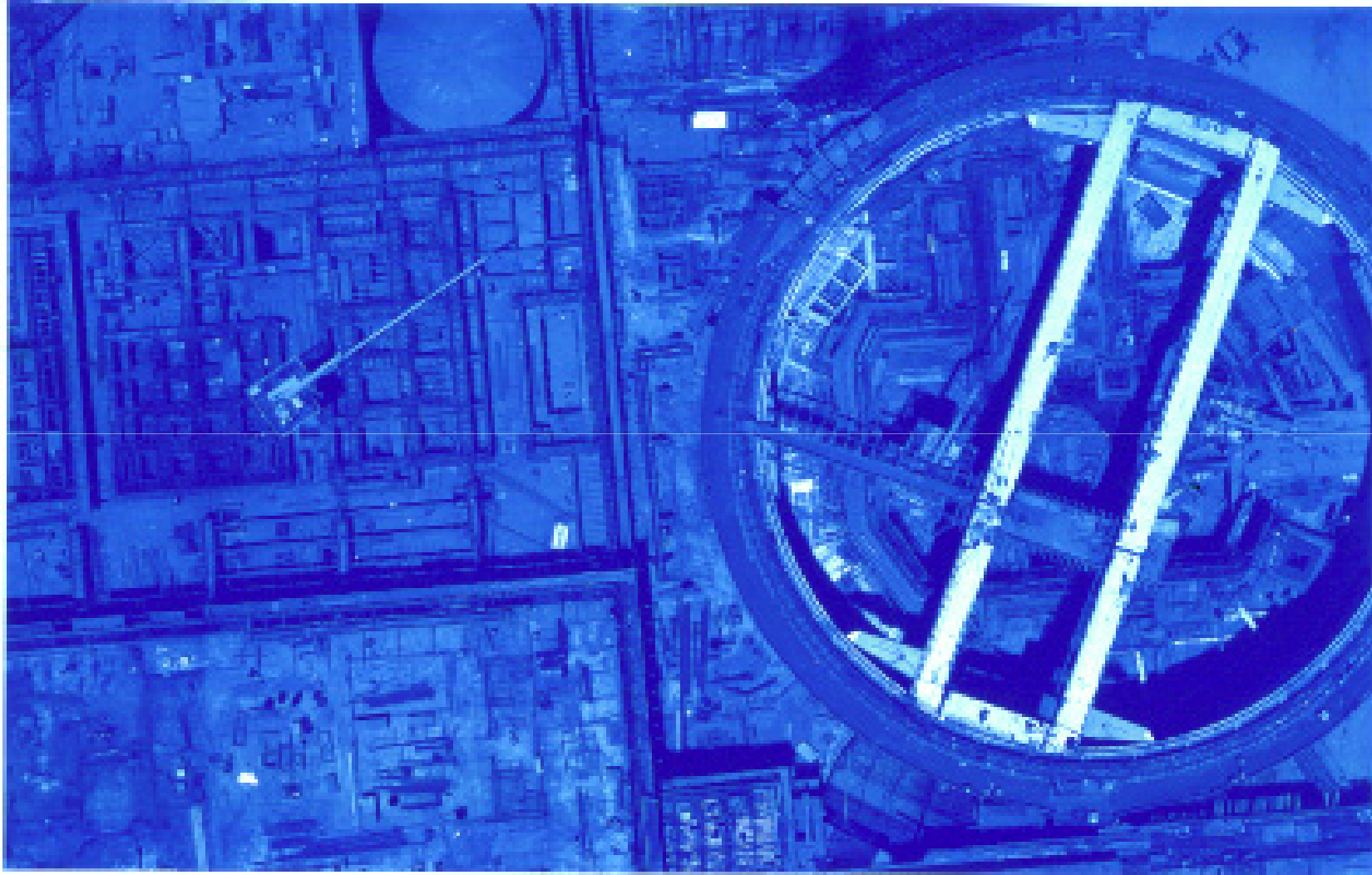


Colorless monomer

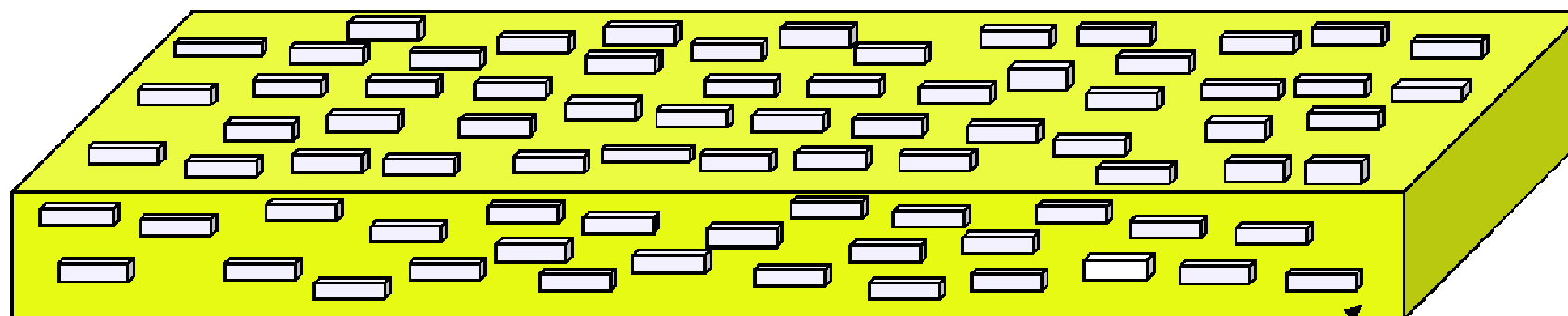
Colored polymer



1988 - Processless Electron Recording Media



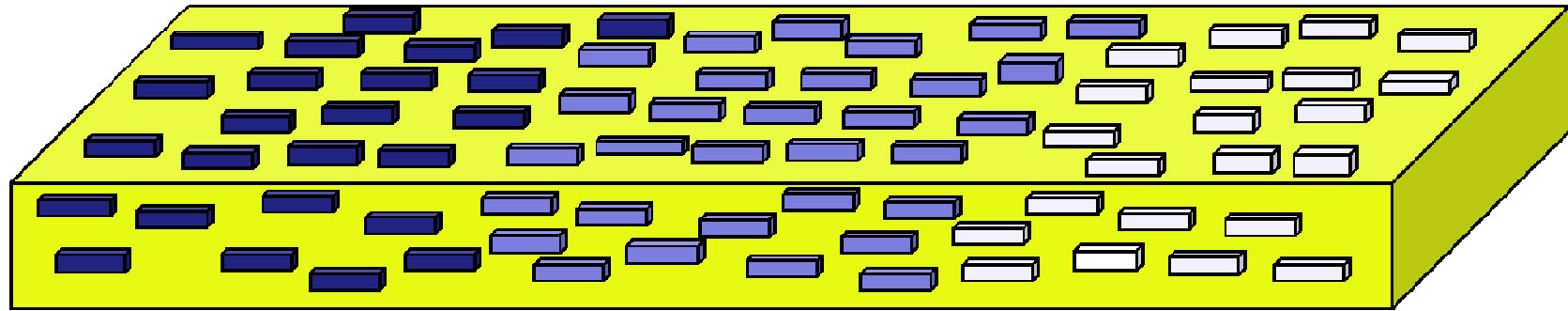
EBT2/EBT3 Dosimetry Film: Active Layer



Polymer matrix with yellow marker dye

 Crystalline diactylene monomer

EBT2/EBT3 Dosimetry Film: Exposure



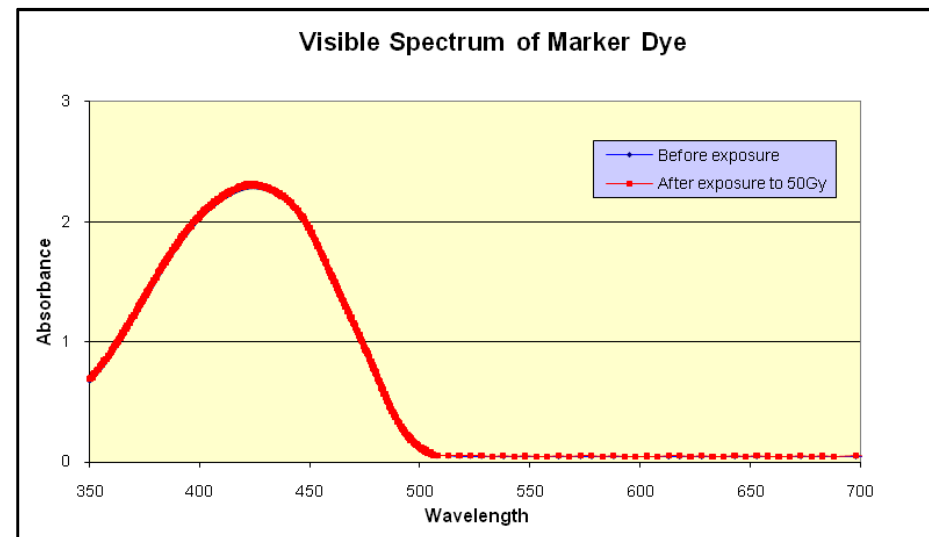
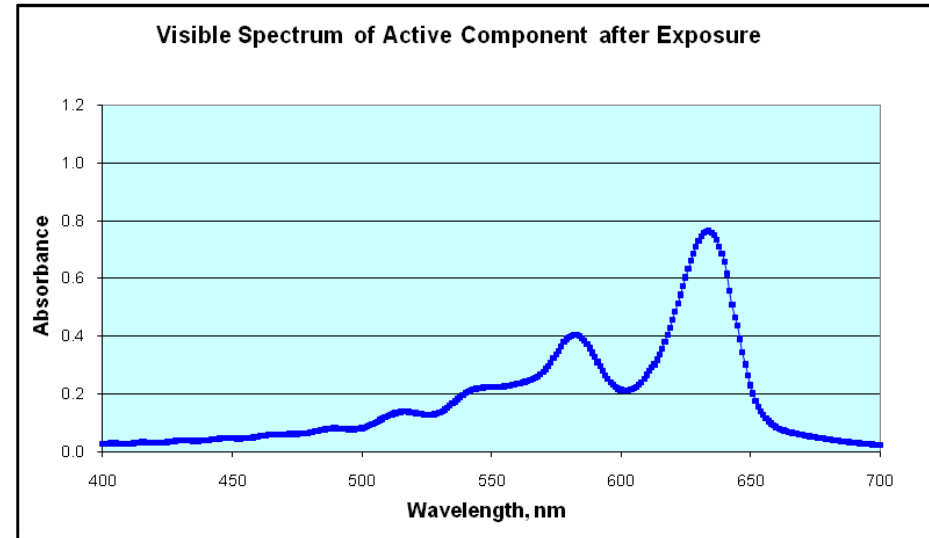
 High exposure

 Low exposure

Light transmission proportional to dose

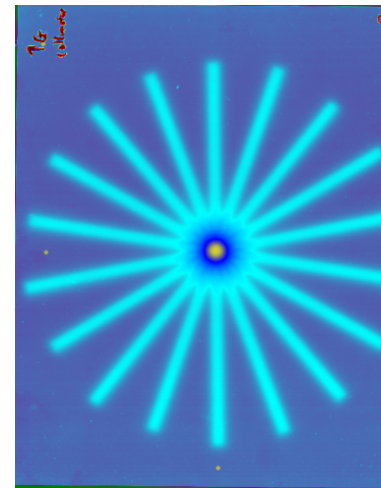
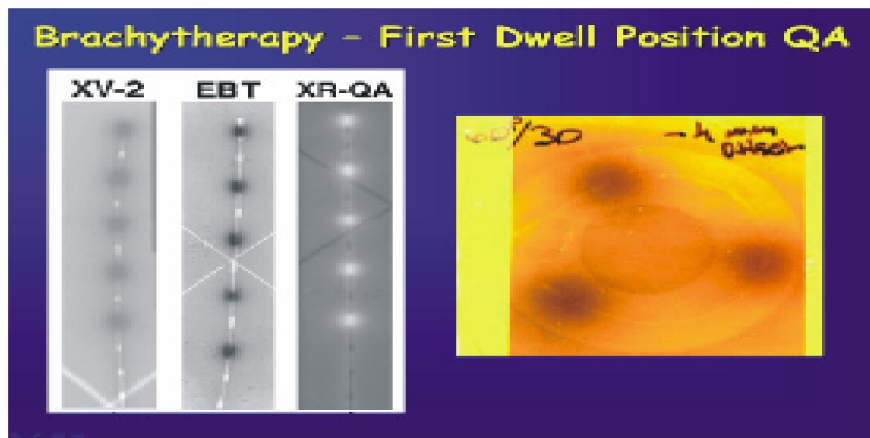
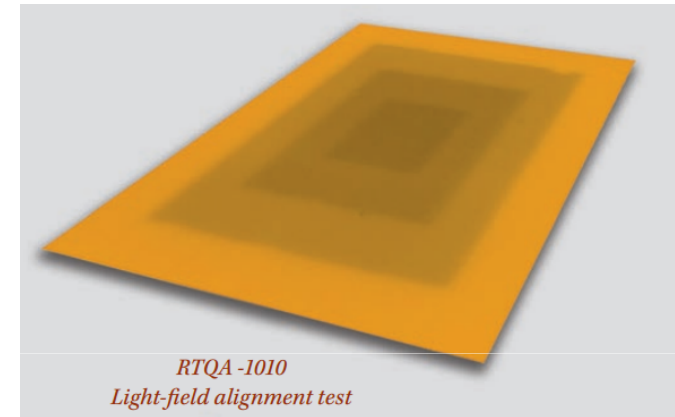
EBT2/EBT3 Films: Visible Absorbance Spectra

- Active component
 - Red/green wavelengths
 - Mainly dose information
- Marker dye
 - Blue wavelengths
 - Mainly thickness information



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



Product Offerings - Radiology



NEW SOFTWARE!
ISP FILM QA-XR™
 See Inside!

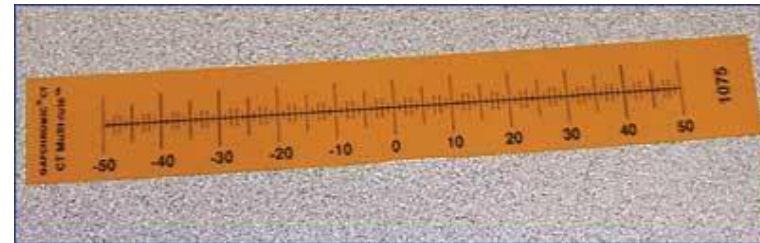
State of the art scanning software and processor-less film products *that save you time and money.*

CONVENIENT, ACCURATE AND COST-EFFICIENT TOOLS FOR RADIOLOGY AND DIAGNOSTIC APPLICATIONS

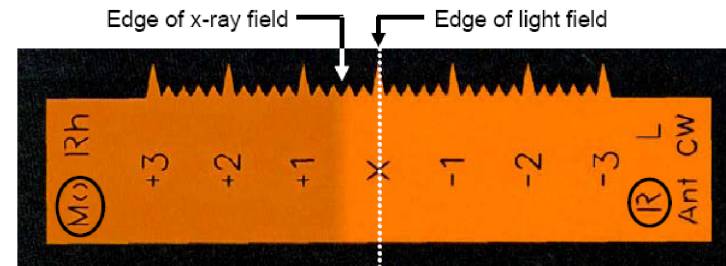
- XRQA2** FILM FOR RADIOLOGY QA
- XRCT2** FILM FOR RADIOLOGY QA
- XR M2** FILM FOR RADIOLOGY QA
- XR RV3** FILM FOR RADIOLOGY QA



+ XR-CT



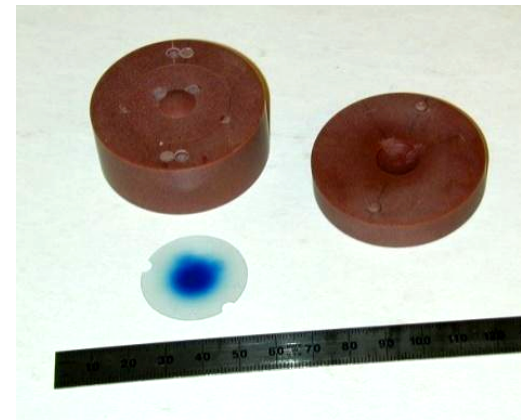
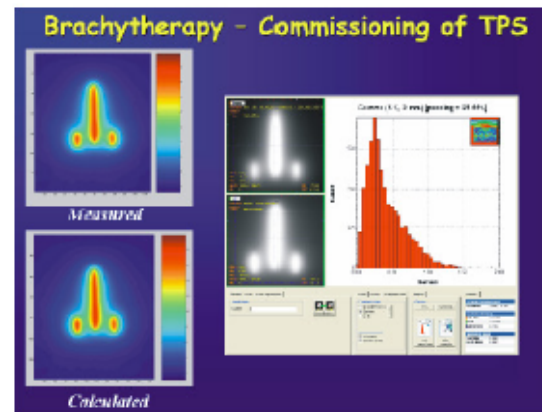
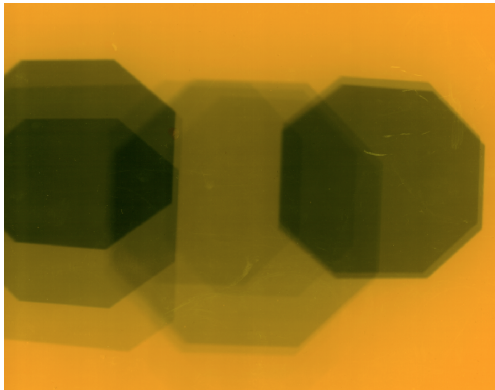
+ XR-M



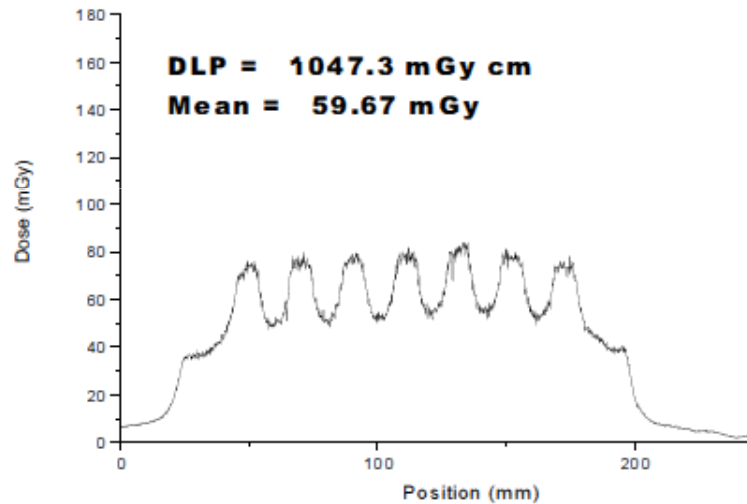
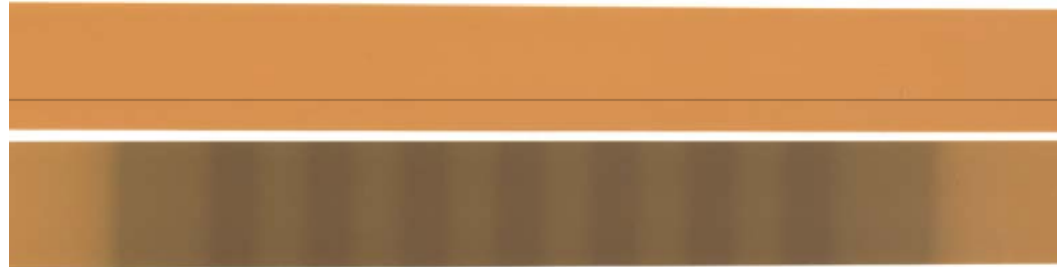
X-ray field-to-Light field deviation = 5 mm in plane of XR-M film

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

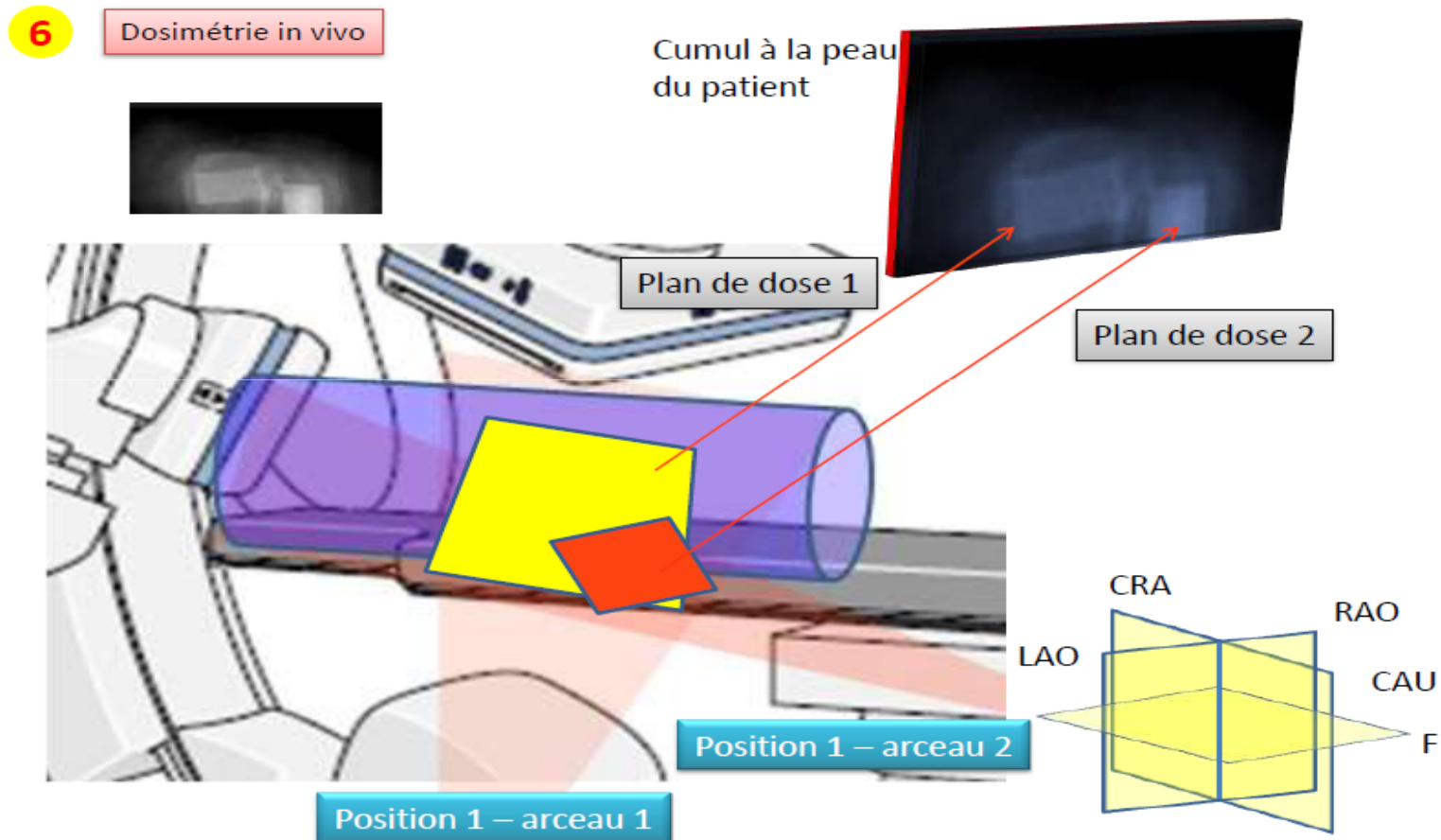
Toshiba Aquilion 64

Queensway Carleton Hospital January 2009

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

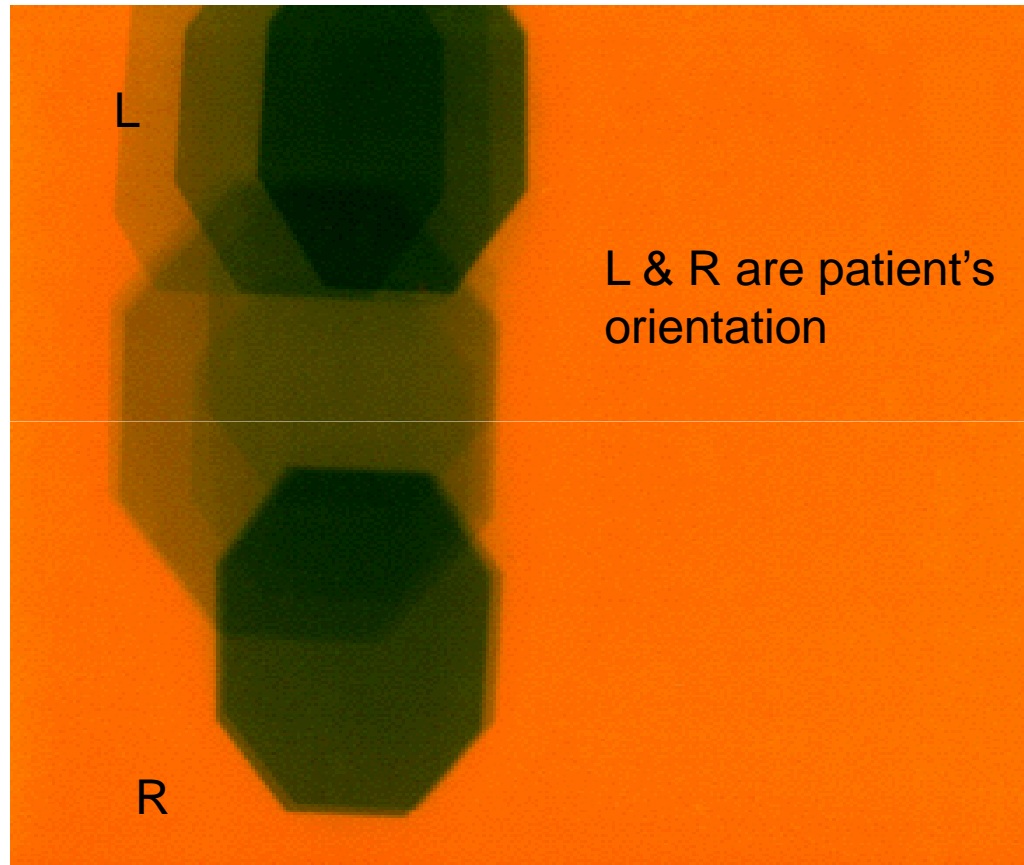


Peak skin dose monitoring with Gafchromic XR-R



*Provided by Les Hopitaux Universitaires de Strasbourg, used with permission

Dose Monitoring with Gafchromic XR-R



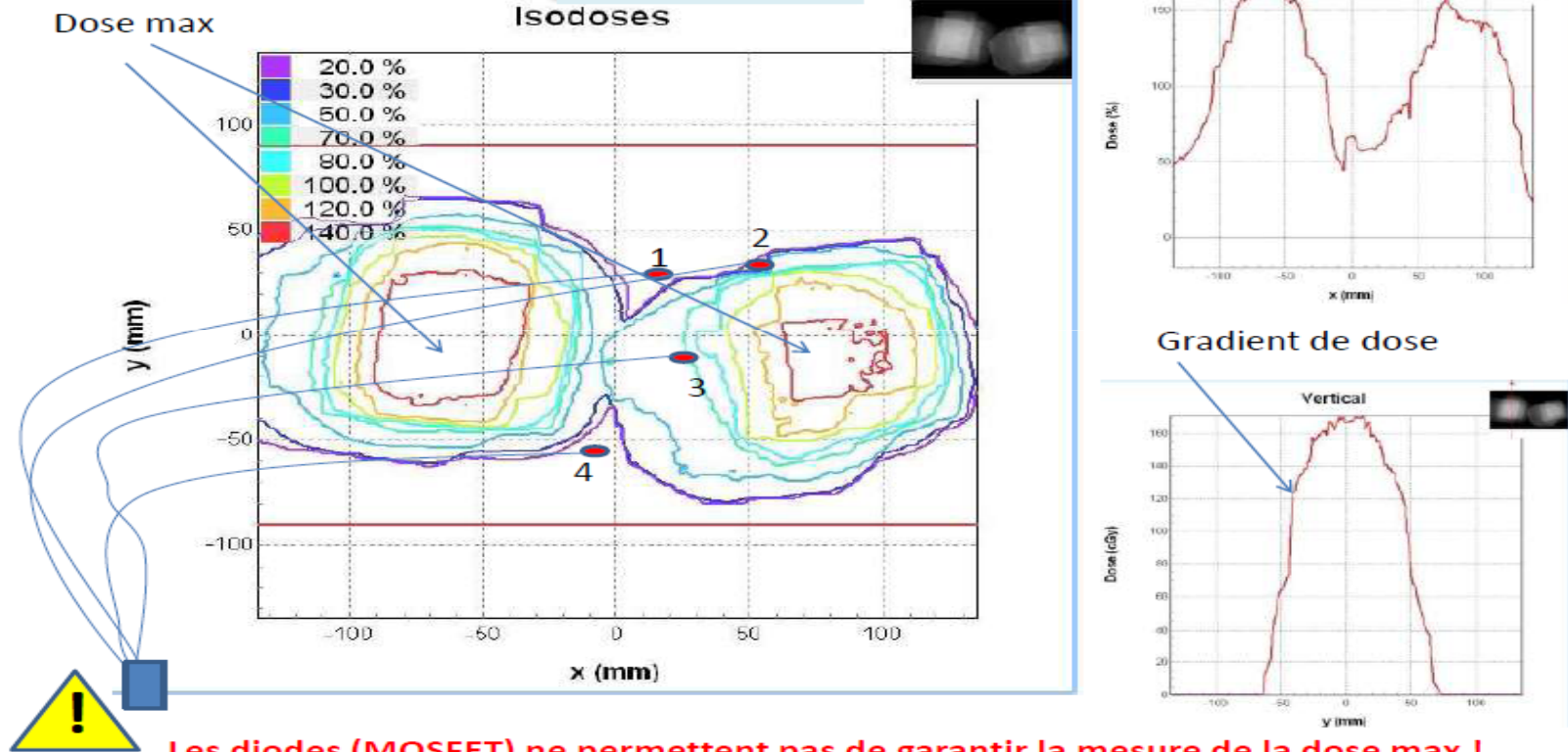
- **Immediate visualization** of patient exposure – magnitude and location
- Detailed **dose distribution**

Comparison of Gafchromic XR-R vs. Diodes

6

Dosimétrie in vivo

Diode 1 : 1 % du max
Diode 2 : 2 % du max
Diode 3 : 5 % du max
Diode 4 : 1 % du max



*Data provide by Les Hopitaux Universitaires de Strasbourg, used with permission

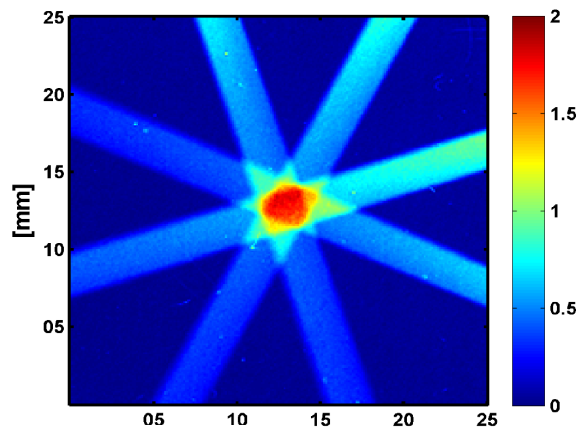
Radiochromic Dosimetry Film – The Advantages

- 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

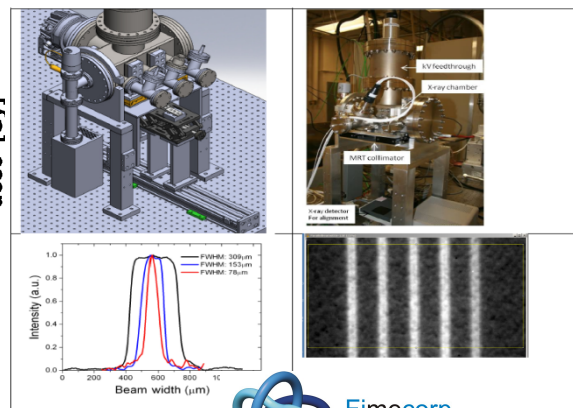


Emerging Modalities

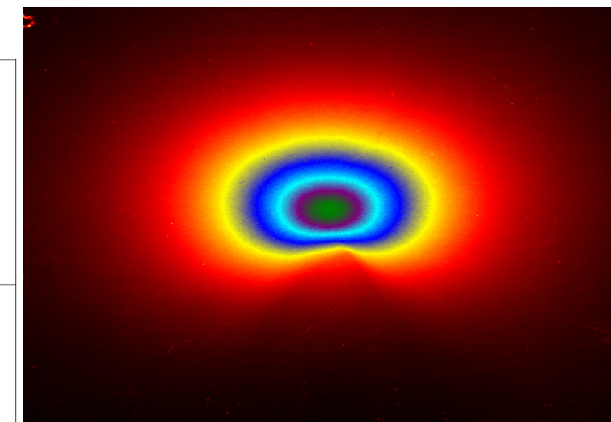
- Trends
 - Small fields
 - High gradients
 - Less fractions
 - Higher dose per fraction
- High value on a dosimeter with:
 - High spatial resolution
 - Wide dynamic range



GafChromic

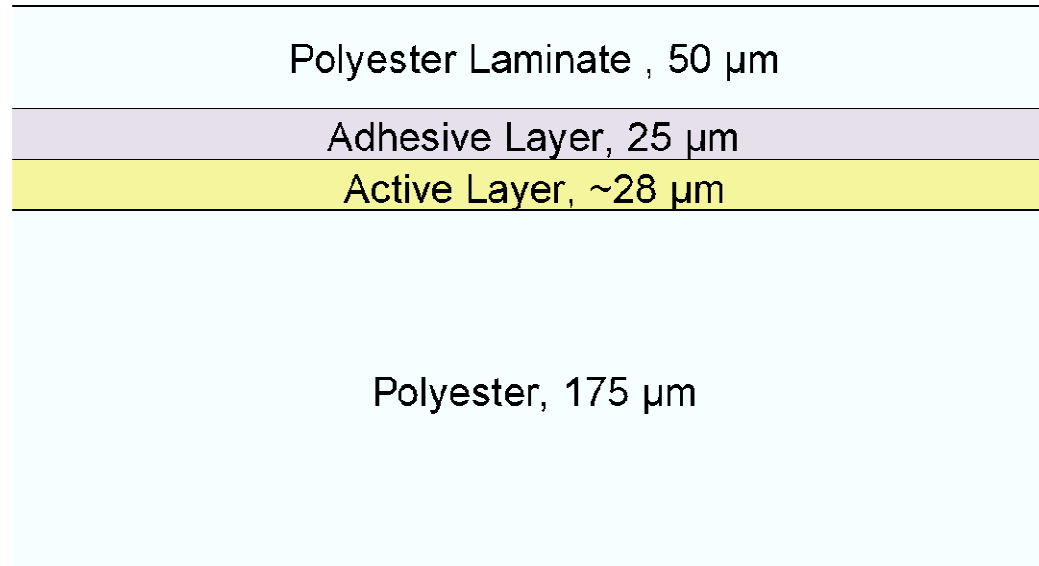


Fimecorp
International s.l.

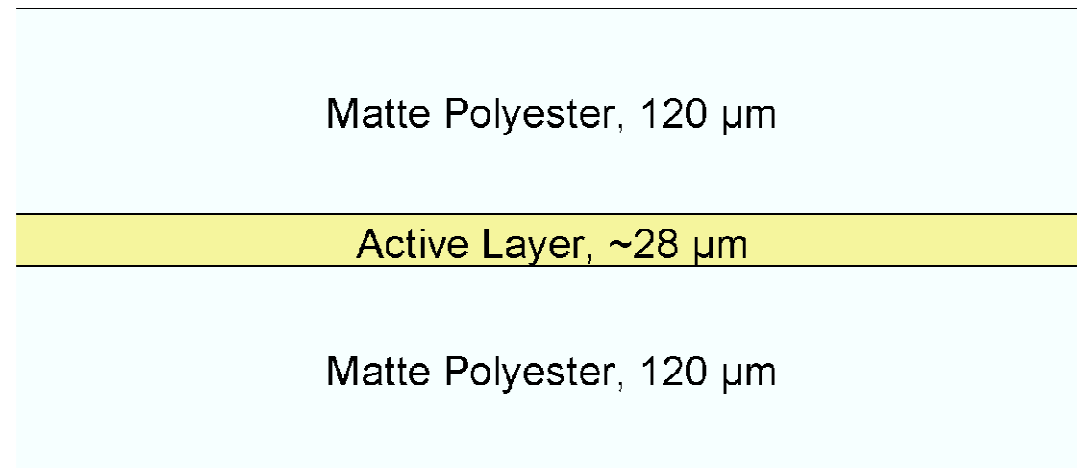


ASHLAND

Configuration of EBT2, EBT3 and EBT3+



EBT2



EBT3 and EBT3+



Composition and Energy Dependence

GafChromic EBT2 Film – since October 2012 (lot A102312)								
Layer	Nominal thickness, μm	Density, g/cm^2	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/cm^2	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

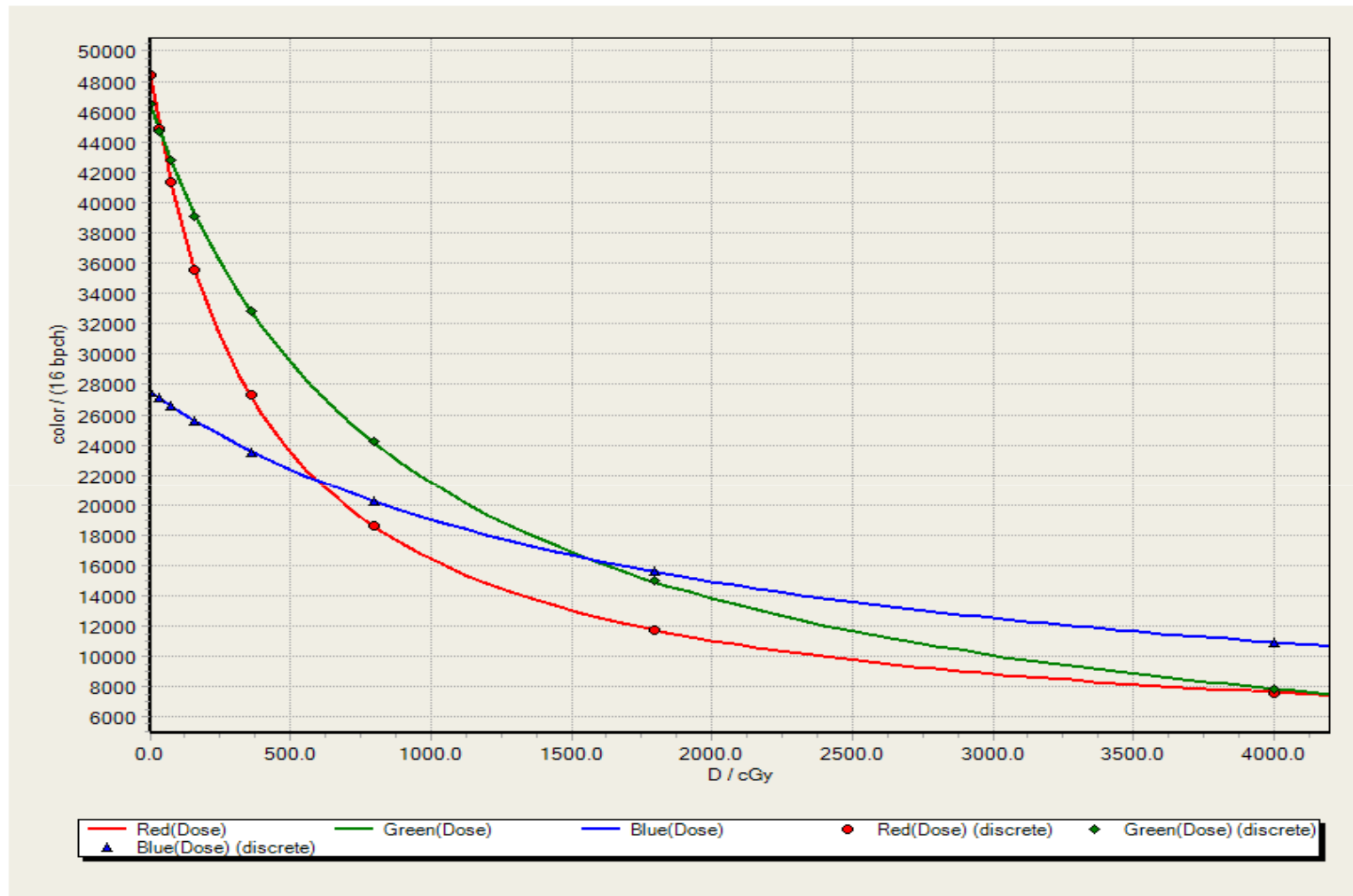
Energy independent MV to 100 keV

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

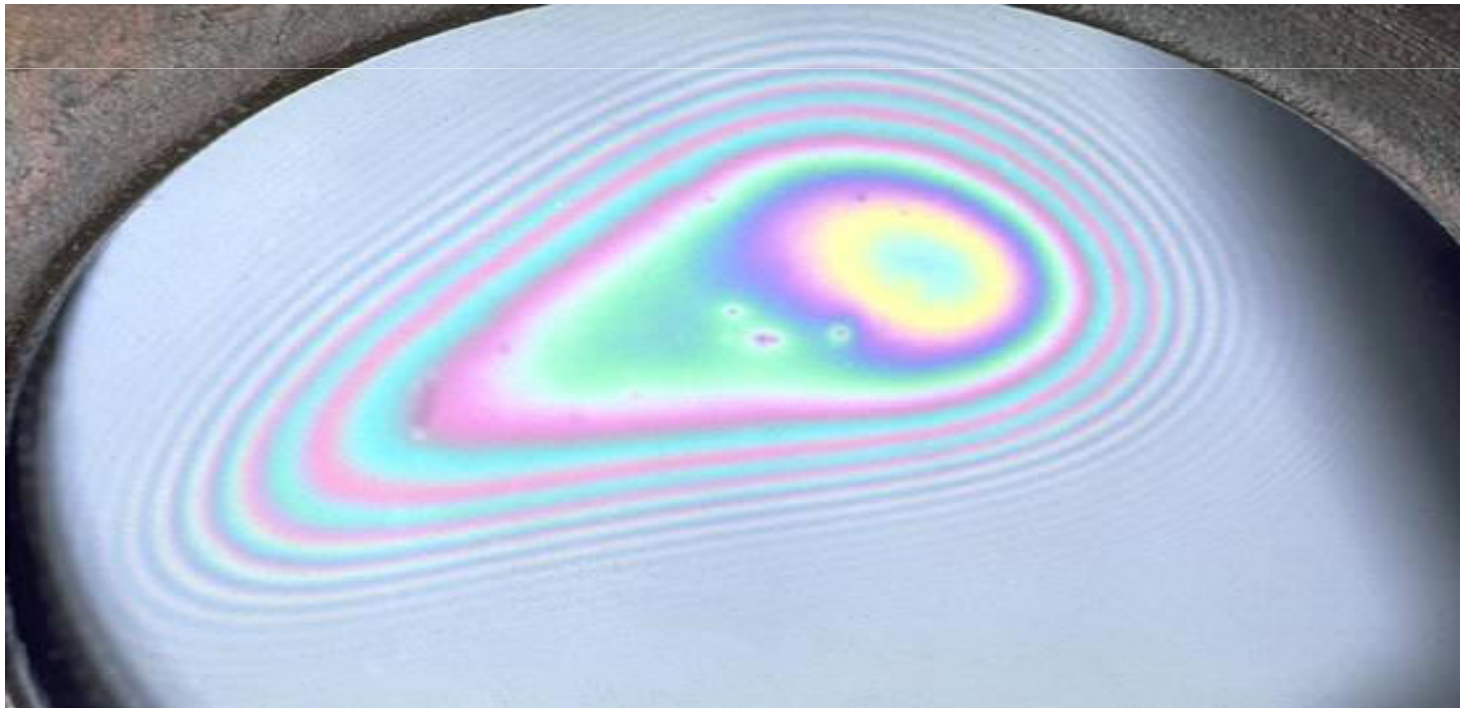


High spatial resolution – to 25 μm
Wide dynamic range – cGy to >40 Gy



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

ISP FilmQA Pro - Anonymous - Image viewer and editor

File Panel Data Help

Case description

- Images only (multiple scans)
 - Data - Image scan #1
 - Data - Image scan #2
 - Data - Image scan #3
 - Data - Image scan #4
 - Data - Image scan #5
 - Data - Image scan #6
 - Data - Image scan #7
 - Data - Image scan #8
 - Data - Image scan #9
 - Data - Image scan #10
 - Data - Image scan #11
 - Data - Image scan #12
 - Data - Image scan #13
 - Data - Image scan #14
 - Data - Image scan #15 (empty)
- Case object management
 - Add new case object
 - New treatment case

Case data selector

Advanced Materials

Image 'Image scan #14' - View 137% - R[32947, 37583] G[38158, 41987] B[26182, 27995] (16 bpc)

0 mm 21 mm 42 mm 63 mm 84 mm 105 mm 126 mm 147 mm 168 mm 189 mm 210 mm

0 mm 26 mm 51 mm 77 mm 102 mm 128 mm 153 mm 179 mm 204 mm 230 mm 255 mm

	Cursor region <(16 bpc)>	Full image <(16 bpc)>	Frame <(16 bpc)>
R average	29028	37034	35859
R std deviation	67	7639	1342
R min	28910	5908	32969
R max	29157	65532	37568
G average	34774	40673	40420
G std deviation	77	5971	1027
G min	34645	6526	38158
G max	34904	65532	41987
B average	25580	27244	27295
B std deviation	54	3589	347
B min	25495	3628	26185
B max	25687	65534	27996
Pixels	9 pix	409.2 kpix	25.6 kpix

Pixel statistics (165, 28)

Profile

Contour

Isomap

Histogram 'Image scan #14'
Color channel: Red
Region: Full image

Histogram 'Image scan #14'

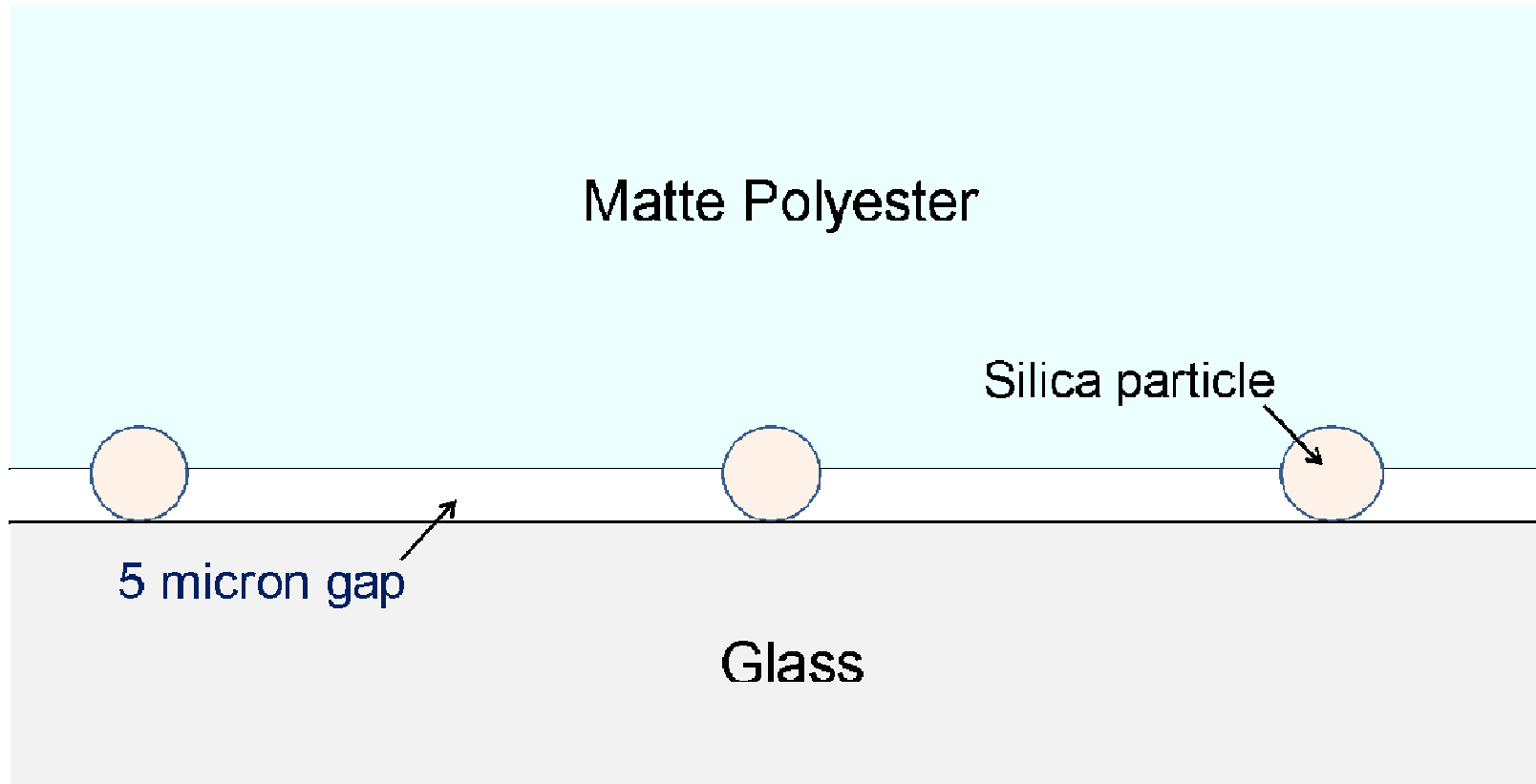
Full image

Image histogram region

11:32 AM > View 137%

start ISP FilmQA Pro - A... Office Communicator rough statistics.xls... cal 10-4 red thumb... cal 10-4 thumbprin... cal 10-4 red thumb... Inbox - Microsoft... Microsoft PowerPol... M - cal 10-4 triple th... EN 11:32 AM

EBT3: Matte Polyester Stops Newton's Rings



$$\text{Gap} \gg \lambda_{\text{light}}$$

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



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



Radiochromic Film Dosimetry: The Basics



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



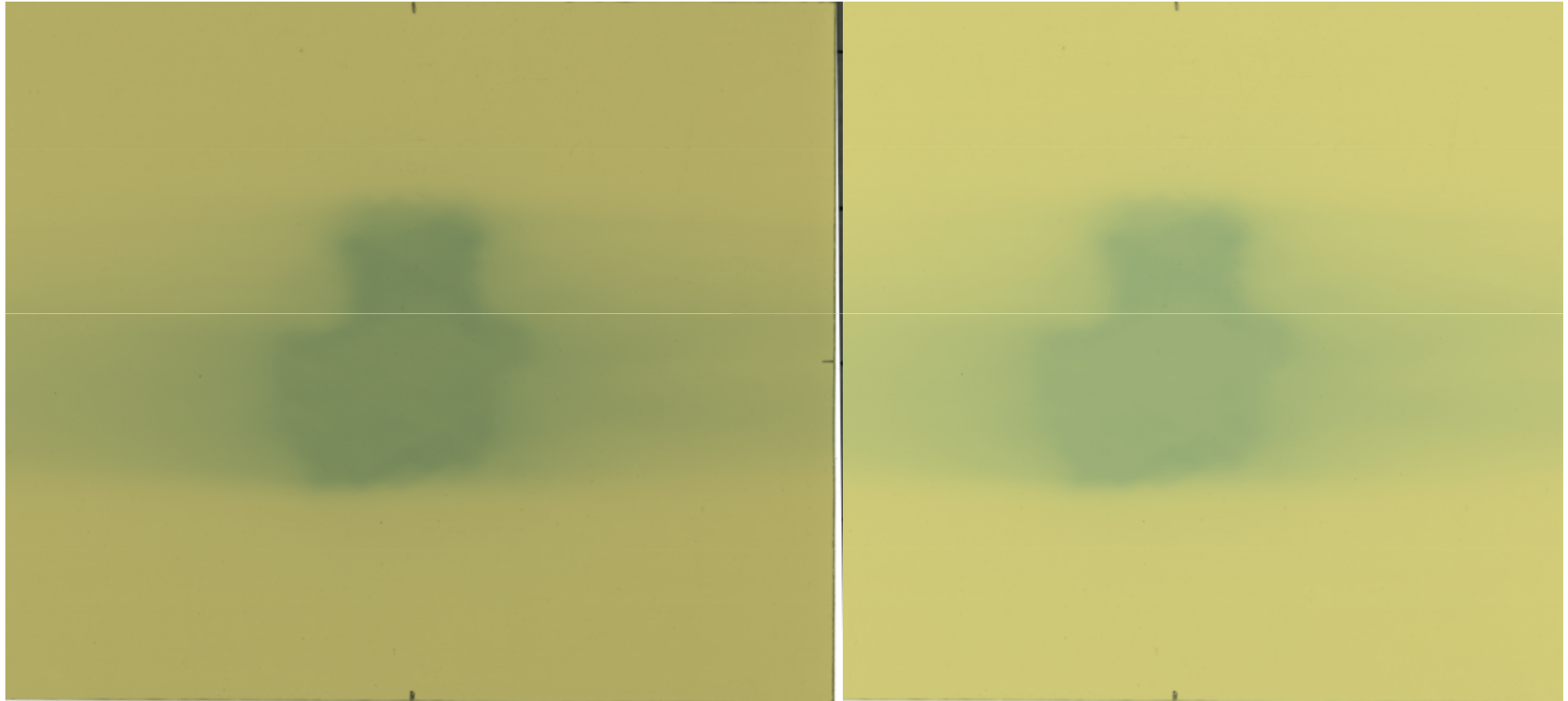
Disable the Color Correction Features

The image illustrates the steps to disable color correction in the EPSON Scan software. It consists of three screenshots:

- Left Screenshot:** Shows the main EPSON Scan interface. A red sad face is overlaid on the 'Adjustments' section, indicating that color correction features are currently active.
- Middle Screenshot:** Shows the 'Configuration' dialog box. The 'Color Control' section is selected, and the 'No Color Correction' radio button is checked. A blue arrow points from the 'Adjustments' section of the left screenshot to this dialog box.
- Right Screenshot:** Shows the main EPSON Scan interface after the configuration change. A green happy face is overlaid on the 'Adjustments' section, indicating that color correction features are now disabled.

Check "No Color Correction"

Image Color Correction

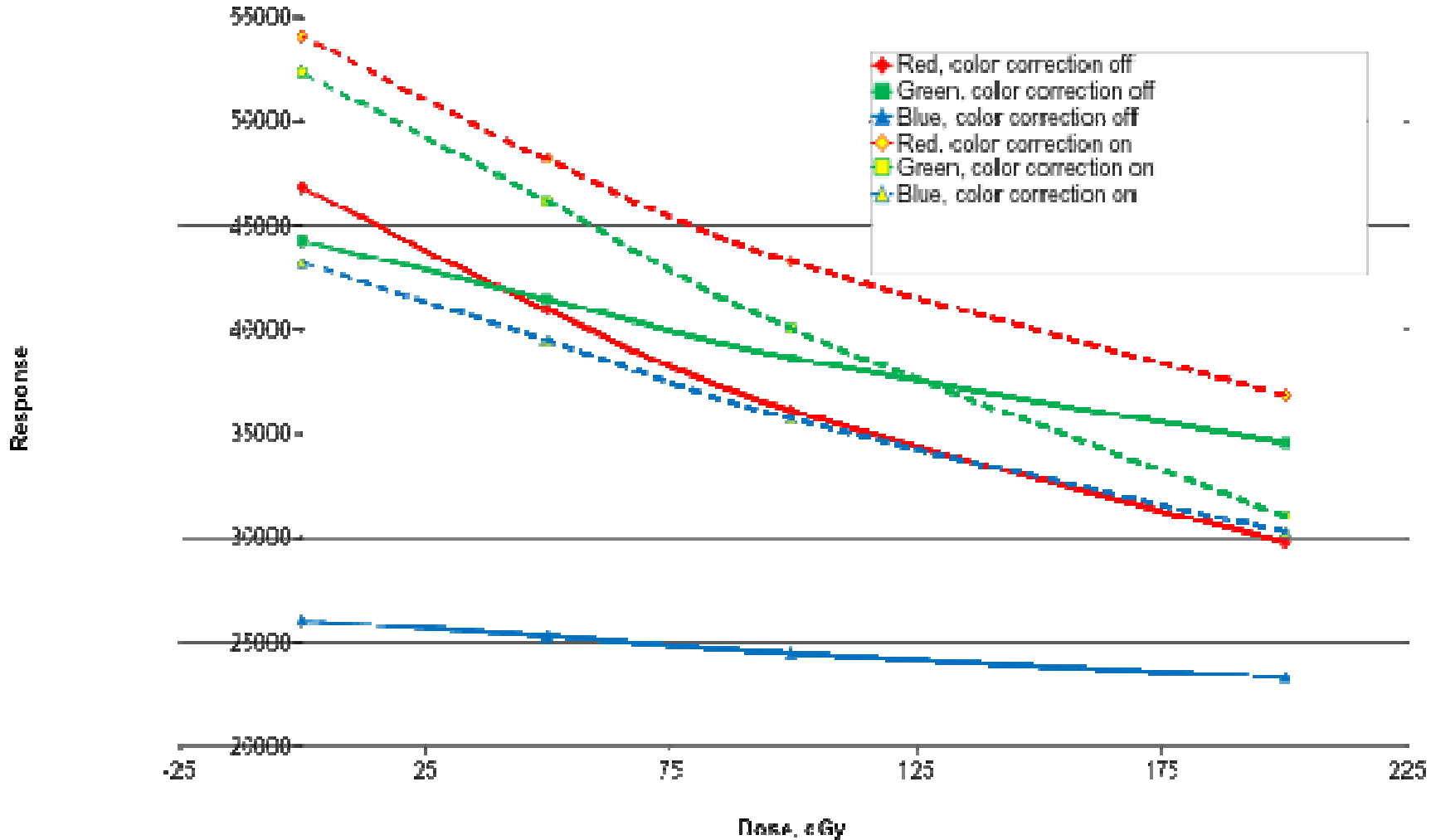


No color correction



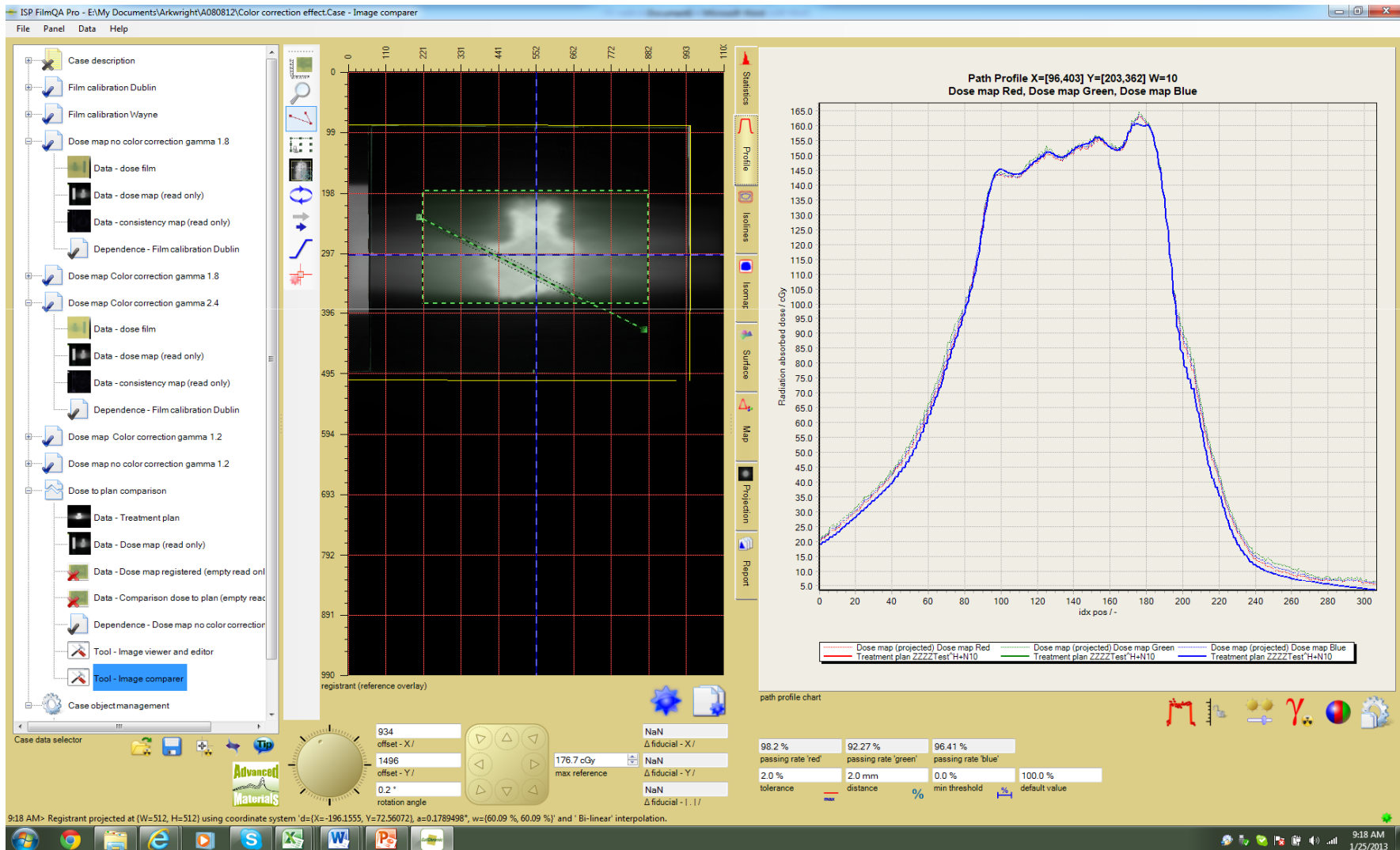
Color correction active

Calibration – Effect of Color Correction



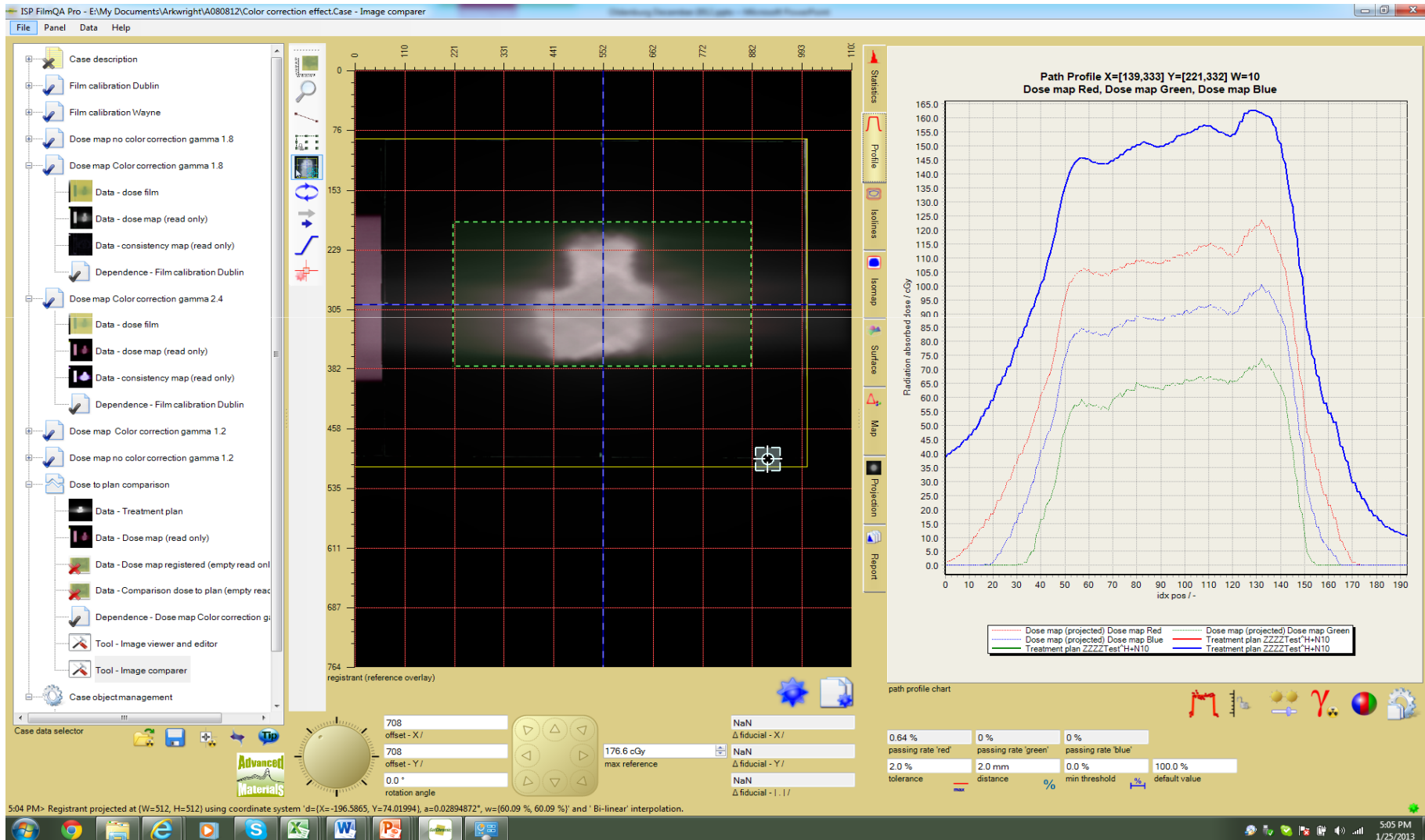
Dosimetry and Color Correction

Color correction turned off for calibration and measurement



Dosimetry and Color Correction

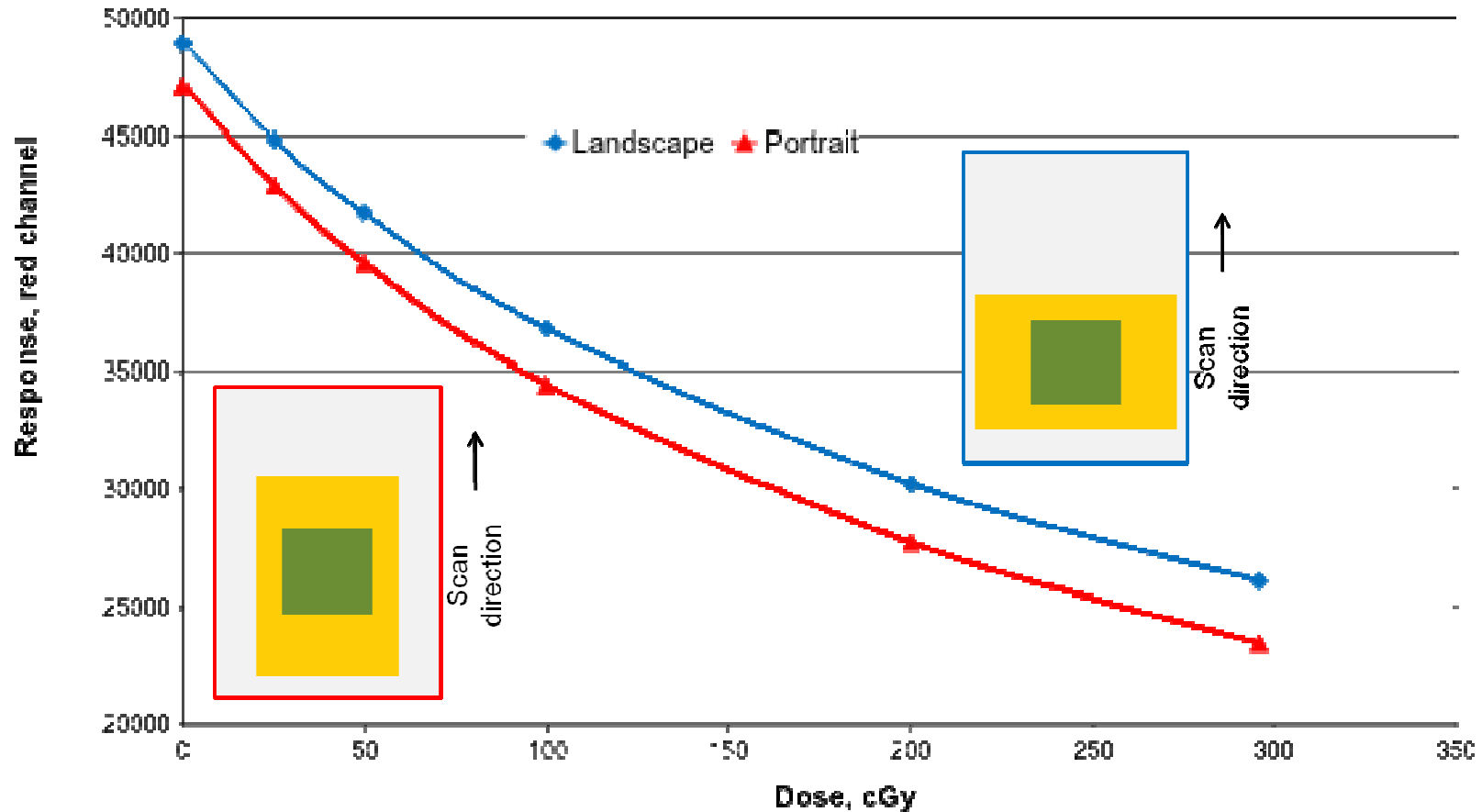
Color correction **off** for calibration and **on** for measurement



Orientation Dependence

Orientation Dependence

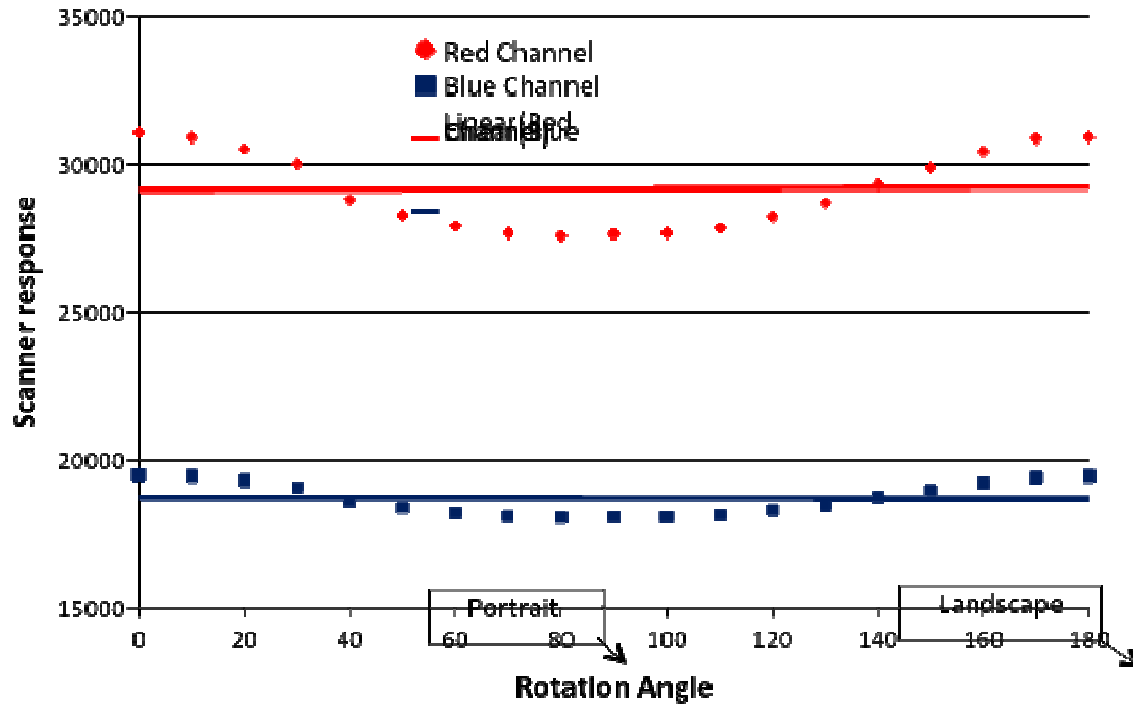
EBT3 A101711; 10000XL scanner



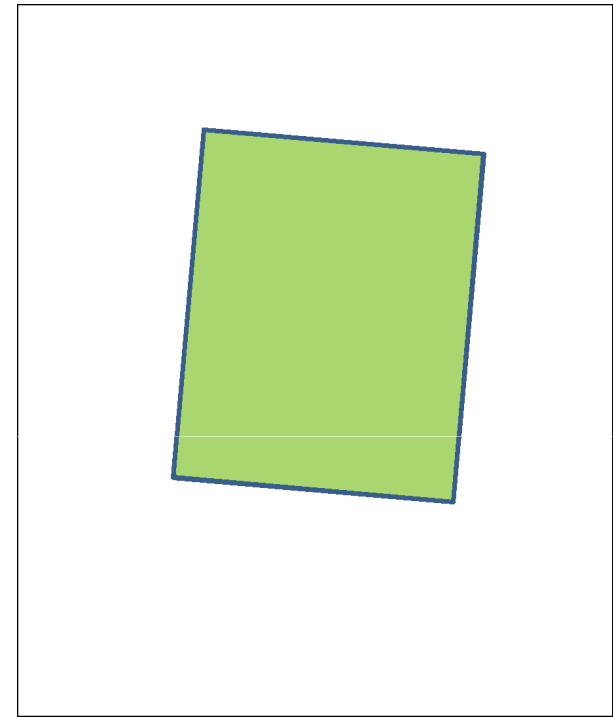
- Either orientation is usable
- But don't mix orientations!

Orientation Dependence

Angular Dependence of EBT2



Response error is $\sim 0.05\%$ per degree
Dose error $\sim 0.15\%$ per degree

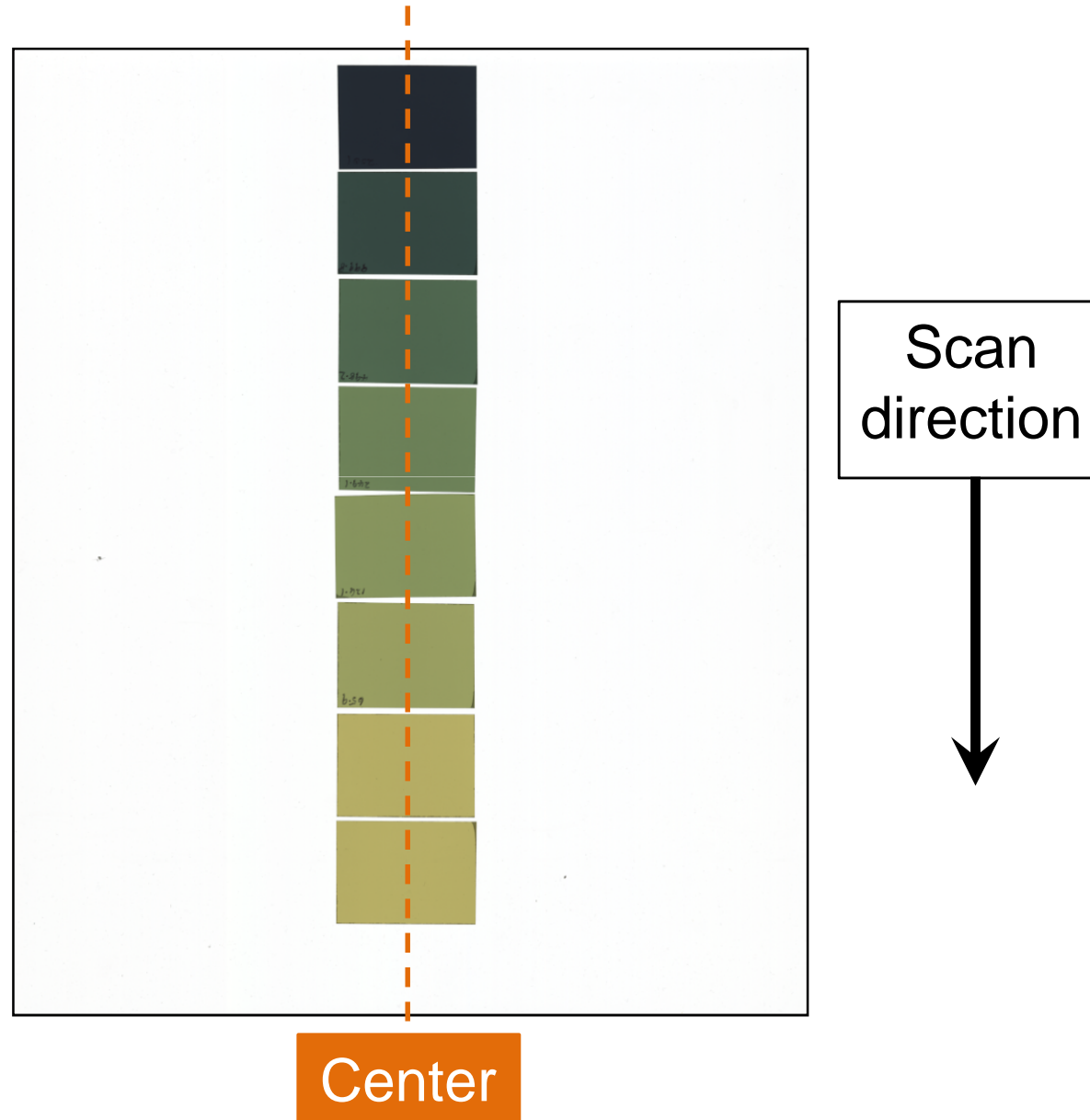


5° misalignment on scanner

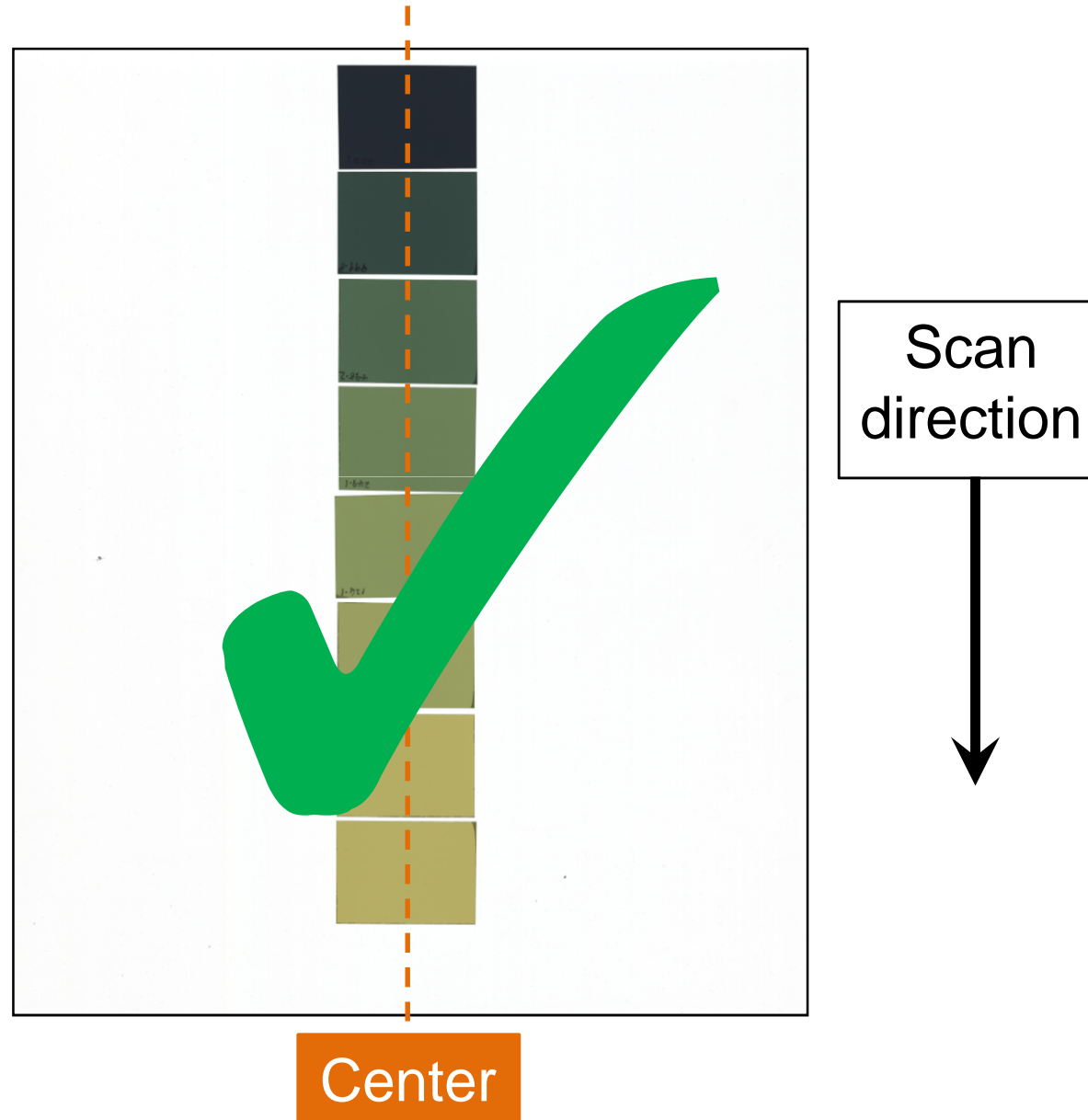
Conclusion: Misalignment is unlikely to cause significant error



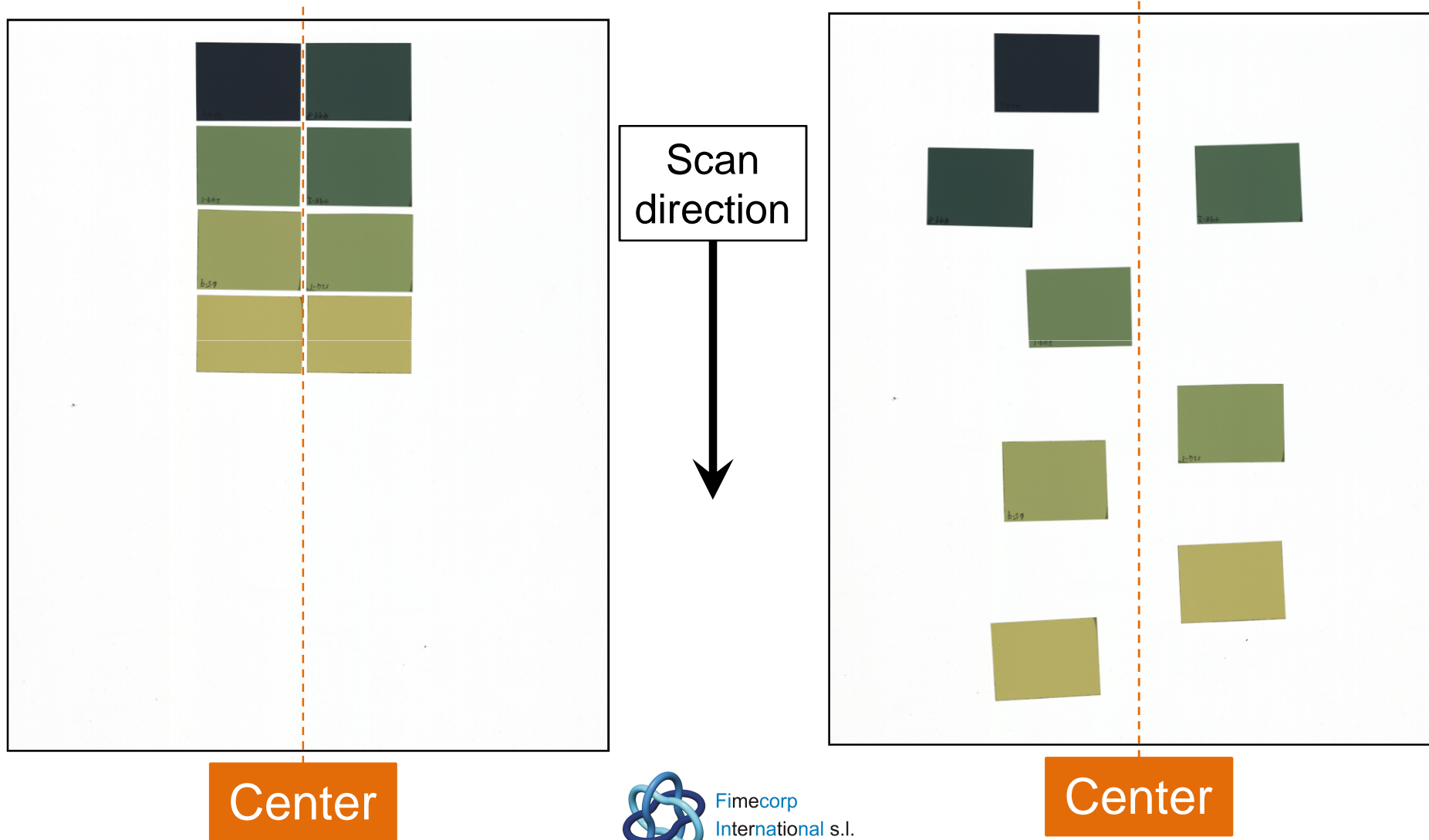
Central Placement for Scanning



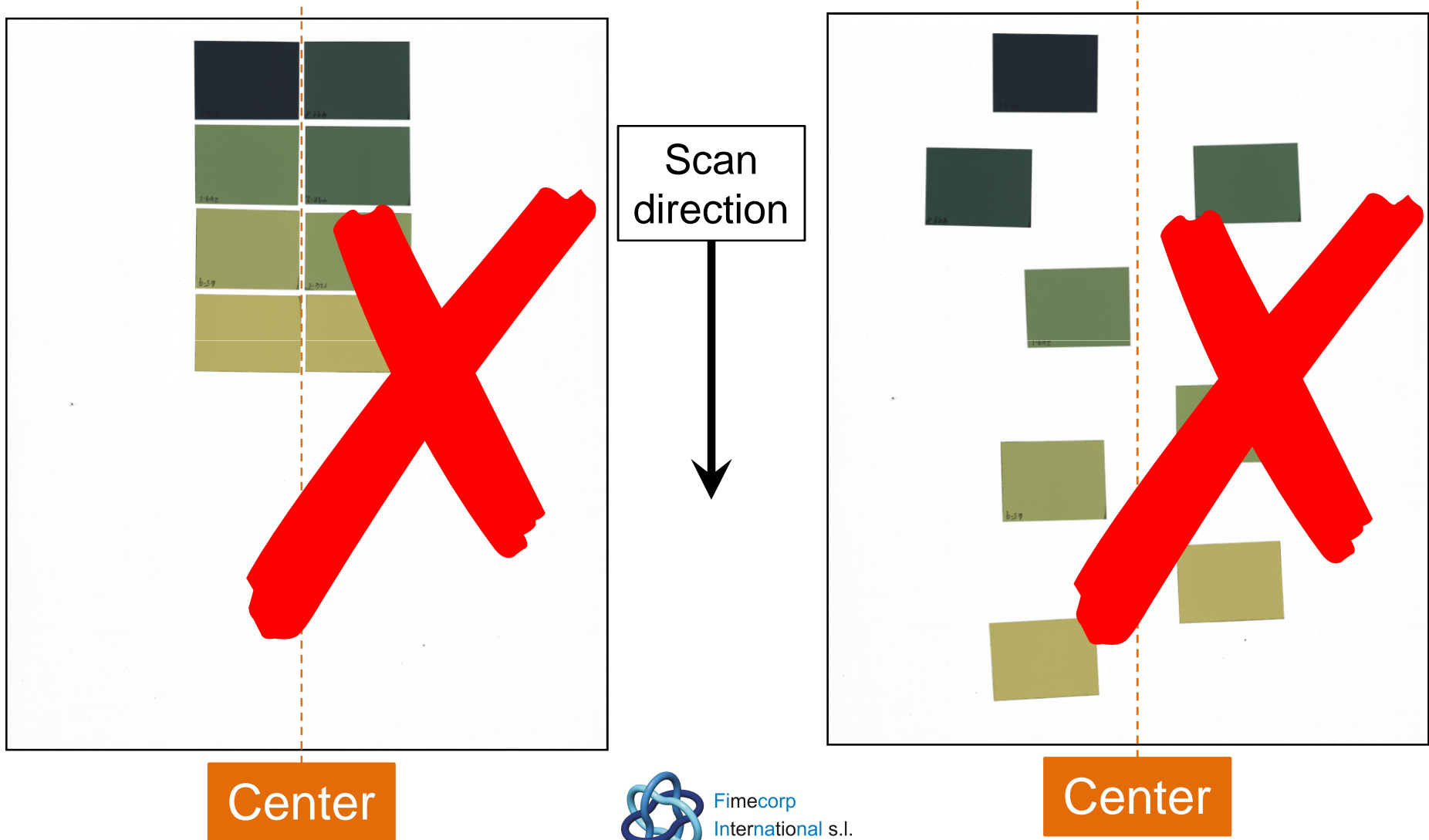
Correct Placement for Scanning



Incorrect Placement for Scanning

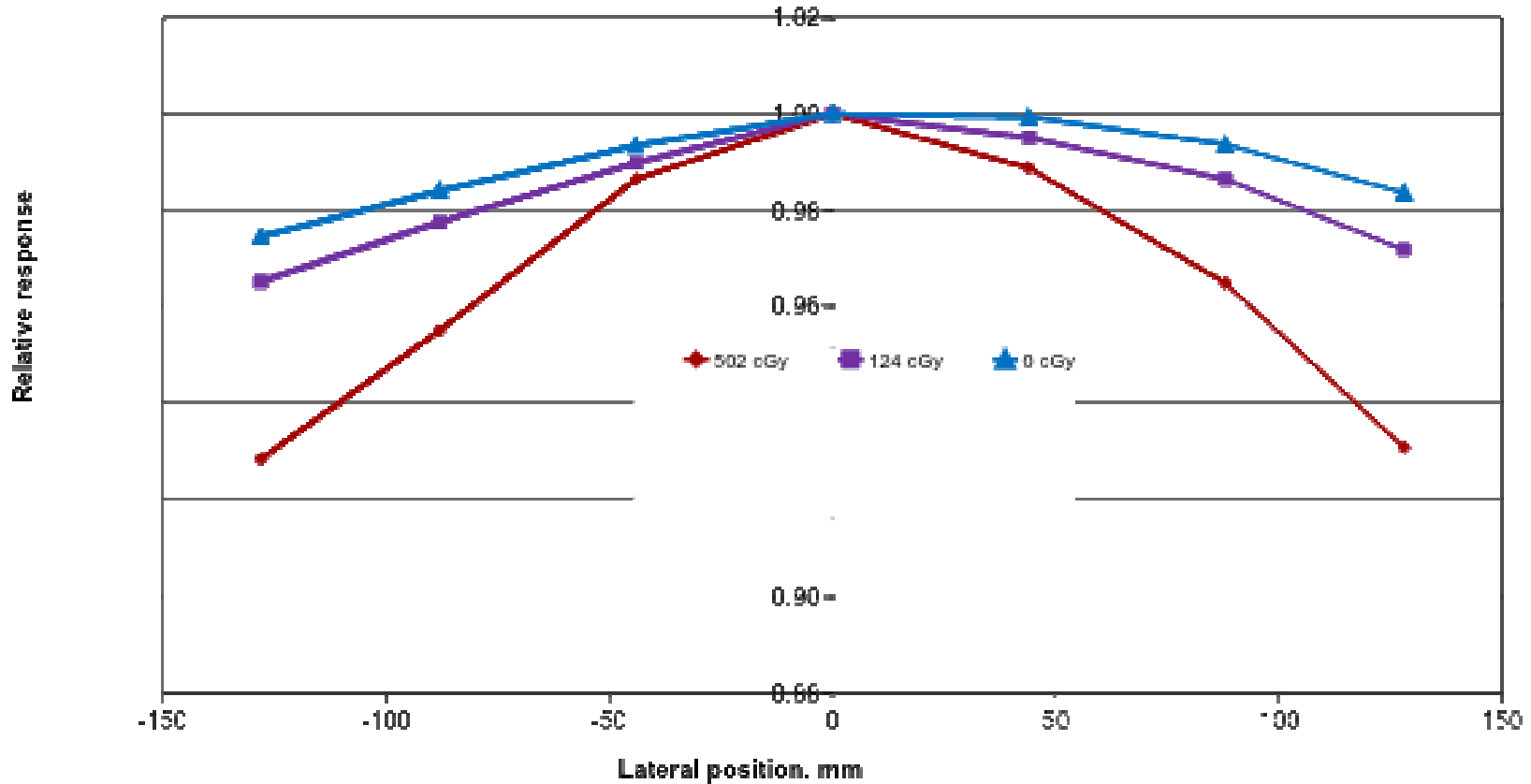


Incorrect Placement for Scanning



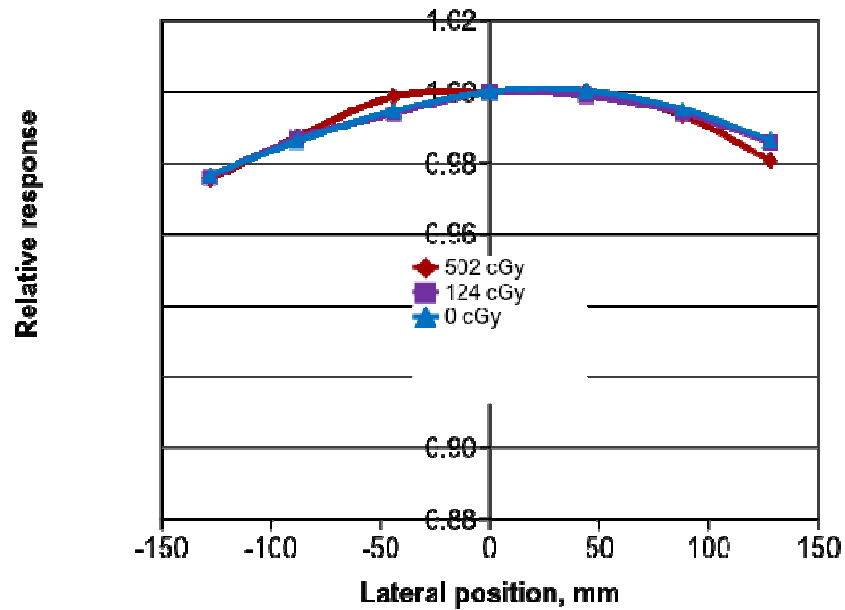
Lateral Position Artifact

Lateral response - red channel, Epson 10000XL

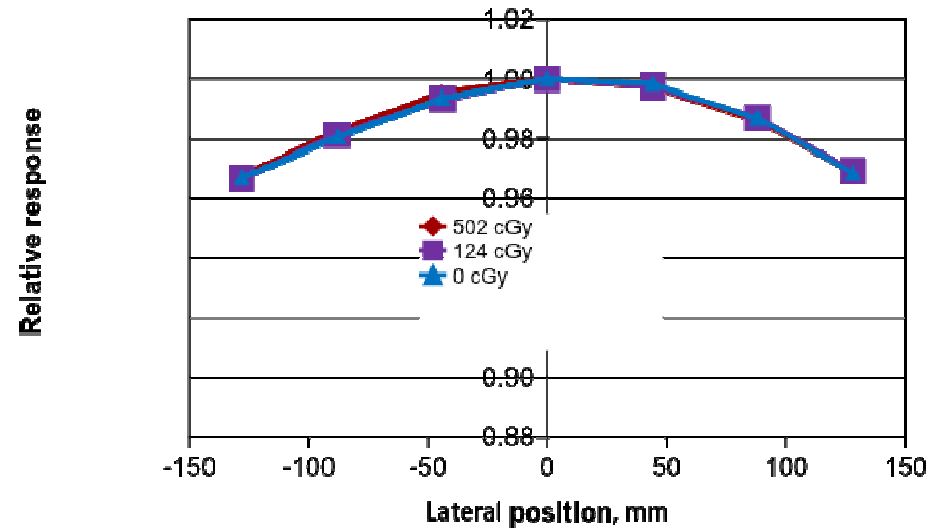


Lateral Position Artifact

Lateral response- green channel

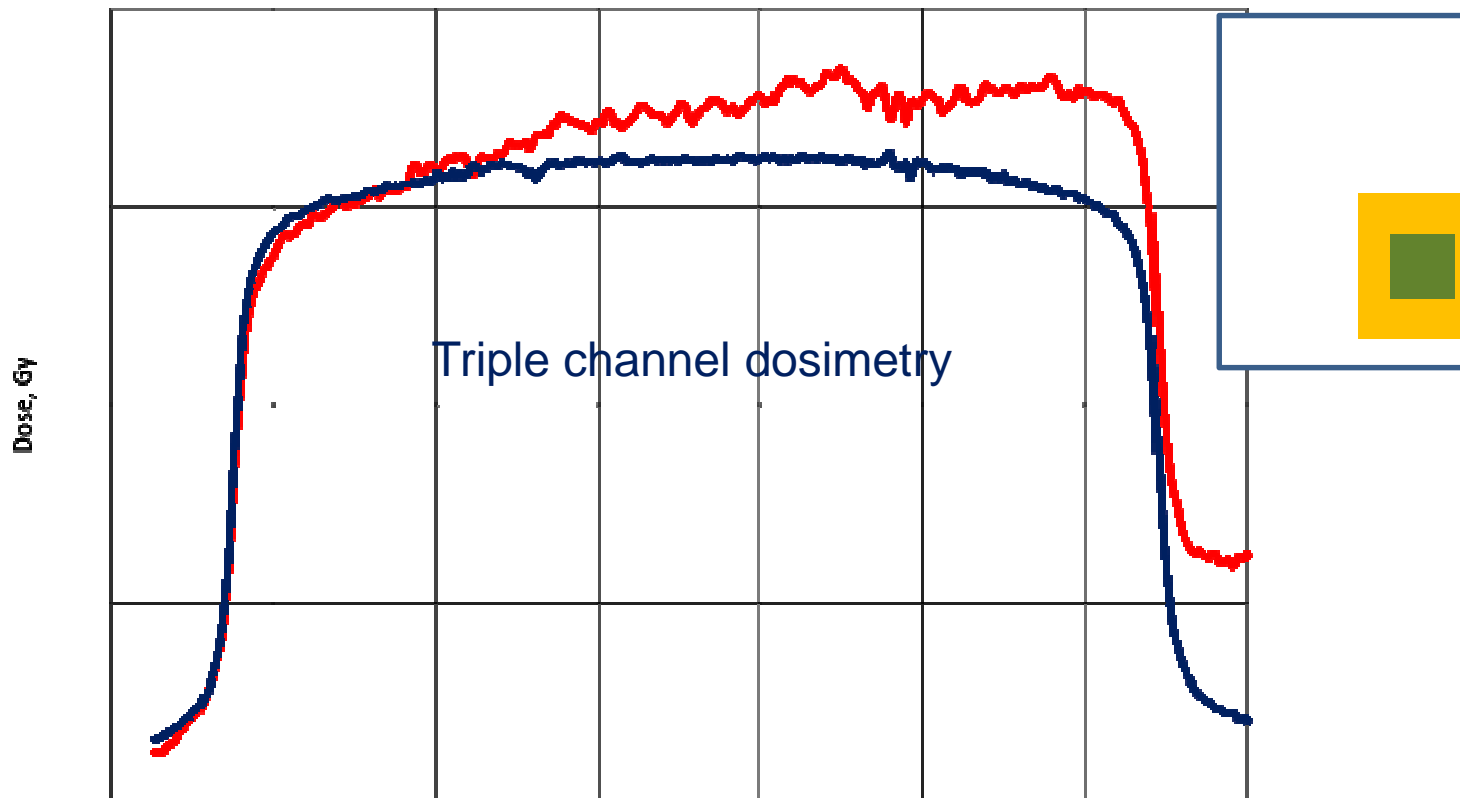


Lateral response - blue channel



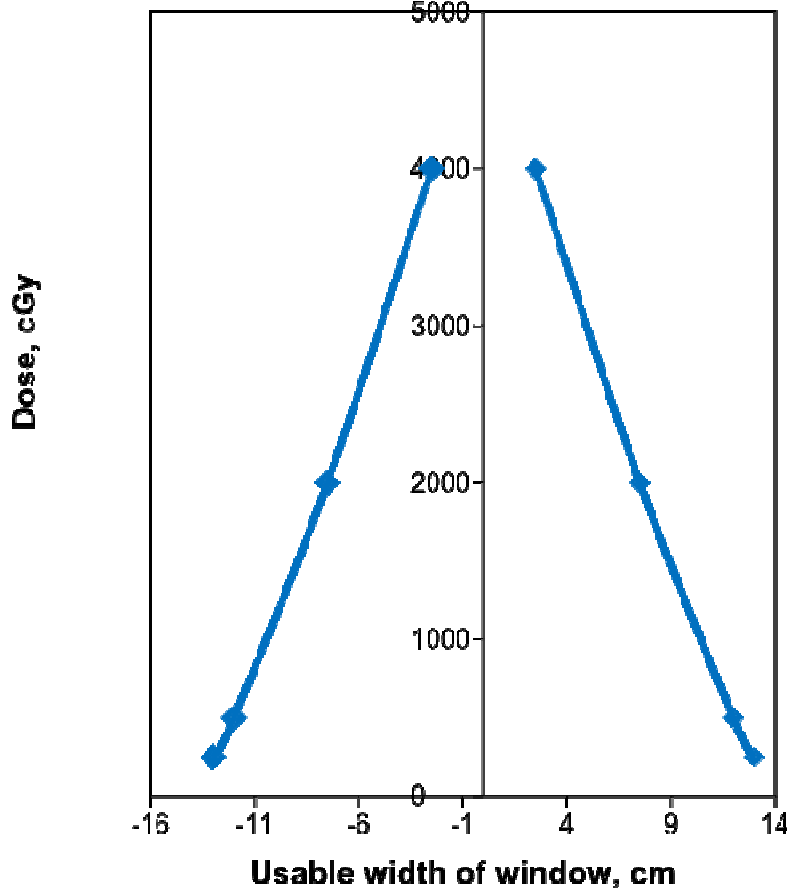
Correcting the Lateral Artifact

Red channel dosimetry

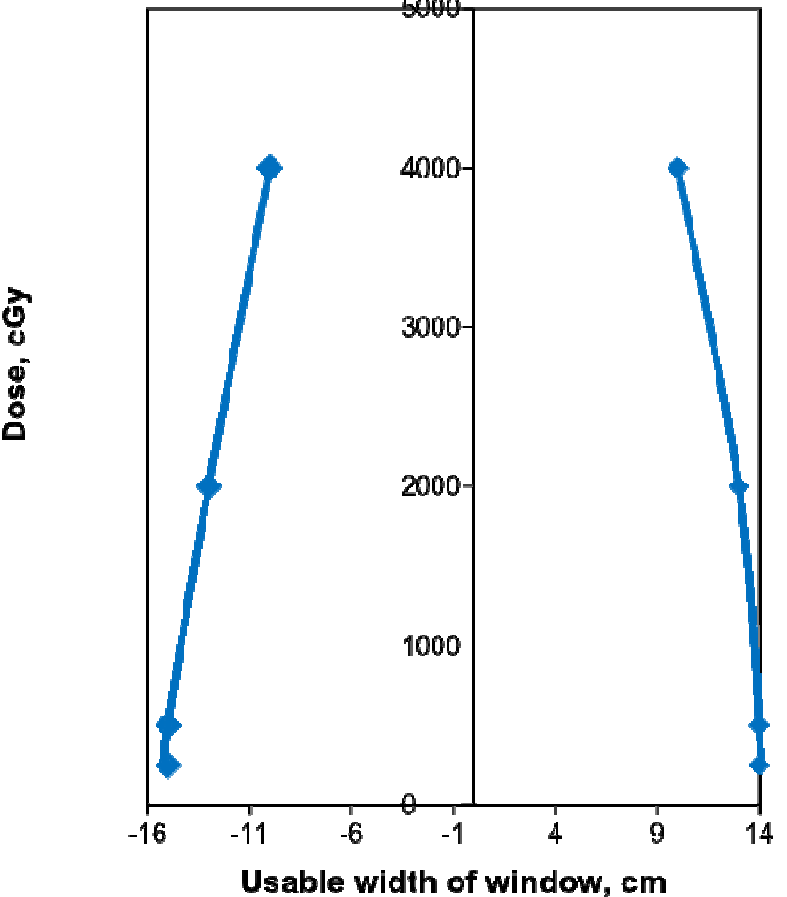


Usable Scan Window, Epson 1000XL

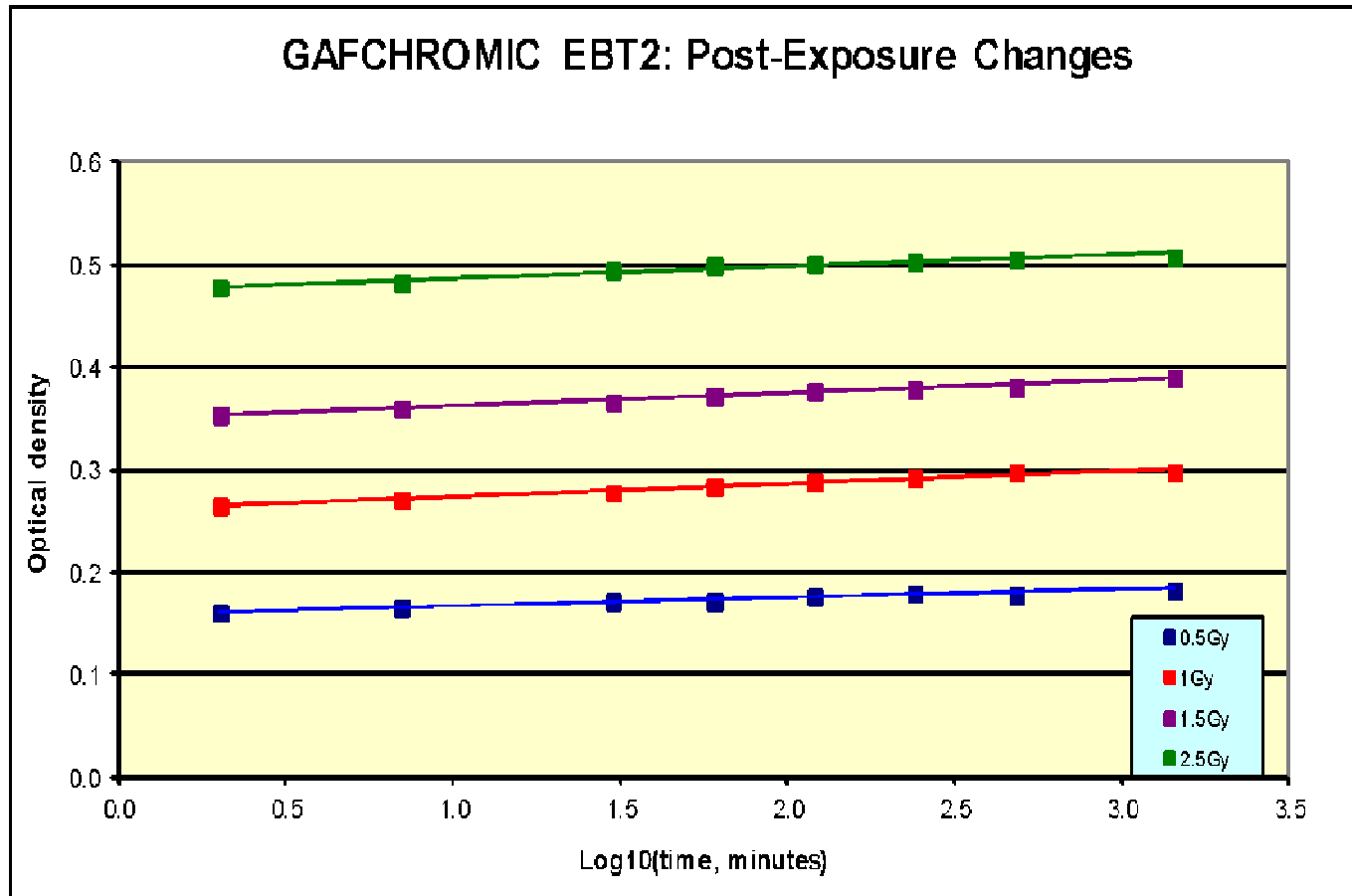
Triple channel dosimetry



Green/Blue dosimetry

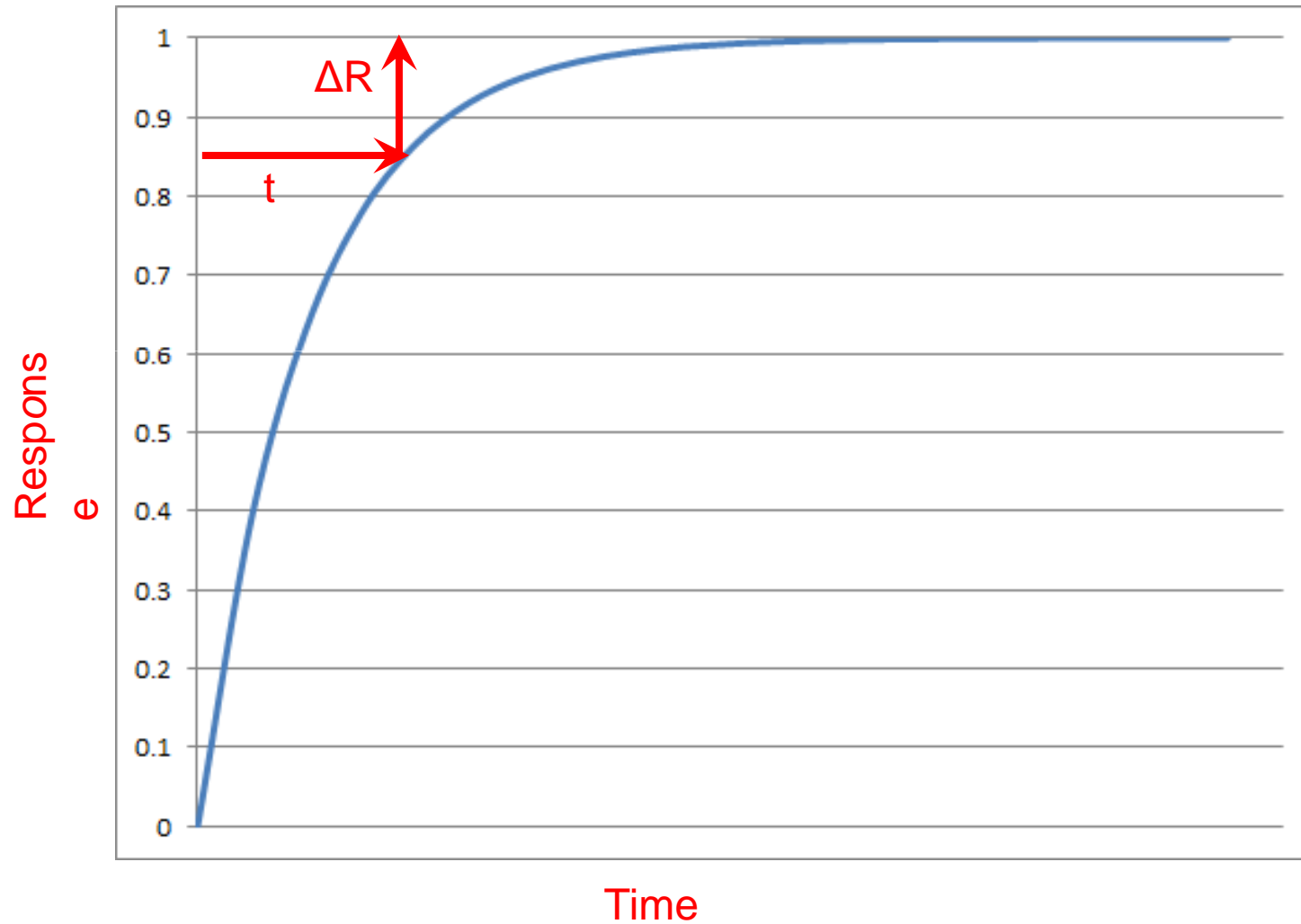


Post-exposure Change

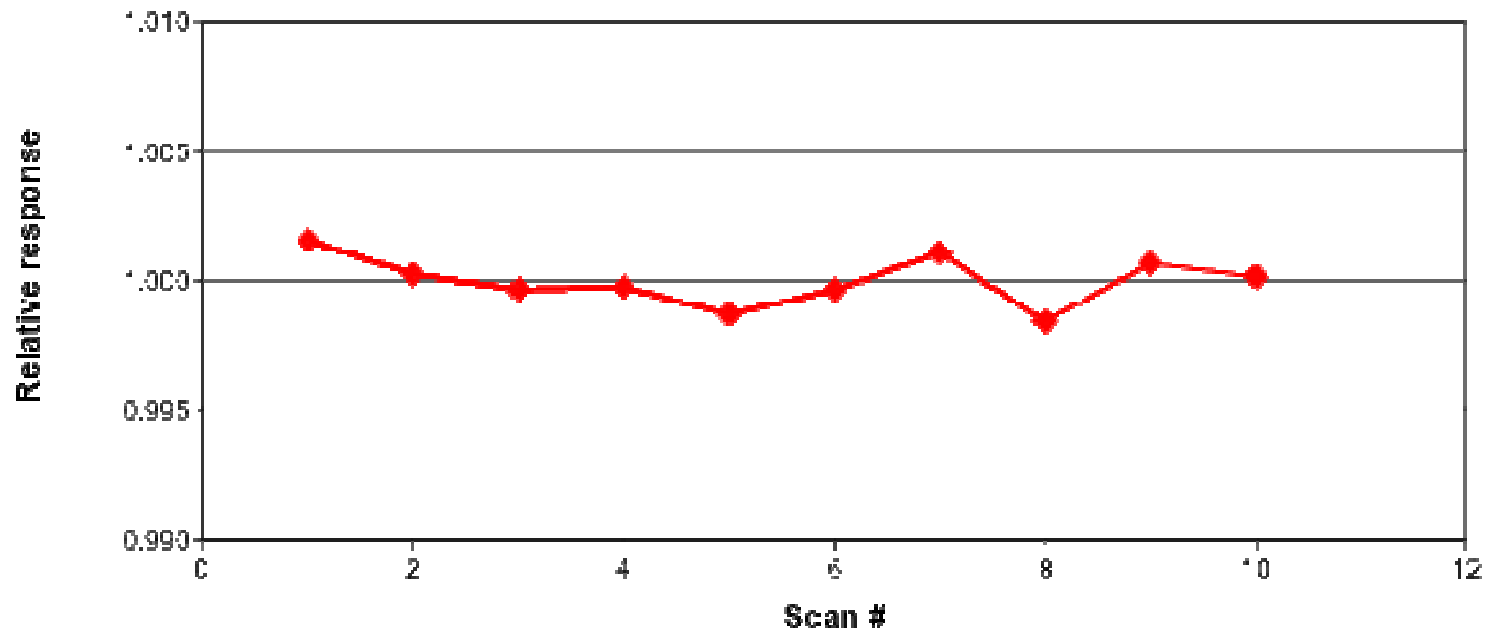


- Wait for the rate of change to diminish

Dealing with Post-exposure Change



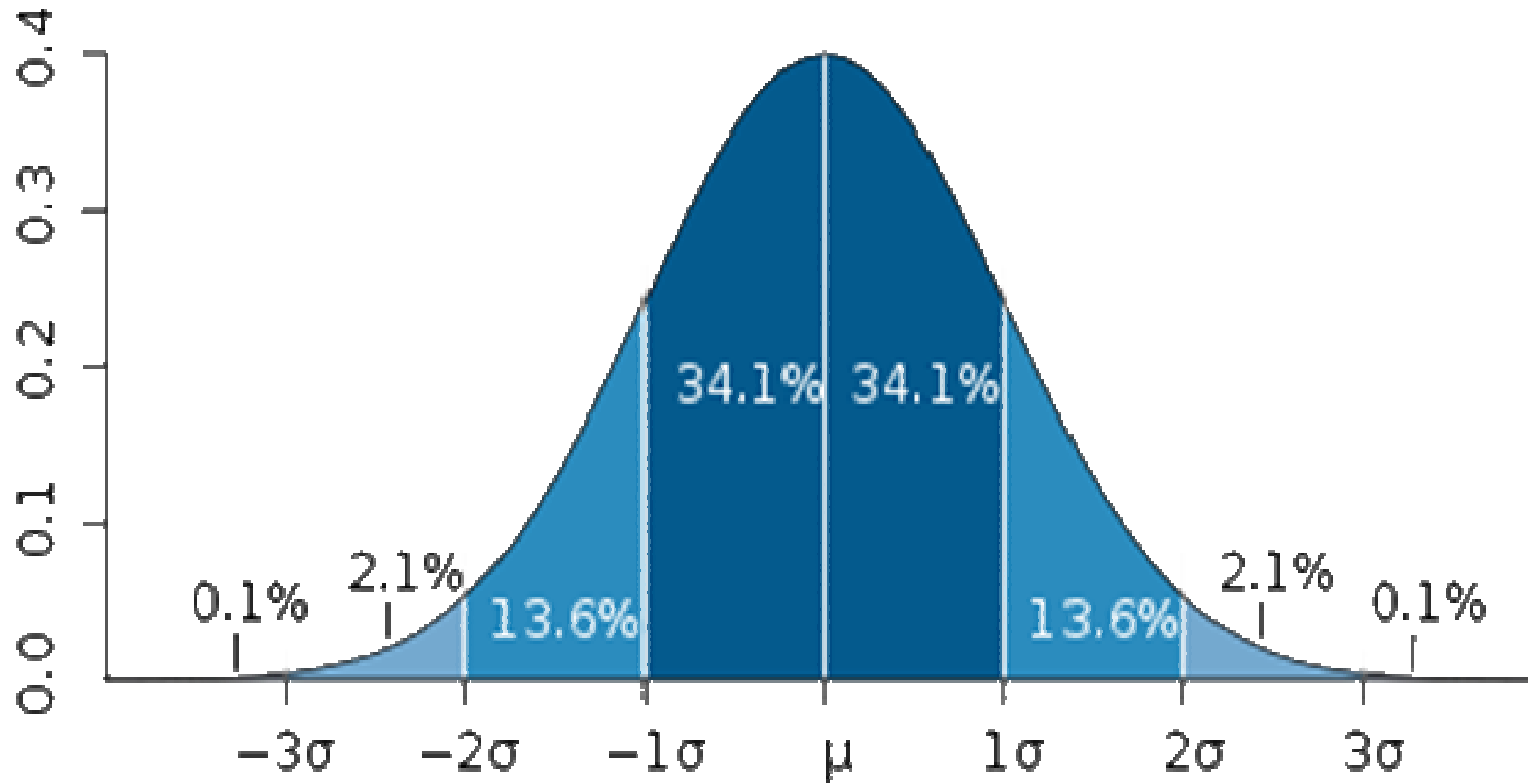
Typical Scan-to-scan Consistency Epson 10000XL



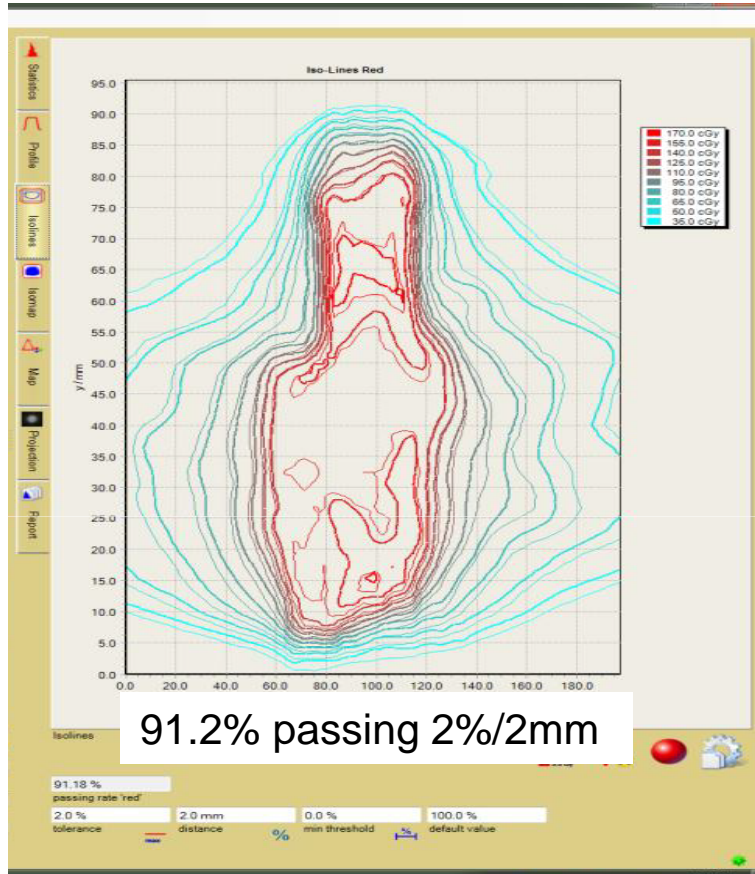
Standard deviation is ~0.15% of response value
“Rule of thumb” - 1% in response \approx 3% in dose



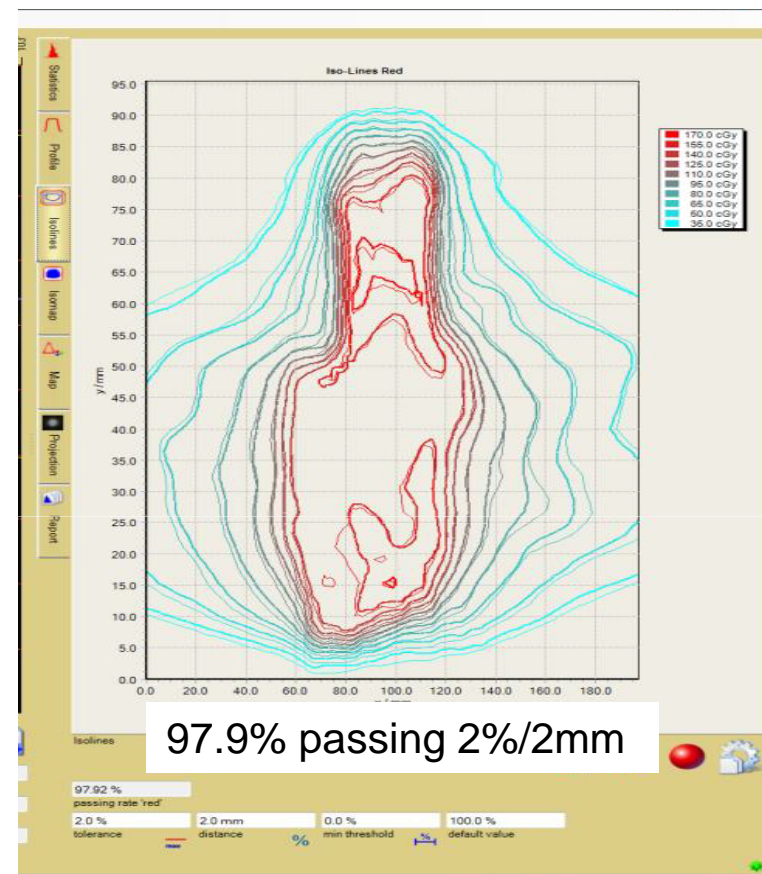
Scan-to-scan variability



Scan-to-scan Variability



First scan

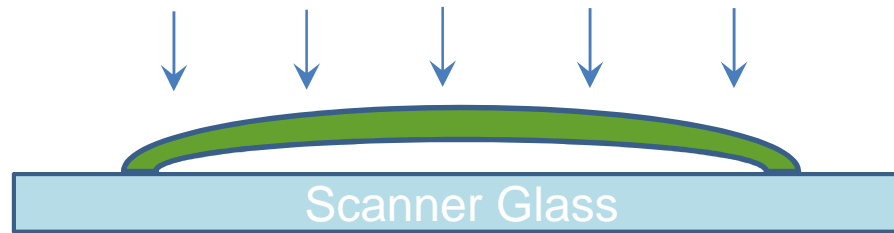


Re-scan

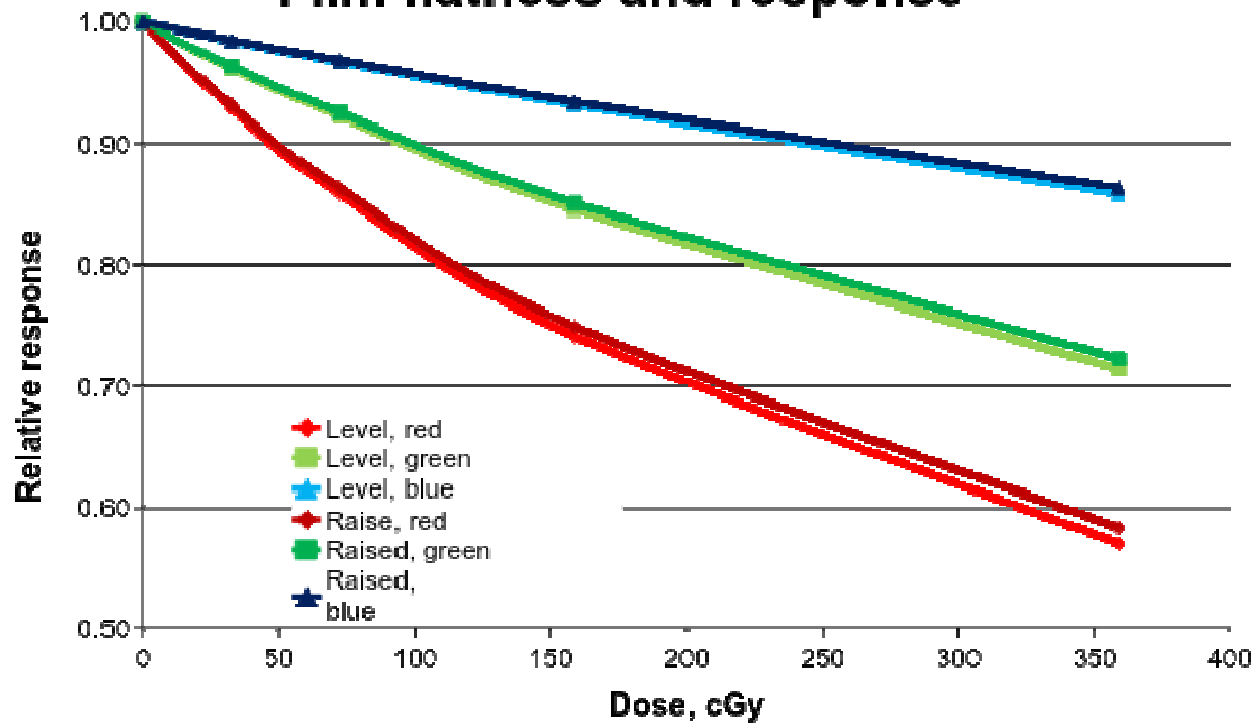
Use the “One-scan” protocol to eliminate scan-to-scan variability



Film Flatness - the Callier Effect

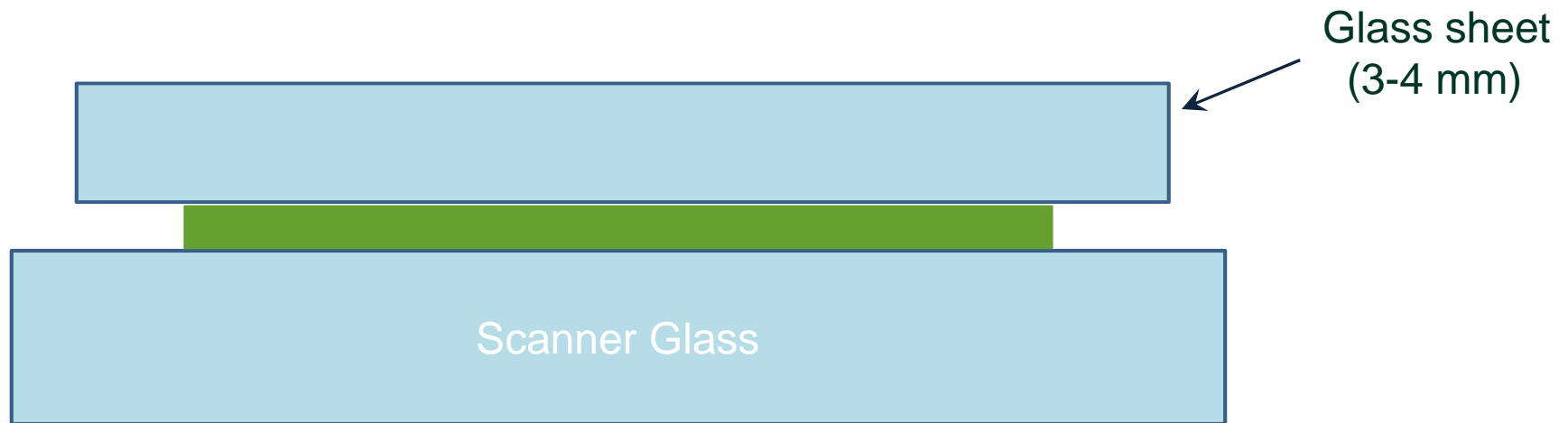


Film flatness and response

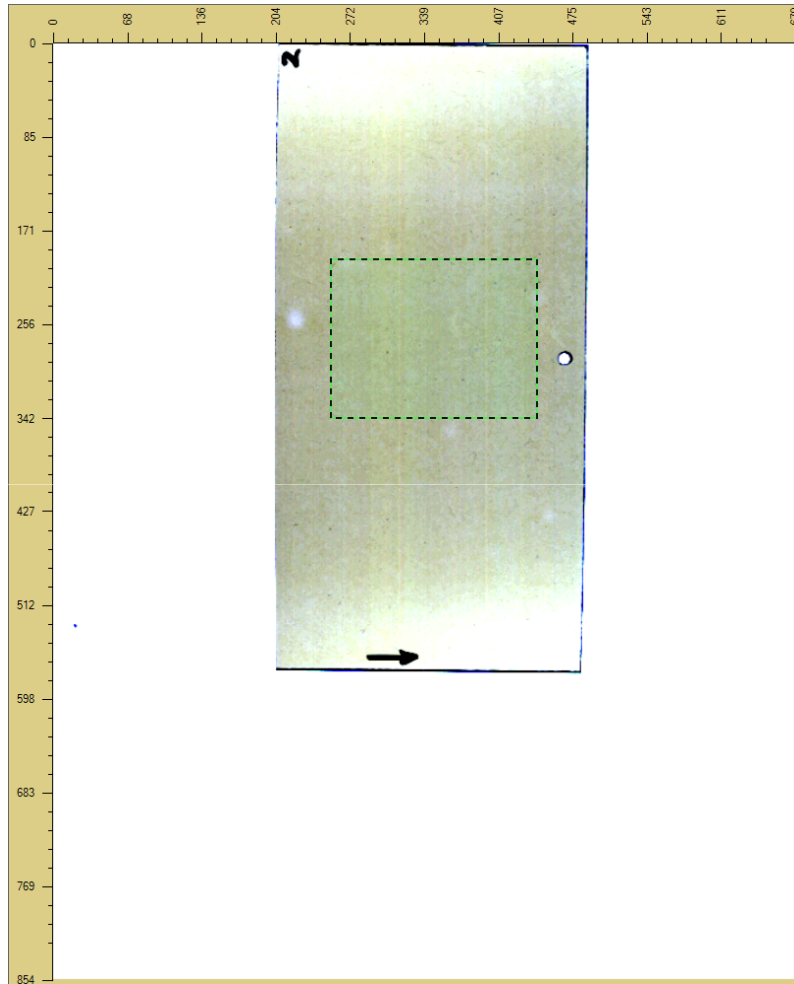


Transmission changes with the distance to a diffuse light source

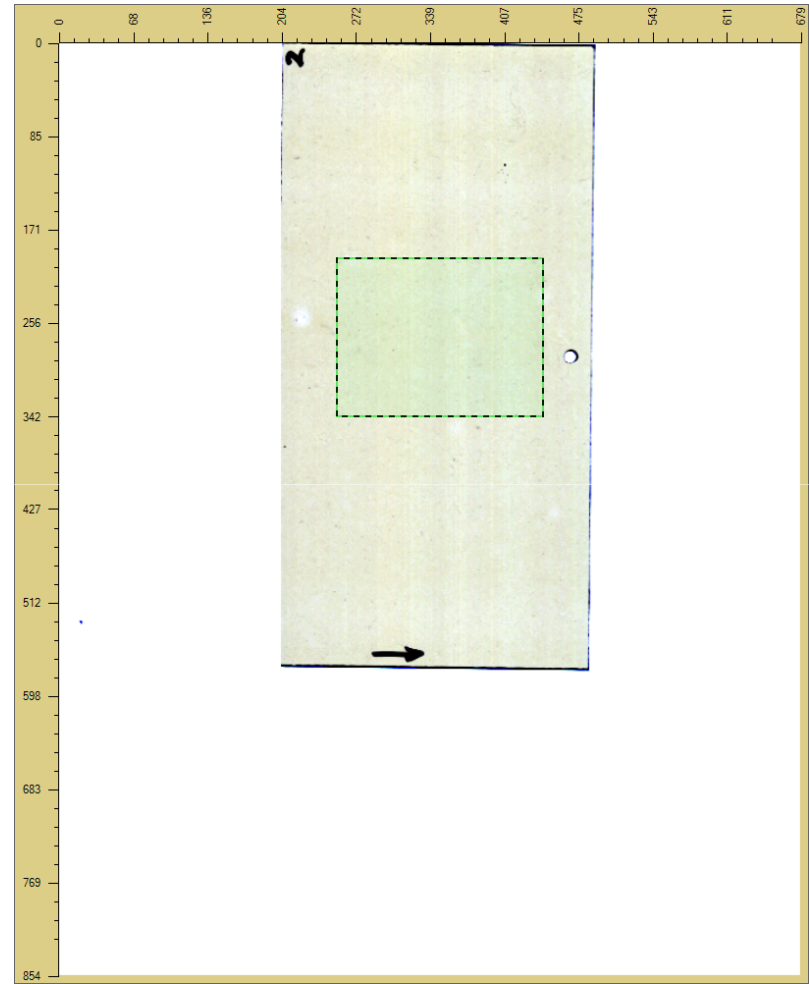
Make the Film Lie Flat



Film flatness and response uniformity



Scanner Glass



Scanner Glass

The 'One-scan' Dosimetry Protocol

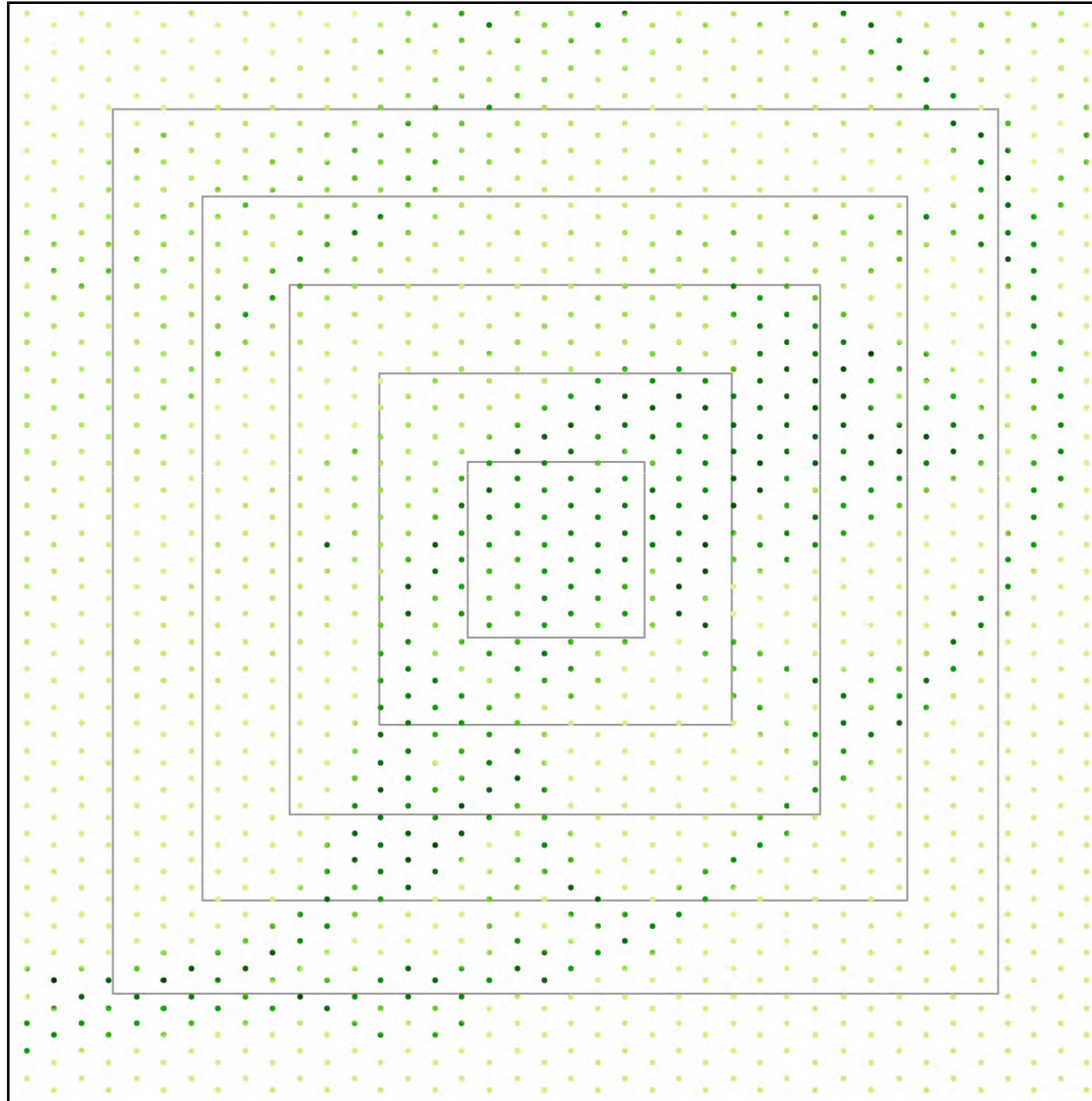
“An Efficient Protocol for Radiochromic Film Dosimetry Combining Calibration and Measurement in a Single Scan” D. Lewis, A. Micke, X. Yu and M. F. Chan, Medical Physics 39(10) p6339-50, October 2012

David F. Lewis
Advanced Materials Group

March, 2014

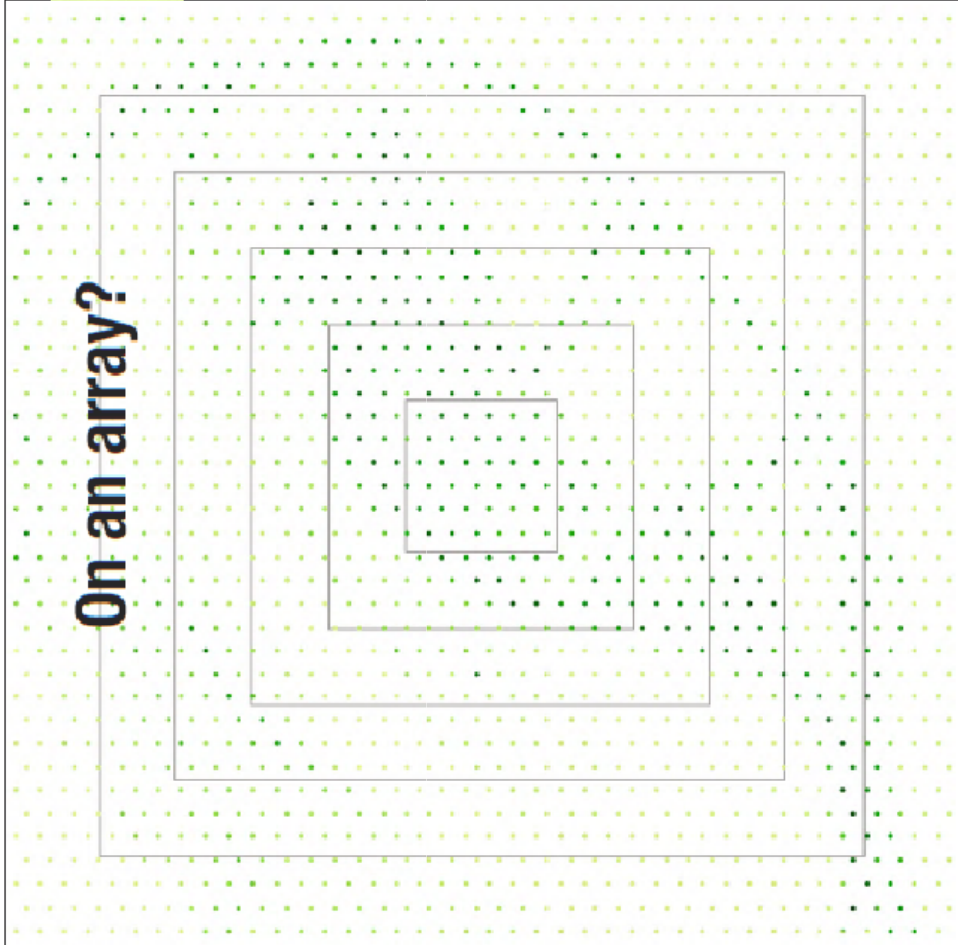


What does an array see?



How do you capture a chameleon?

On an array?



Or on our film?



GafChromic

ASHLAND

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**

Film Dosimetry – The Past

**Film is
a hassle.**

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

Film Dosimetry – The Present

Film is
~~a hassle.~~

sna

p

How did we do that?

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

'One-scan' Calibration

ISP FilmQA Pro - RapidArc - 2 arcs A012412 for web - Calibration tool

File Panel Data Help

- Case description
- Film calibration (ordinary)
 - Data - Calibration film
 - Tool - Image viewer and editor
 - Tool - Calibration tool
- Dose map (single scan)
- Dose to plan comparison
- Case object management

0 87 175 262 349 436 524 611 698 786 873

0 171 341 512 682 853 1023 1194 1364 1535 1705

color / (16 bpch)

D / cGy

— Red(Dose) — Green(Dose) — Blue(Dose)

◆ Green(Dose) [discrete] ▲ Blue(Dose) [discrete] ● Red(Dose) [discrete]

Calibration function

$1/x$
Color reciprocal linear vs dose - $X(D) = A + B / (D - C)$

Calibration model equation

Radiation absorbed dose <cGy>	Red <(16 bpch)>	Green <(16 bpch)>	Blue <(16 bpch)>
368.8	21519	26878	19640
138.3	31101	35039	22299
69.2	36513	38583	23375
0.0	44162	42479	24340

Calibration table

8:29 AM > 51 %

Start | Inbox - Micros... | Complete Glob... | RE: The brandi... | ISP FilmQA P... | 4 Microsoft O... | Medical Physic... | Medical Physic... | Ashland Pres (... | Document1 - M... | Efficient Calbr... | 8:31 AM

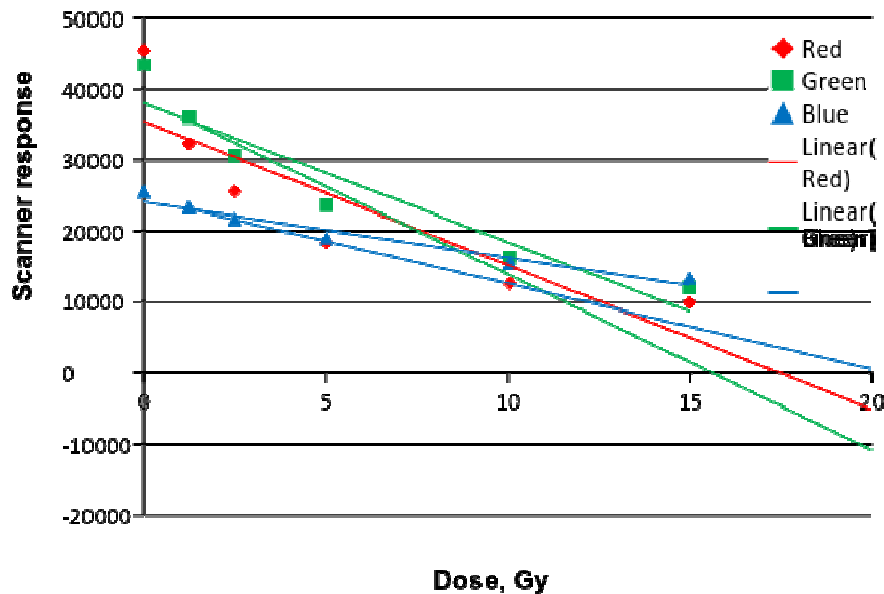


Correlating Calibration Data

Polynomial Functions

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

D = dose, X(D) = response

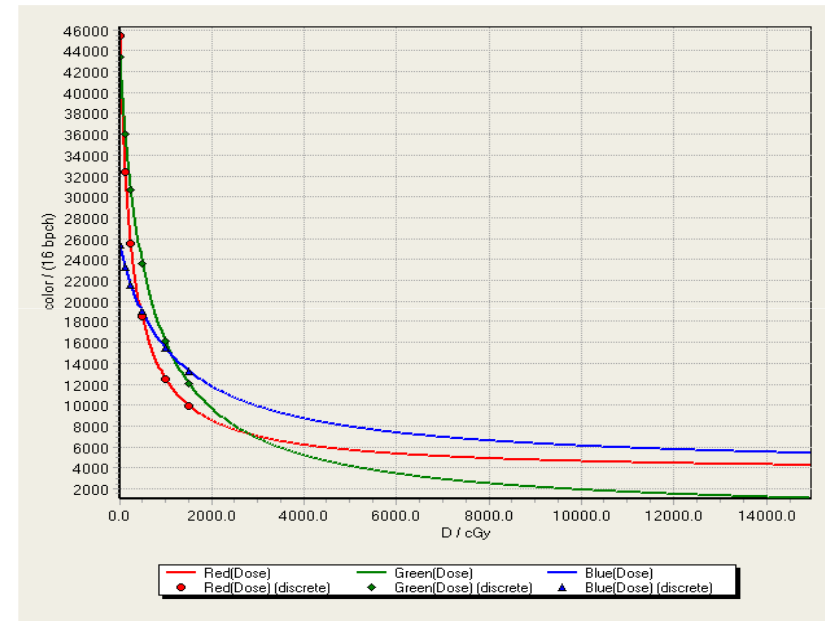


Not consistent with core properties of film ✗
 Function often oscillates between values ✗
 Cannot be inverted ✗

Rational Functions

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

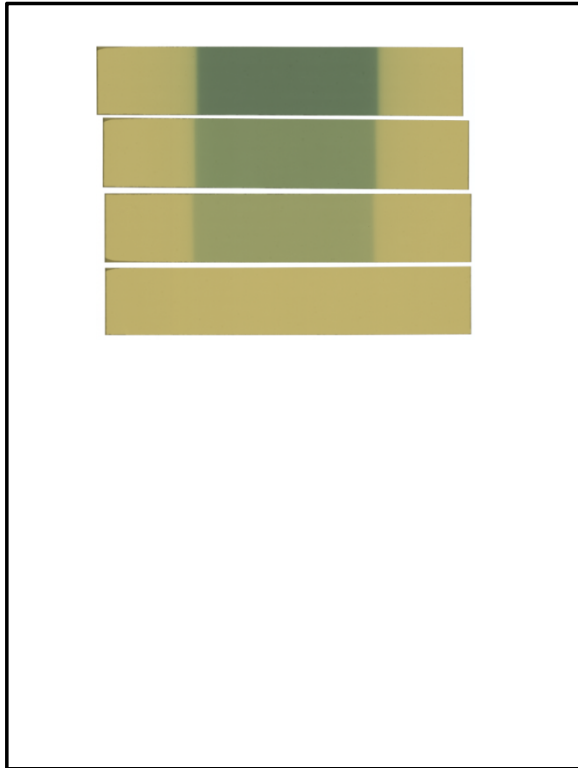
D = dose; X(D) = response



“Behaves” like film ✓
 Easily inverted - $D = c + b/(X(D)-a)$ ✓



Just 'One-scan' for Calibration



4 strips: ~ 4x20 cm²
10x10 cm² field for exposure



Don't waste your time with too many calibration exposures

'One-Scan' for Measurement

ISP FilmQA Pro - RapidArc - 2 arcs A012412 for web - Image viewer and editor

File Panel Data Help

Case description

- Film calibration (ordinary)
 - Data - Calibration film
 - Tool - Image viewer and editor
 - Tool - Calibration tool
- Dose map (single scan)
 - Data - dose film
 - Data - dose map (read only)
 - Data - consistency map (read only)
 - Dependence - Film calibration (ordinary)
- Dose to plan comparison
- Case object management

Image 'dose film' - 78 %

reference 0.0 cGy

reference 313.0 cGy

	Cursor region <(16 bpch)>	Full image <(16 bpch)>	Union of all frames <(16 bpch)>
R average	43302	47384	33636
R std deviation	85	14824	10646
R min	43183	3646	22328
R max	43401	85533	44983
G average	41832	48239	35445
G std deviation	127	13623	7086
G min	41612	4289	27659
G max	42003	85534	43407
B average	23915	38985	22143
B std deviation	54	20390	2140
B min	23899	2503	19541

Pixel statistics (631 , 319)

Histogram 'dose film'

Color channel: Red

Region: Rectangle [326, 484] x [89 x 168] = [W=158, H=80]

Probability / %

Color channel / (16 bpch)

Histogram 'dose film'

Selected, first or full frame

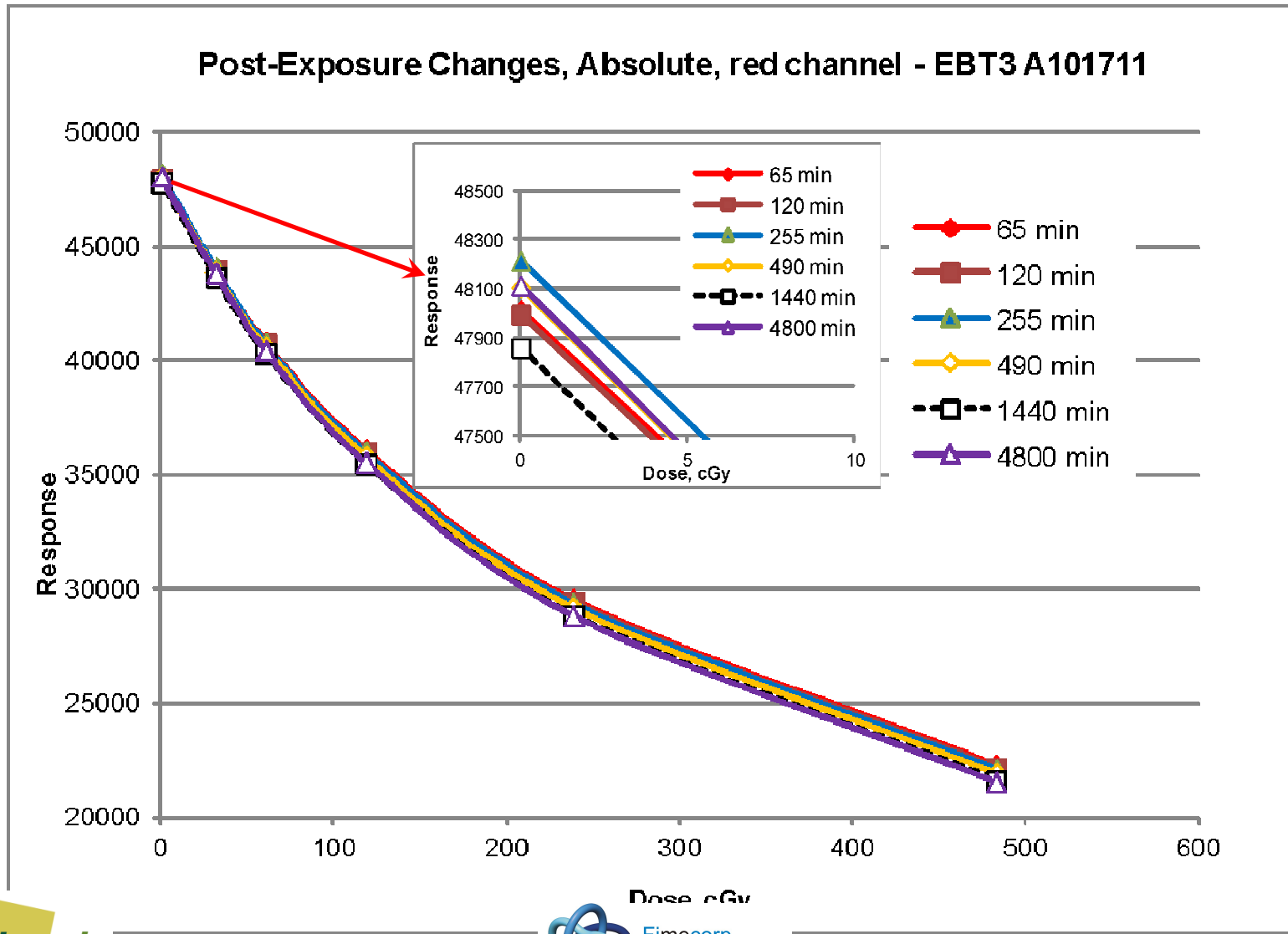
Image histogram region

8:32 AM - Auto scale contour palette is off.

Start | Inboxes - Micros... | Complete Glob... | RE: The brandi... | ISP FilmQA P... | 4 Microsoft O... | Medical Physic... | Medical Physic... | Ashland Pres (... | Document1 - M... | Efficient Calbr... | 8:33 AM

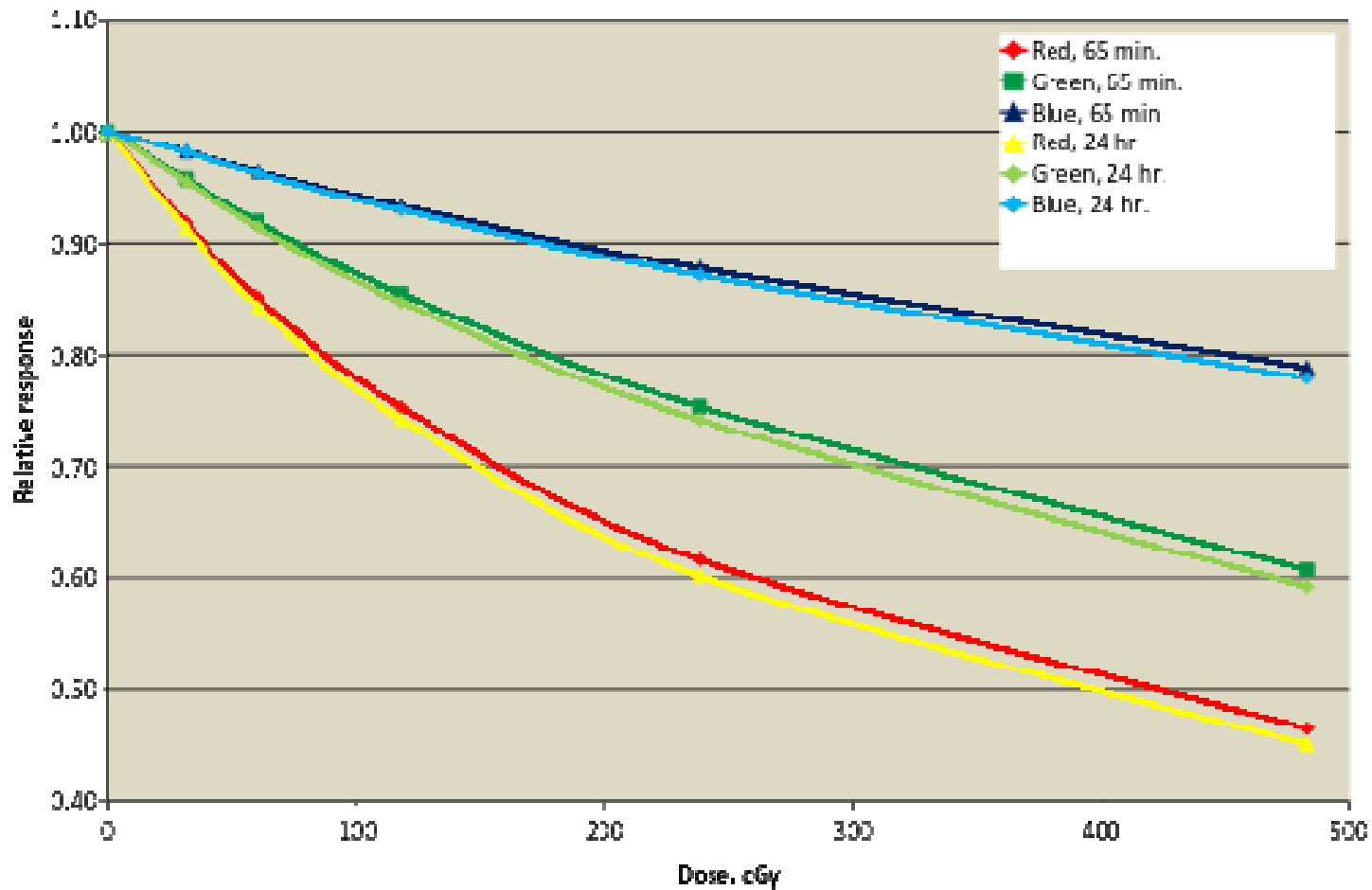


Post-Exposure Change



Response Normalized to Unexposed Film

Post-exposure change and normalized response



Scale the Normalized Responses

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

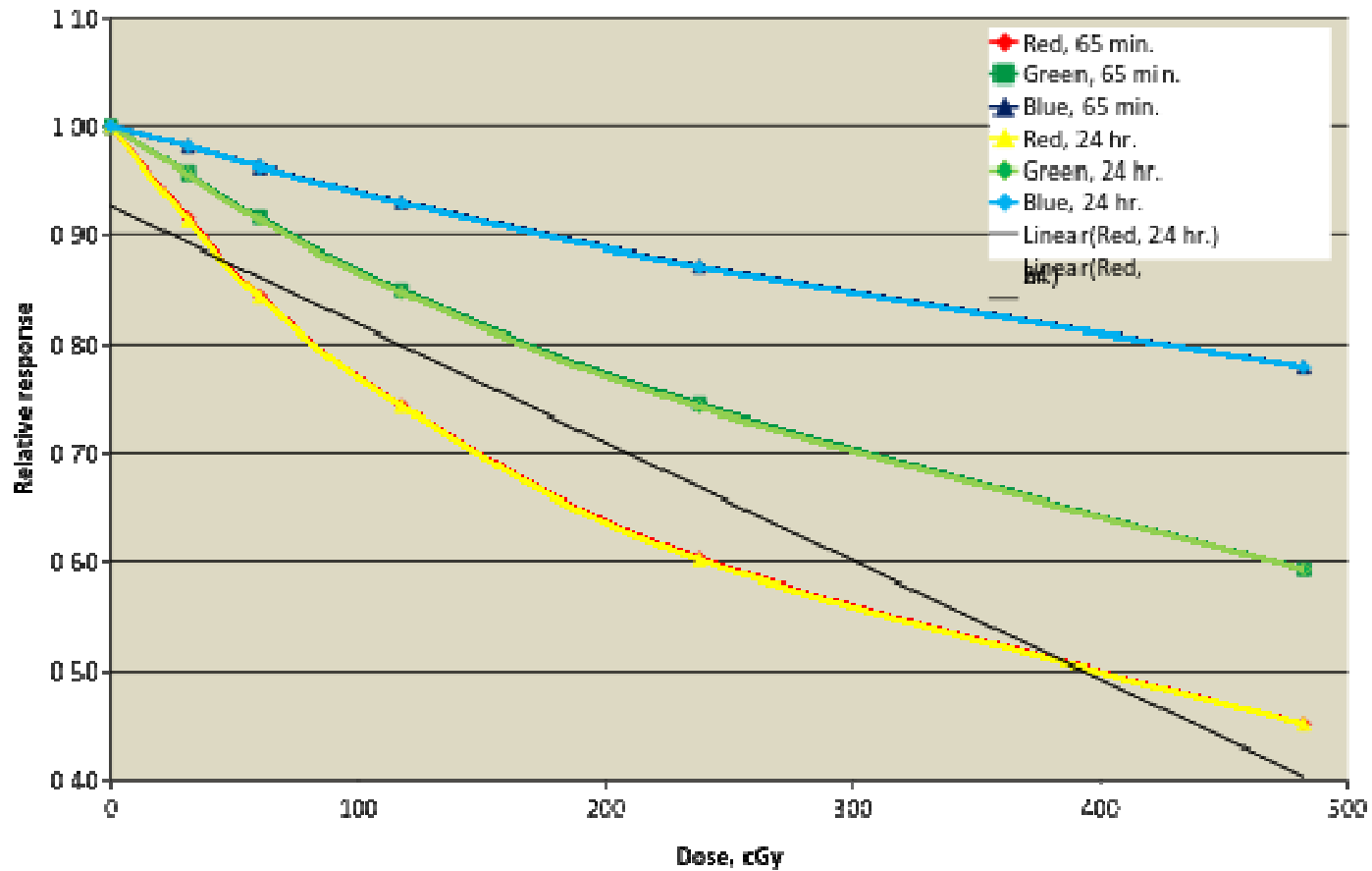
$$\begin{aligned} X_{\text{net}}(C,D,t) &= X(C,D,t) - X(C,\text{zero},t) \\ &= X(C,D,t) - 1 \end{aligned}$$

- For all doses:

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

After Normalization and Scaling

Relative responses after scaling

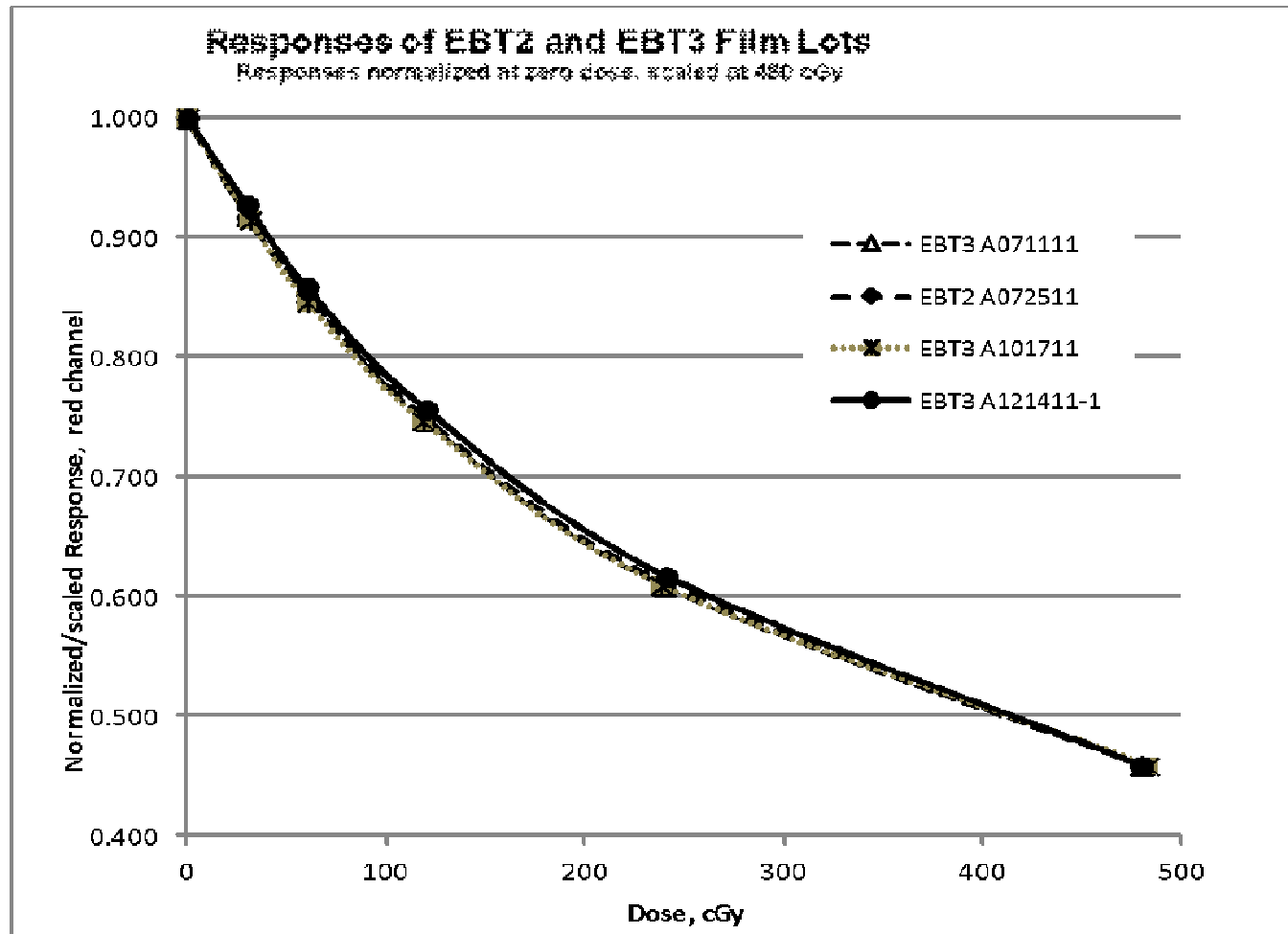


Similar Equivalences

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



Lot-to-lot: Curves Have Different Shape



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



Dosimetry with Two-point Re-scaling

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



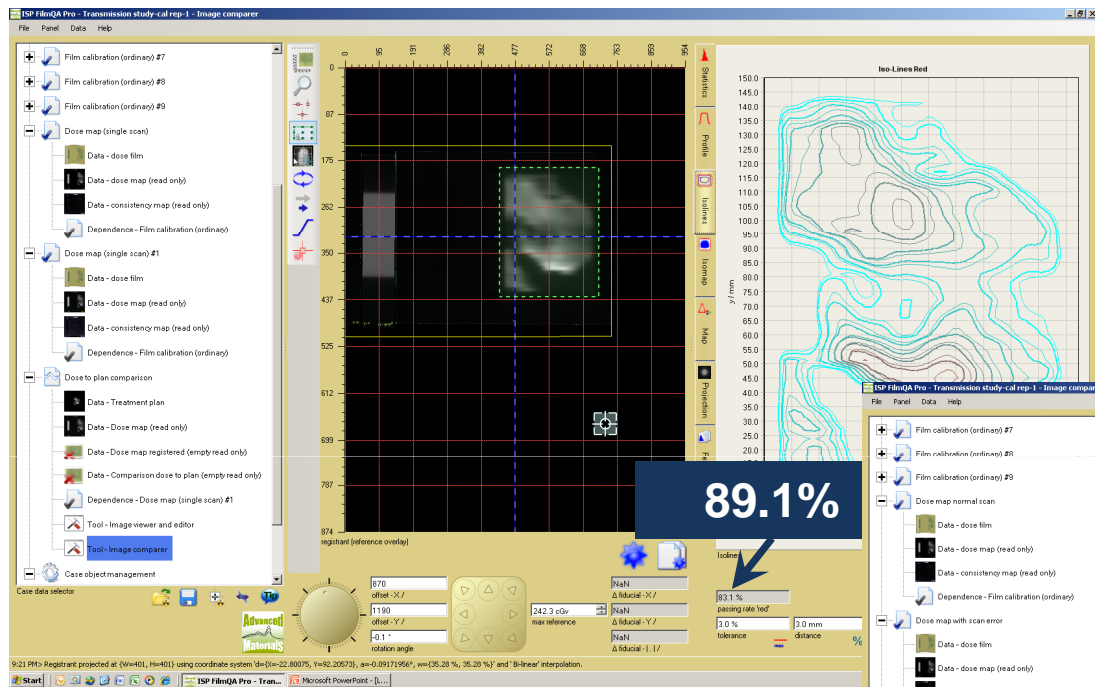
Benefit of Re-Scaling

- 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

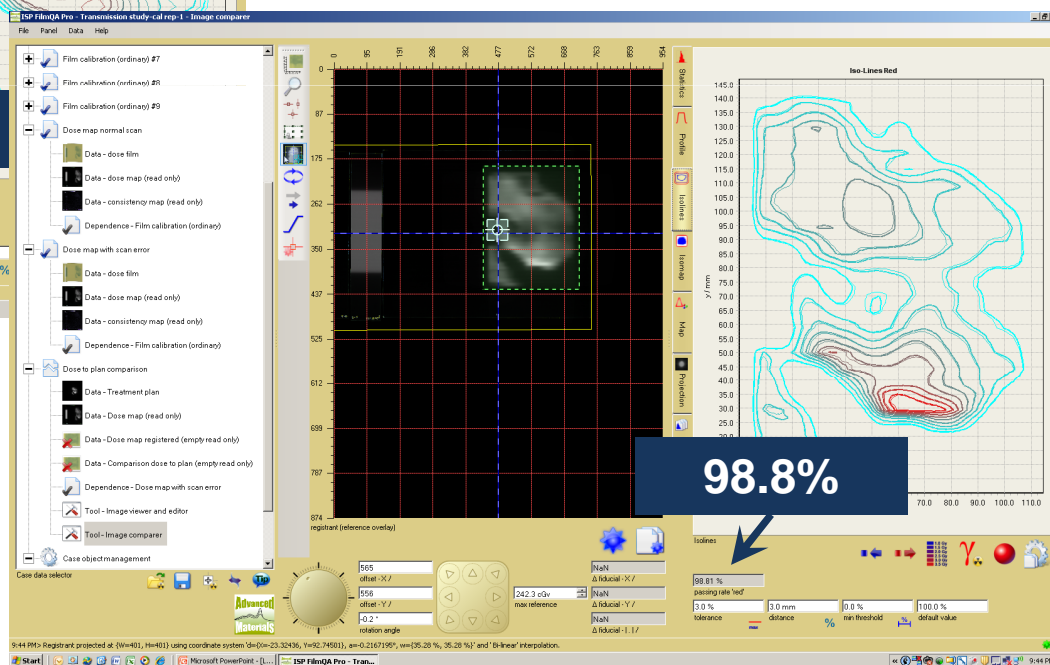


Response Variability may Impact Results

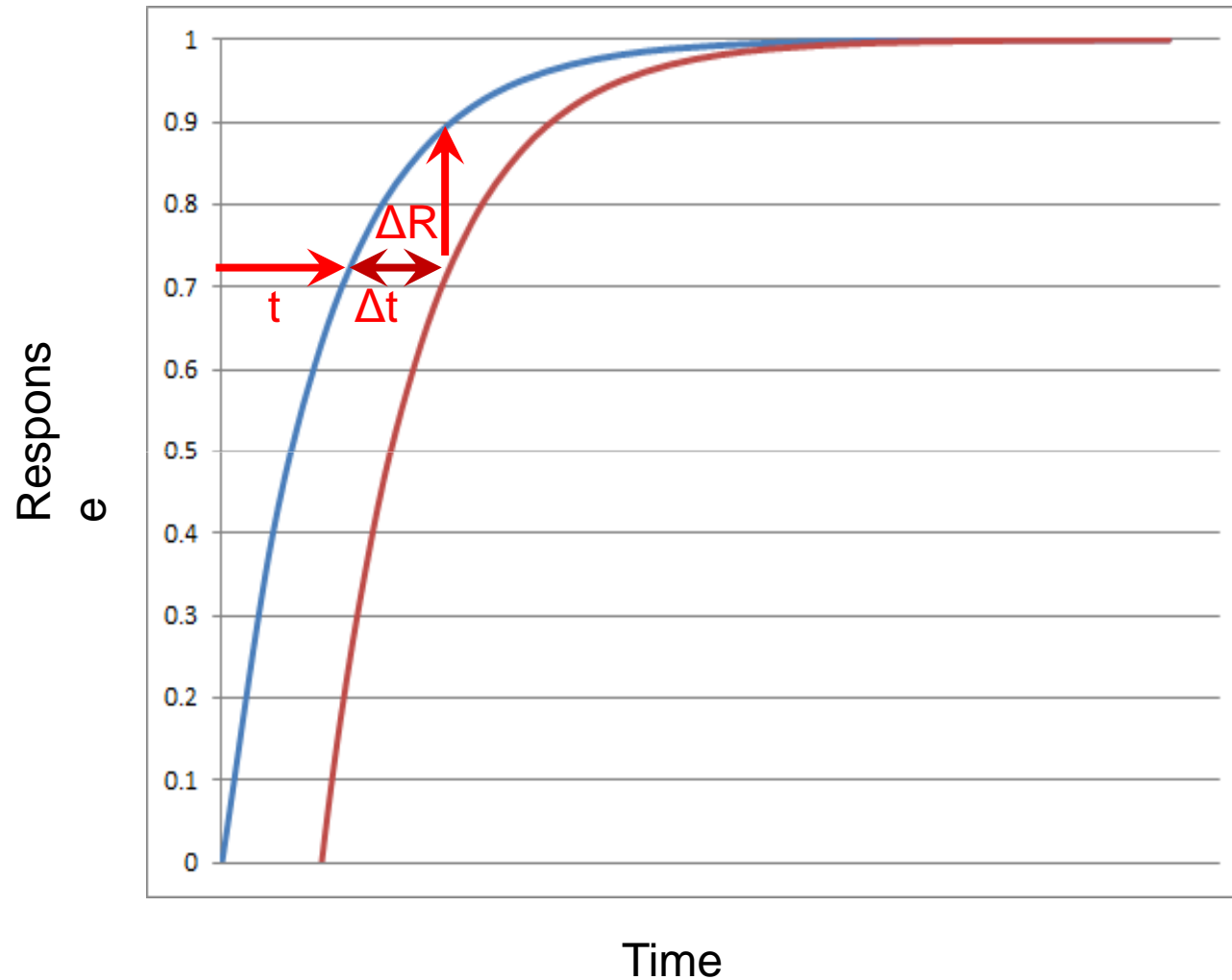
Without reference films



With reference films



Accommodate post-exposure change - Use relative aging



When $t > 2.\Delta t$ 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

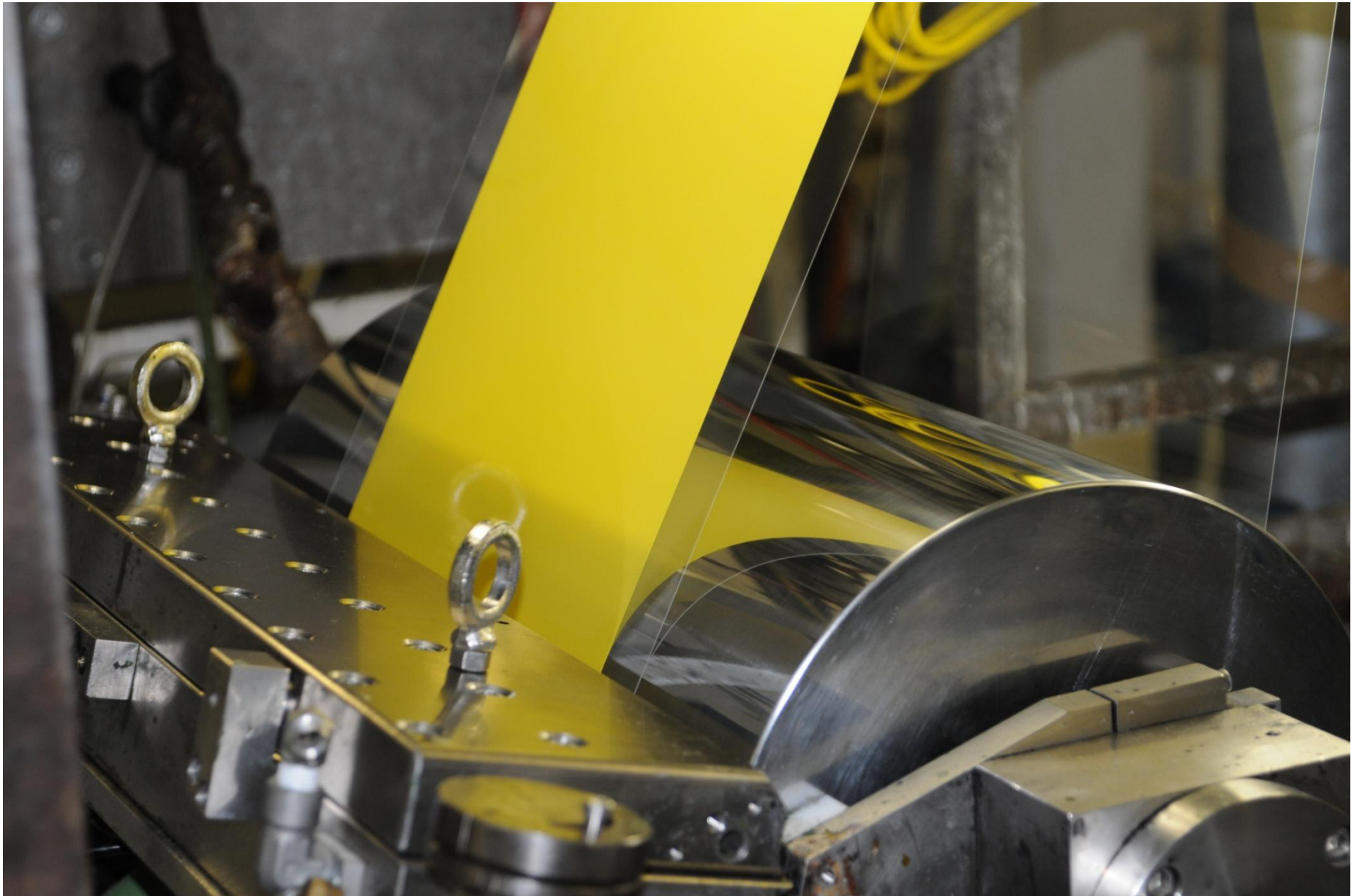
- Calibration films scanned at various times after exposure
- Use a calibration function for film scanned at 2 hours
- Calculate dose maps using two-point re-scaling



'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

Coating Radiochromic Films

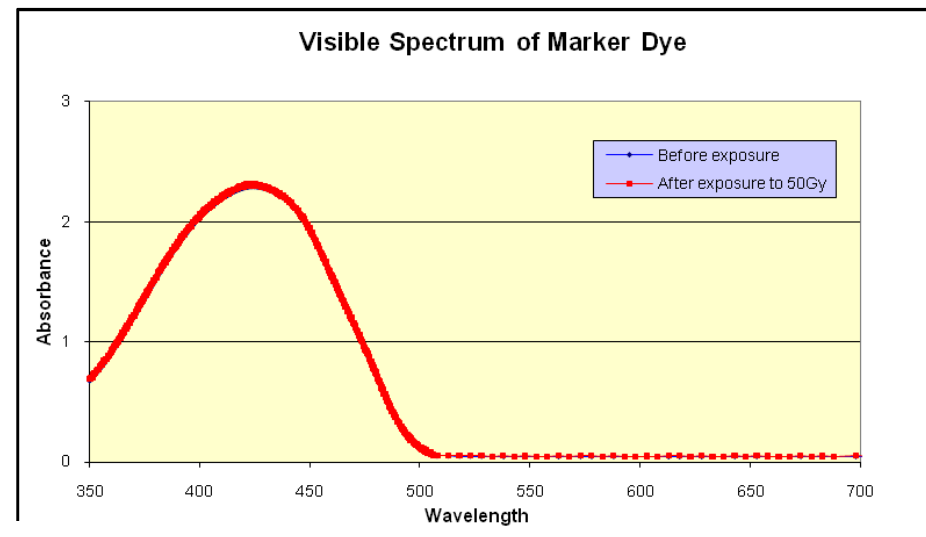
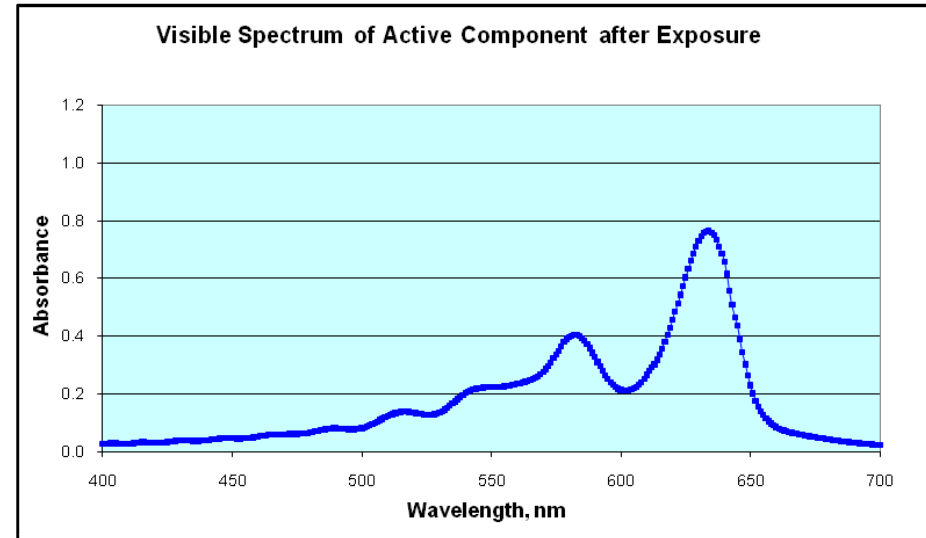


So tell me, why is that film yellow?



Visible Spectra – EBT2, EBT3 and EBT3+

- Active component
 - Red/green wavelengths
 - Mainly dose information
- Marker dye
 - Blue wavelengths
 - Mainly thickness information



With multi-channel
dosimetry and
FilmQAPro 3.0
software

GafChromic

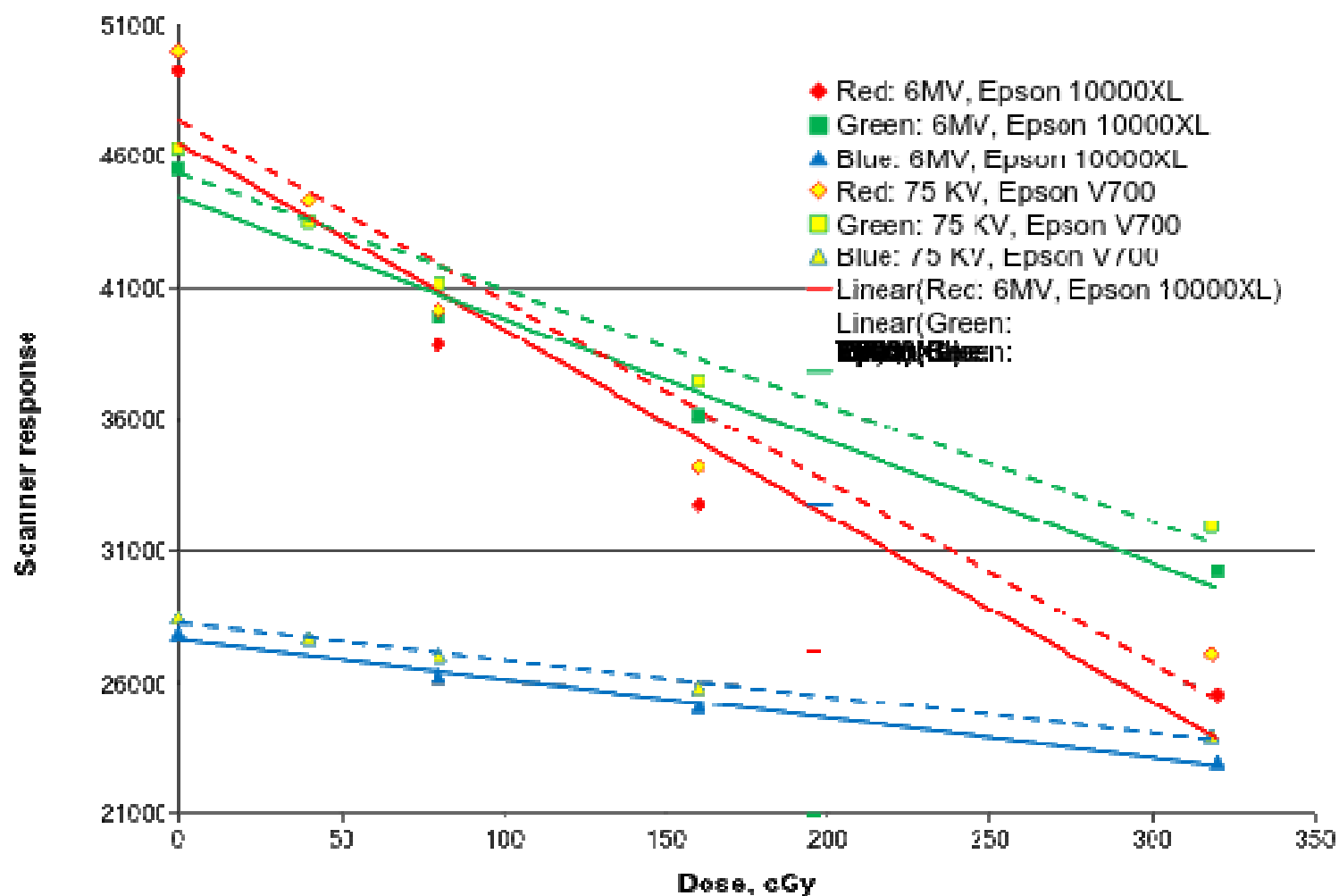
The future is film

ASHLAND

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

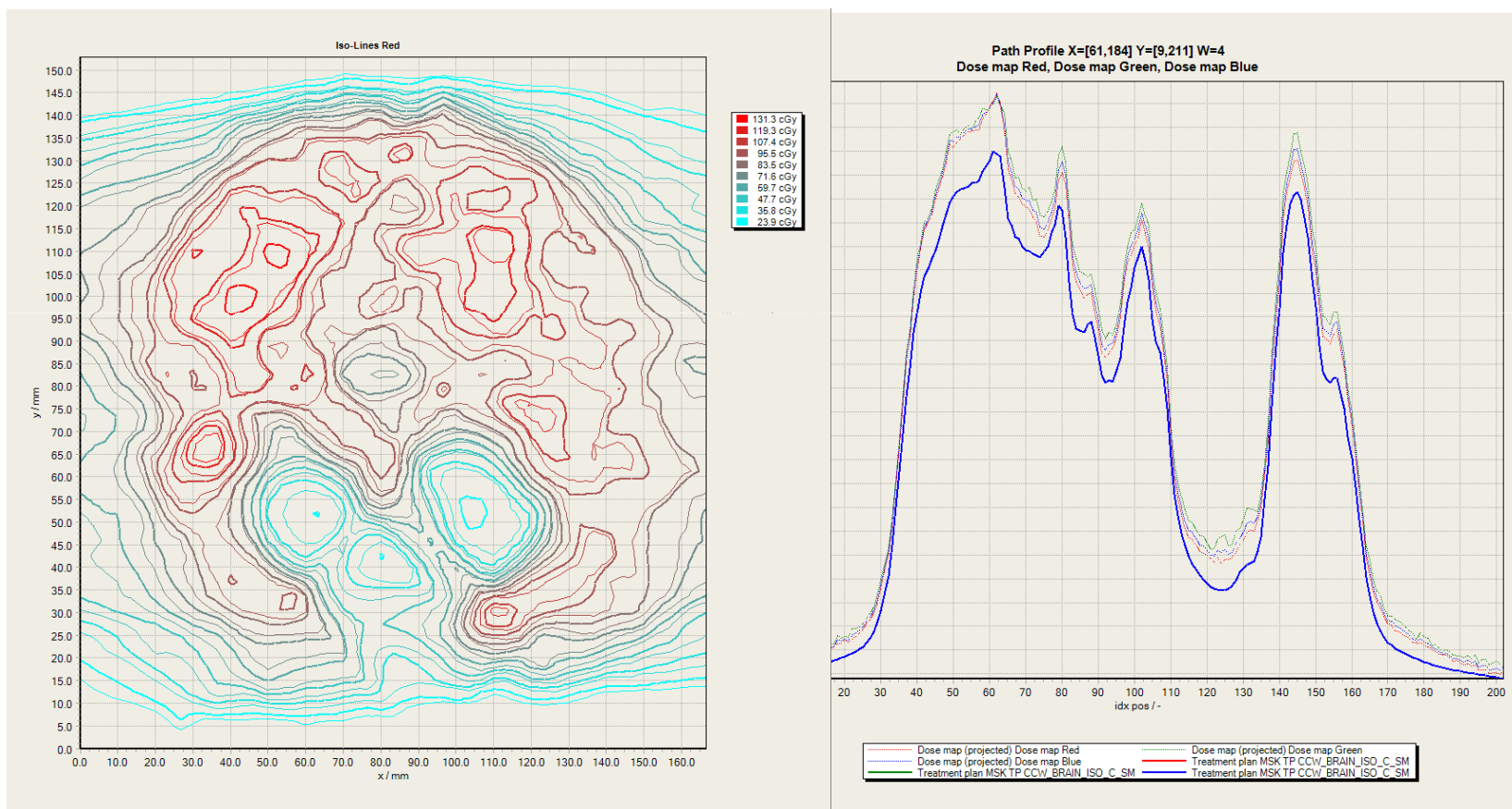
Calibration under Different Conditions



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

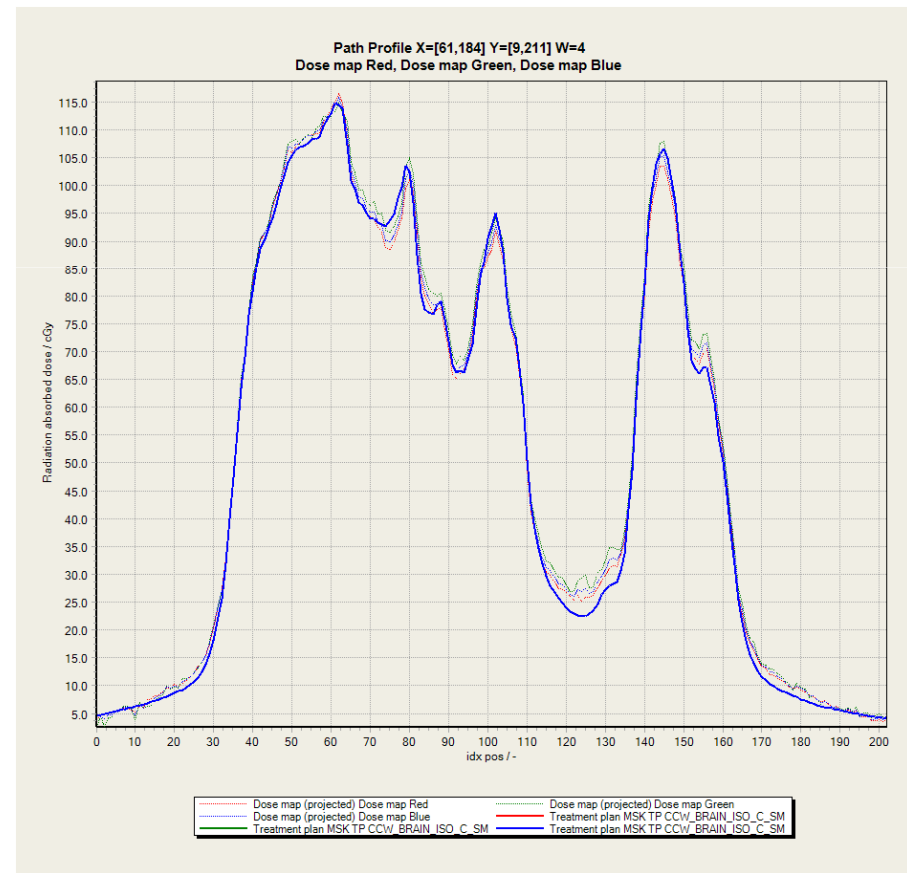
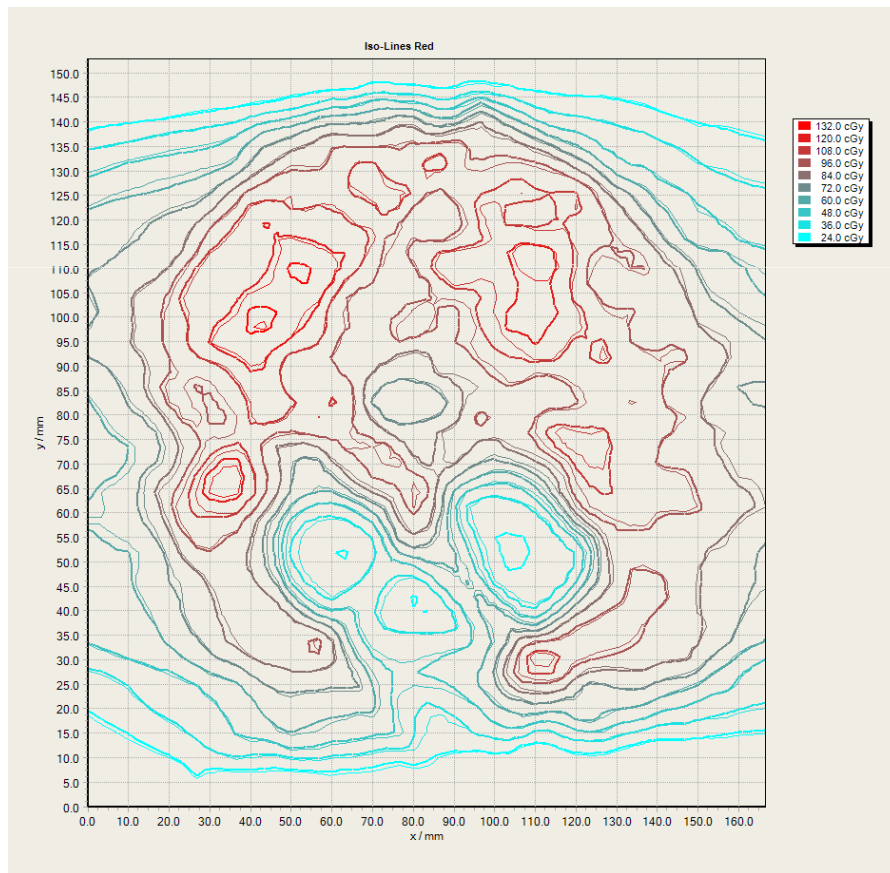
Public function with reference films

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

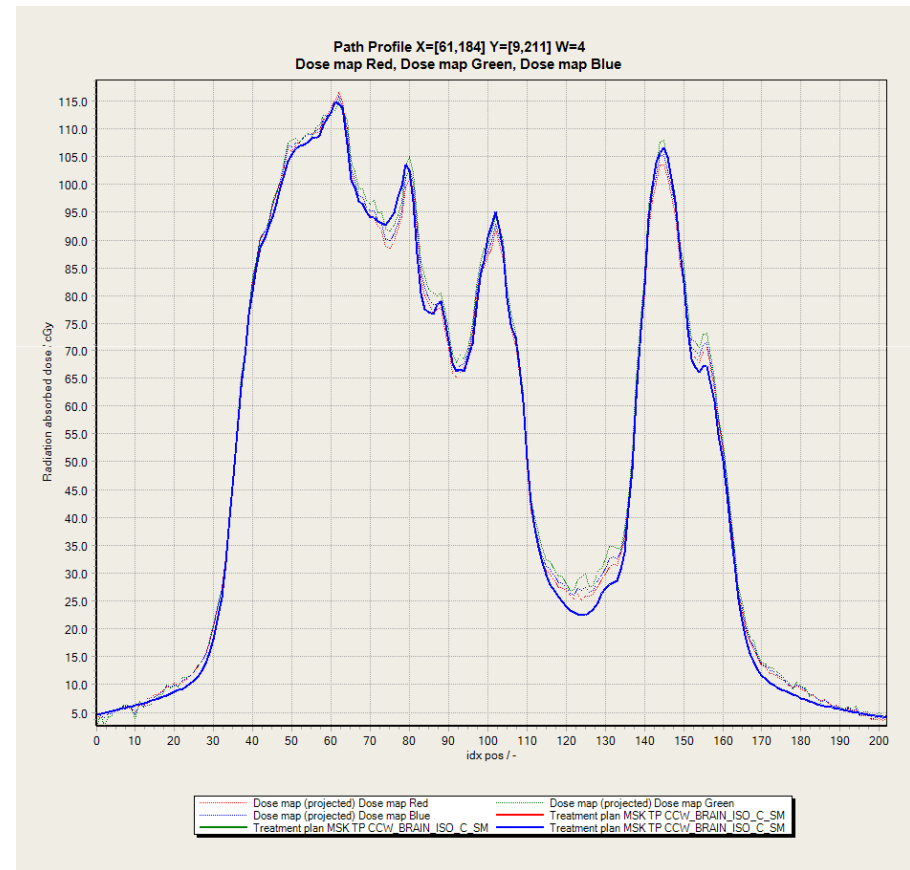
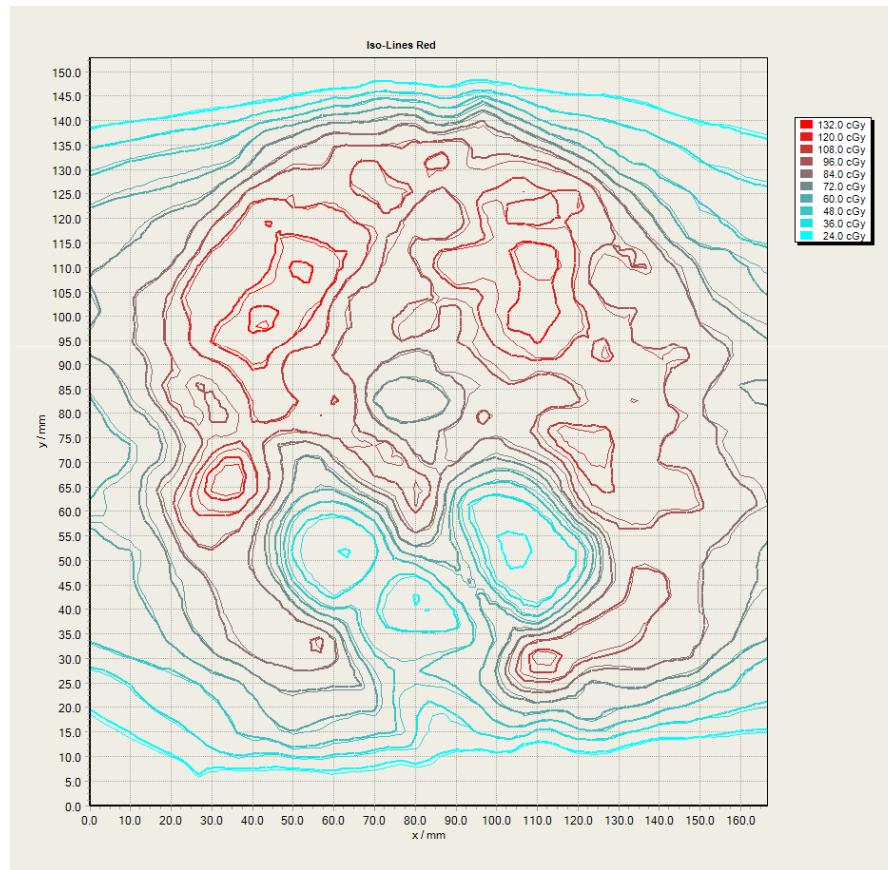


Gamma test (2%/2mm): 96.6% agreement

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

