State of the Art Film Dosimetry

Micke A., Lewis D.

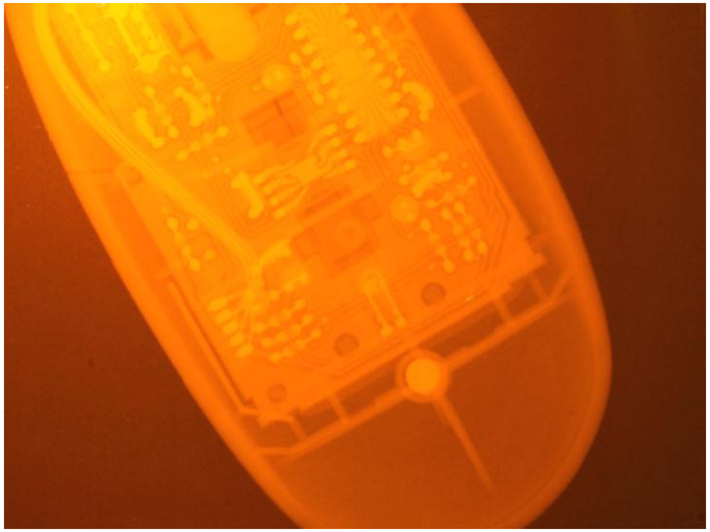
Ashland Inc. – Advanced Materials

Ashland proprietary technology, patents pending

Film Dosimetry

- Radiochromic Film EBT2/EBT3
- One-Scan Protocol
- Multi-channel Film Dosimetry
- FilmQA Pro software

Radiochromic Film



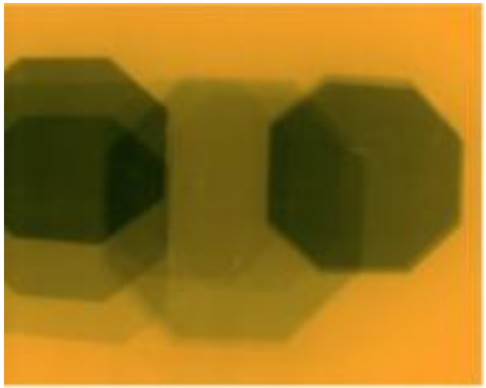
A film that

- changes color on exposure to ionizing radiation
- Color change instantly
- No chemical or physical processing

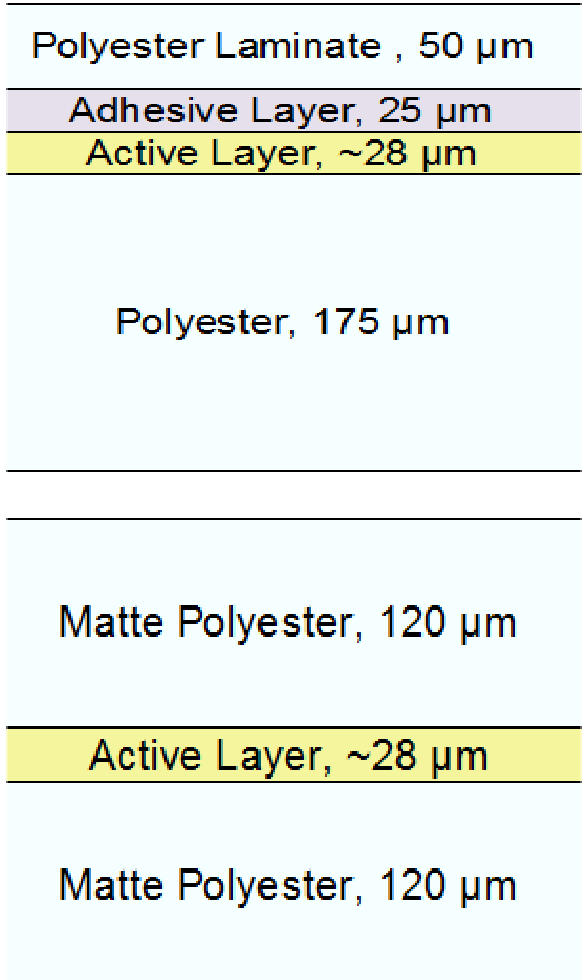
Films for Dose Measurement

- Radiotherapy MV photons, electrons, protons
  - EBT2/EBT3 - 1 cGy to >40 Gy
  - MD-55-V2 - 2 Gy to 100 Gy
  - HD-810 - 10 Gy to 400 Gy

- Radiology kV photons
  - XR-RV3 - 5 cGy to 15 Gy
  - XRQA2 - 1 mGy to 20 cGy



EBT2 and EBT3 - Configuration



EBT2

EBT3

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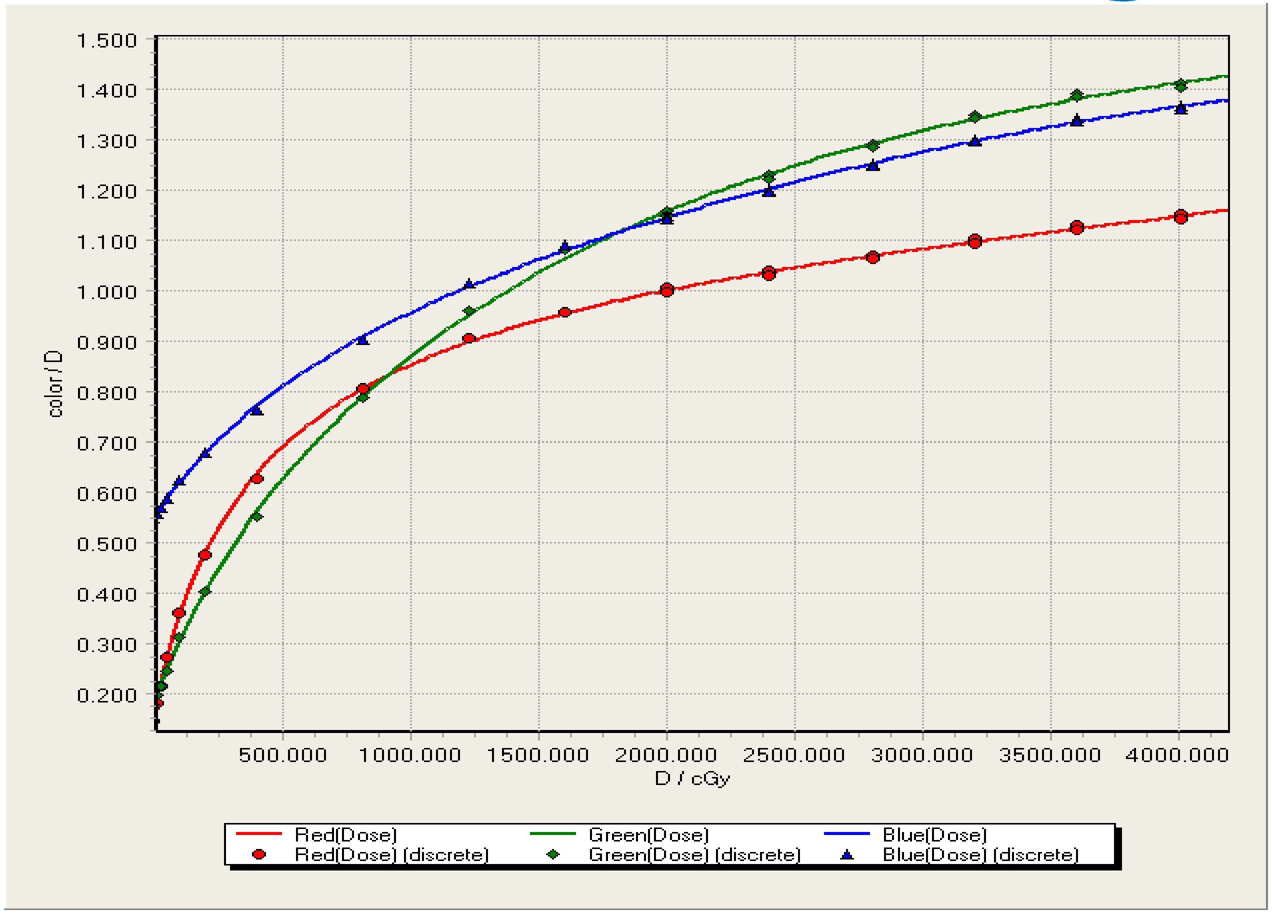
Radiochromic Film Trends

- Trends in conformal therapy
  - Less fractions
  - Higher doses per fraction
  - Tighter conformity
  - Arc therapy
- Trends place high value on radiochromic film
  - High spatial resolution
  - Wide dynamic range
  - Angular independence

EBT2/3 - Dose Range



Dynamic range ~2 cGy to >>40 Gy

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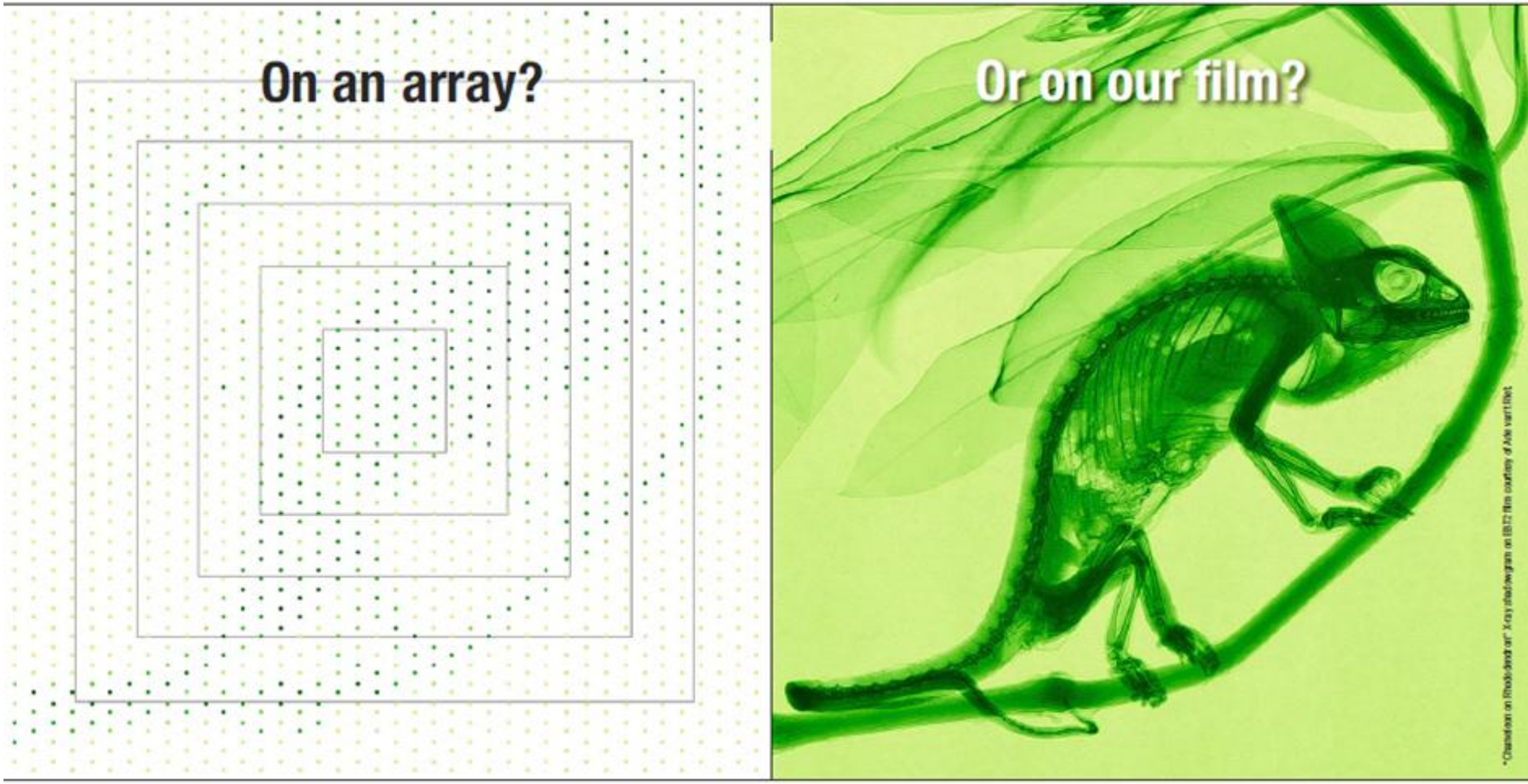
EBT2/3 – Spatial Resolution

Measure, recognize reality – 5 dpi *vs.* 1000 dpi



EBT2/3 – Benefits at a Glance

- High spatial resolution
- Shoot from any angle
- Near water-equivalent
- Nearly energy independent
- Handle in light
- Cut to size, bend to shape
- Immerse in water
- Wide dynamic range

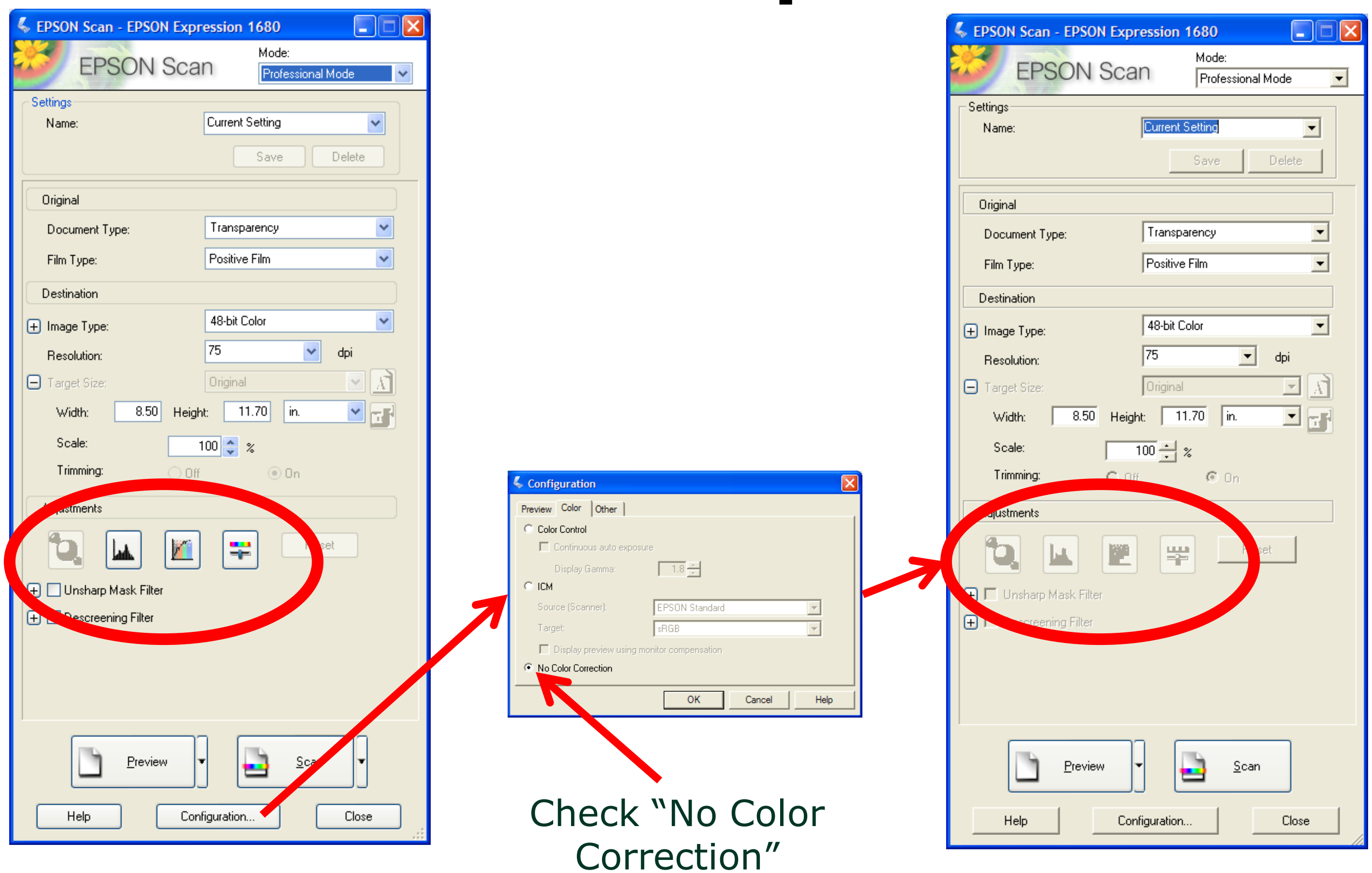
Highly valuable for new conformal therapies

Measuring Gafchromic Film

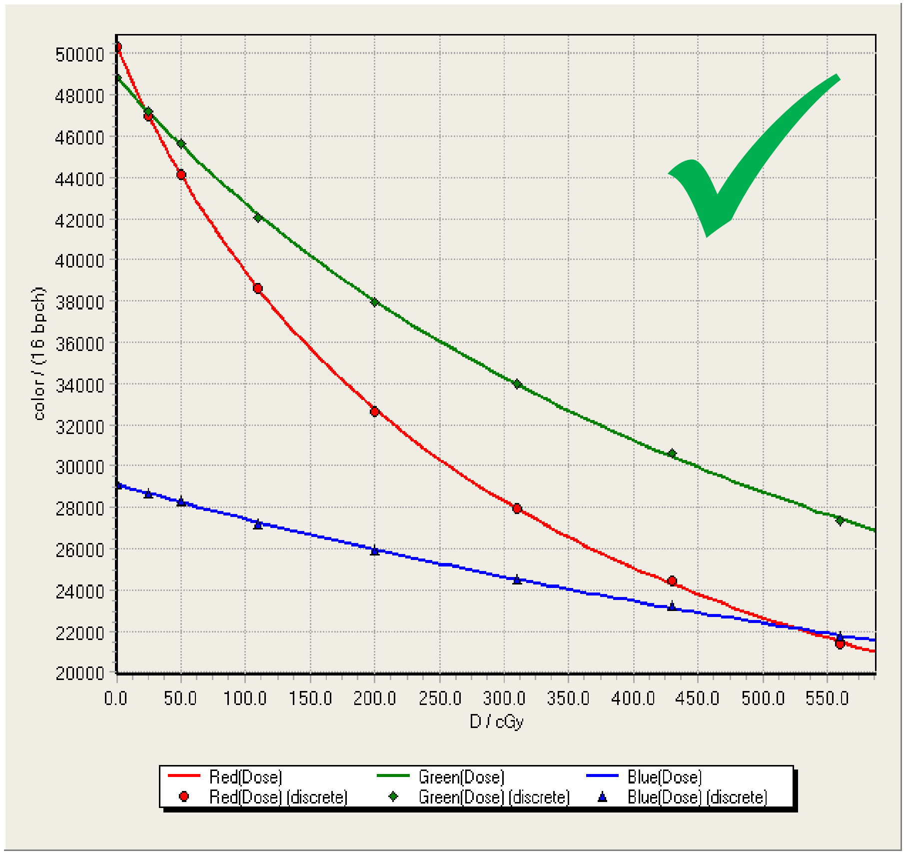
- Color reference chart
- Densitometer
- Scanner
  - Flatbed
  - 16 bit/channel
  - Preferably RGB (enables multi-channel)
- Epson flatbed scanners
  - 10000XL + transparency adapter
    area 12.2″ x 17.2″
  - V700, V750, 1680 and 4990
    area 8” x 10”

Measuring – Color Correction

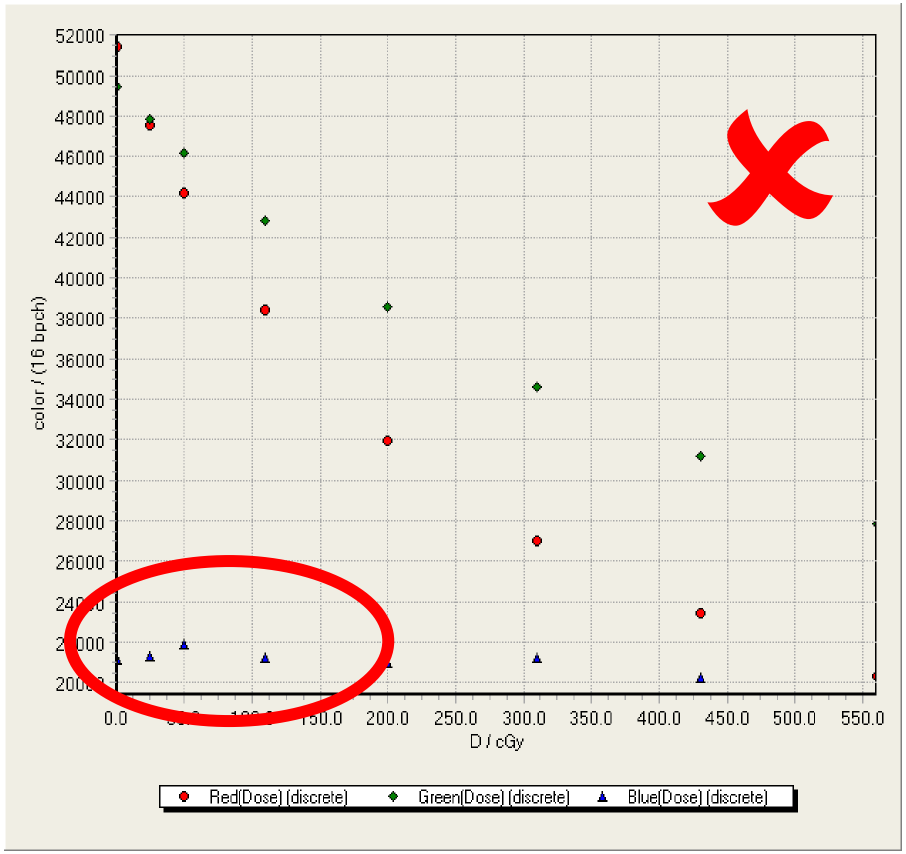
- **Disable color correction options !**
- Epson:



Measuring – Color Correction



Off



On

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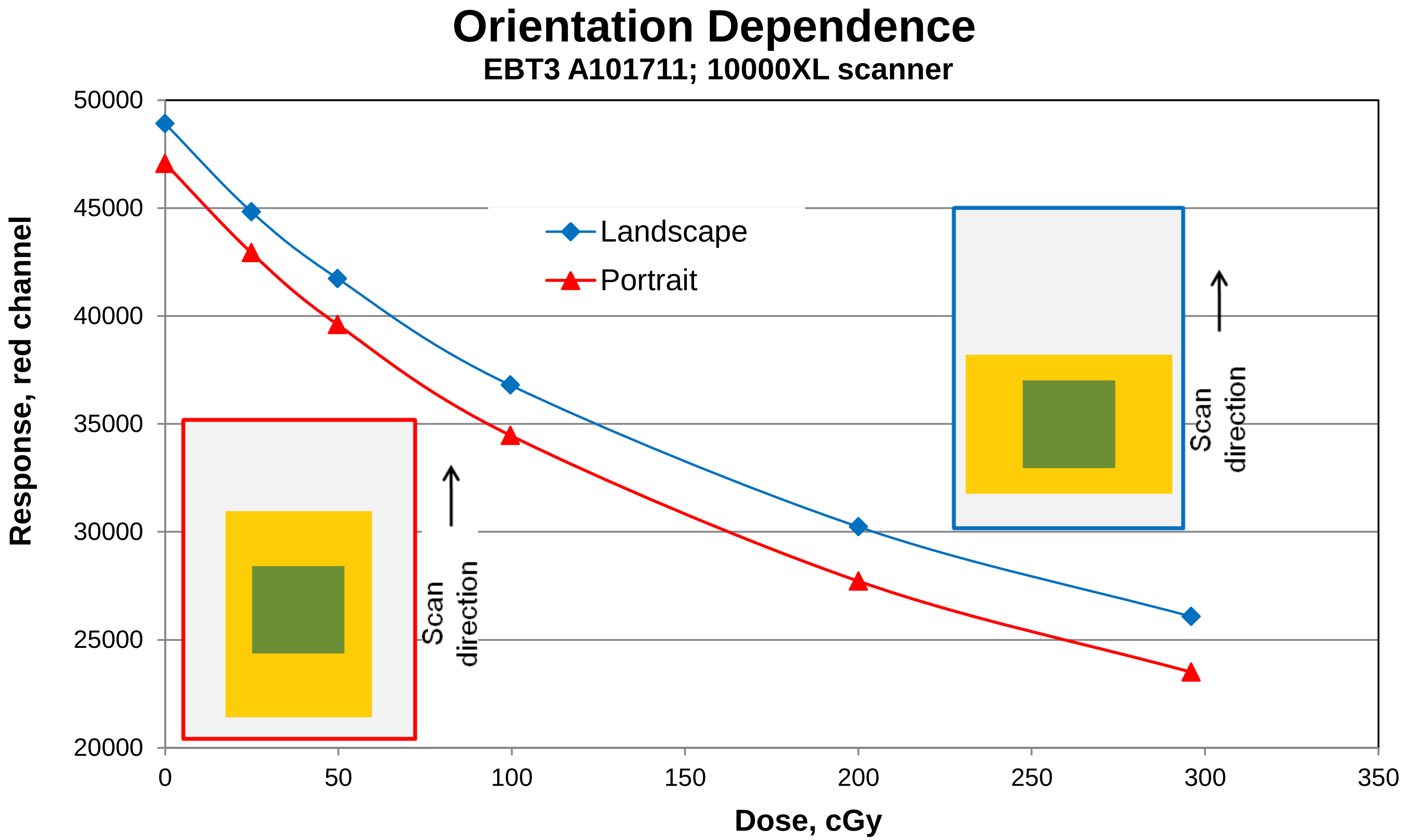
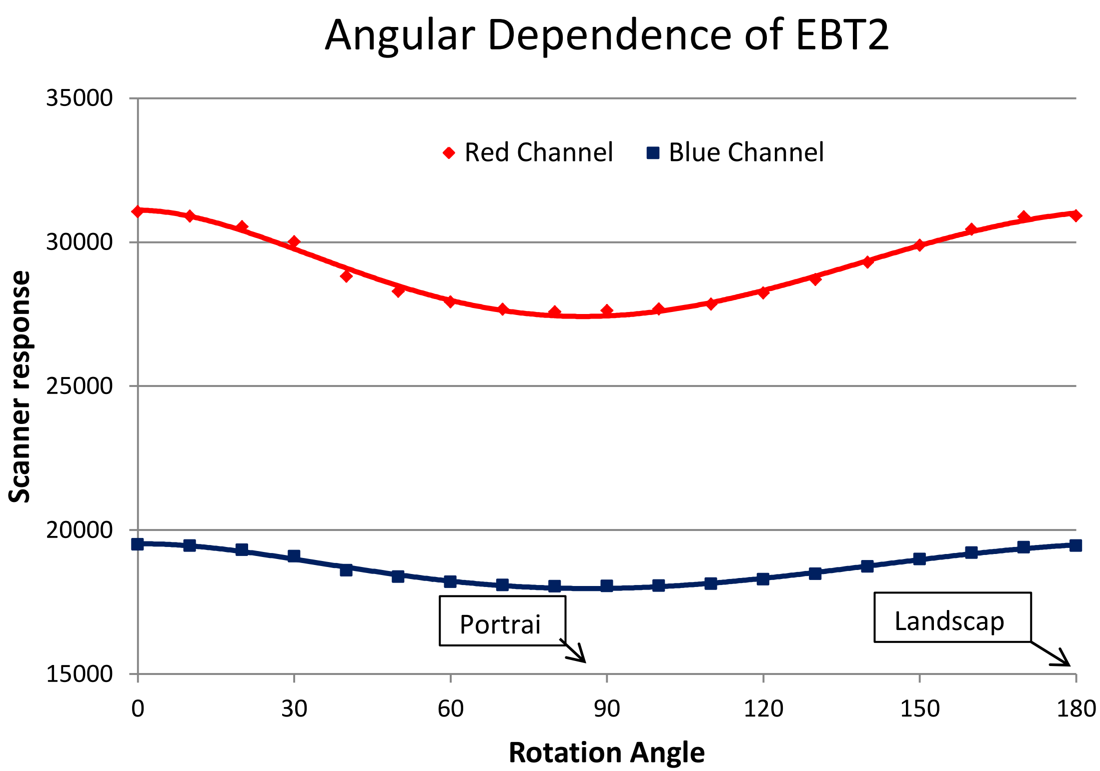
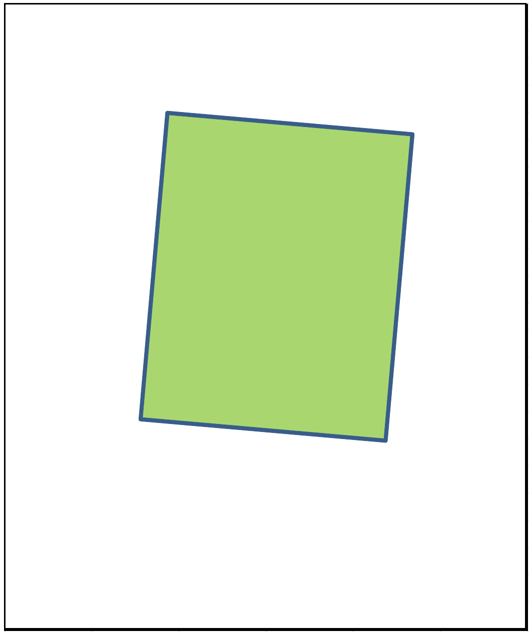
Measuring – Scan Orientation



Both deliver similar results – choose and be consistent!

Measuring – Scan Orientation



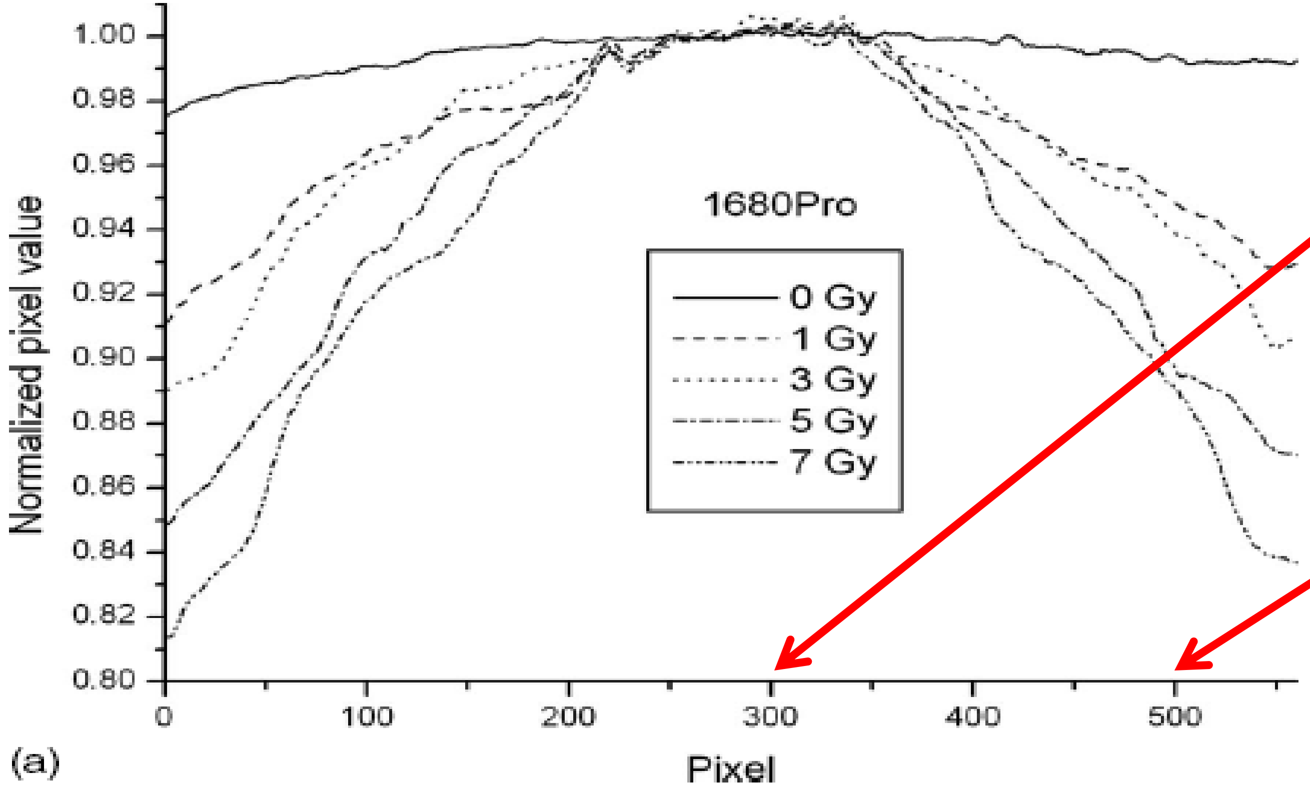


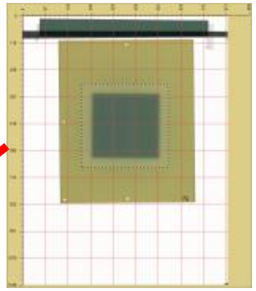
5° misalignment on scanner

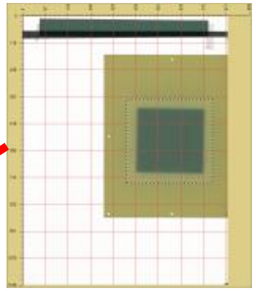
Response error is ~0.05% per degree
Dose error ~0.05 – 0.2% per degree (0-300 cGy)

Measuring – Lateral Effect

Menegotti et al. 2008 Med. Phys., 35, 3078 - 84, Epson 1680, Red channel



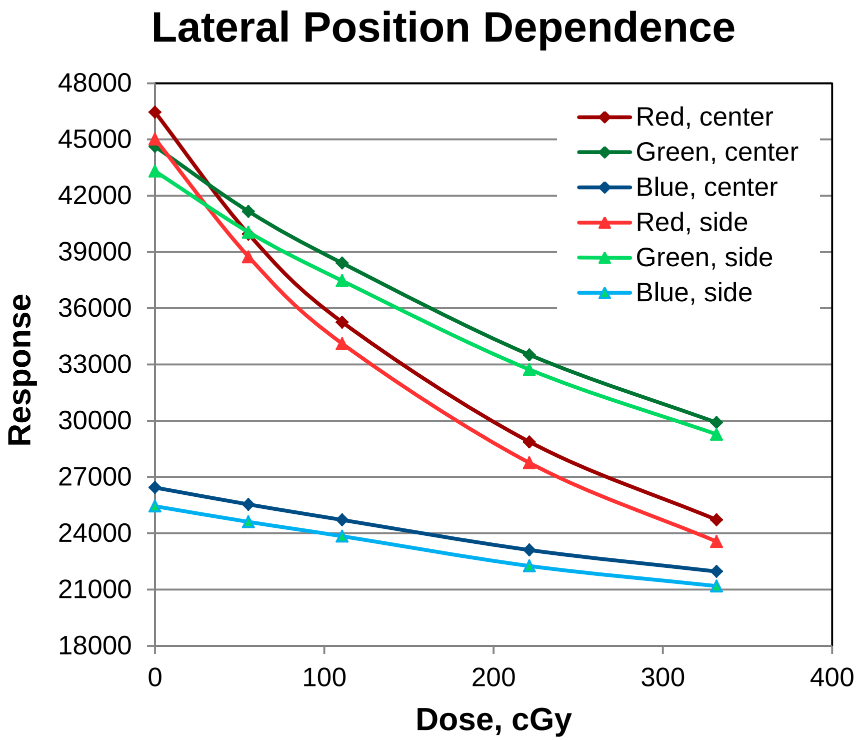


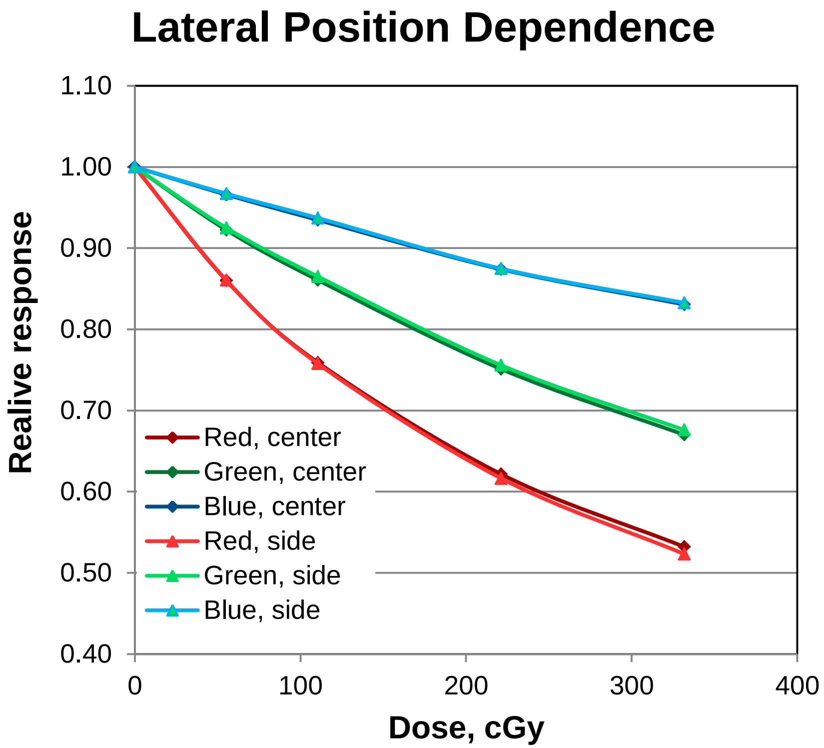


Color value depends on lateral scanner position

Scanner specific, strong in R, weaker in G + B

Measuring – Lateral Effect



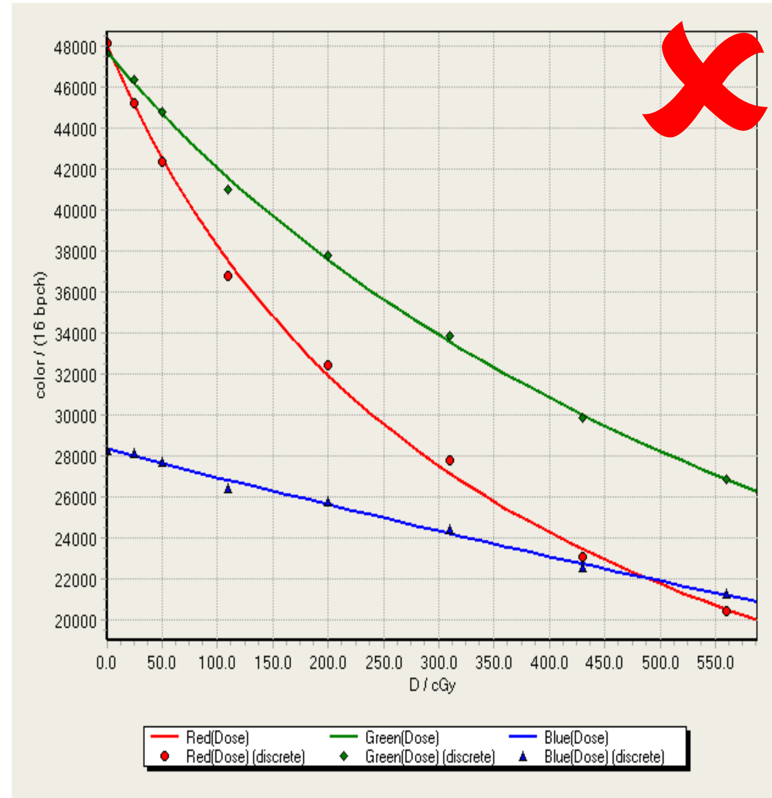


Color value depends on lateral scanner position

Dependence is Scanner specific, strong in R, weaker in G + B

Calibration – Lateral Effect

Lateral center position



Random lateral positions

Calibration Regions - Not Films - must be in lateral center!

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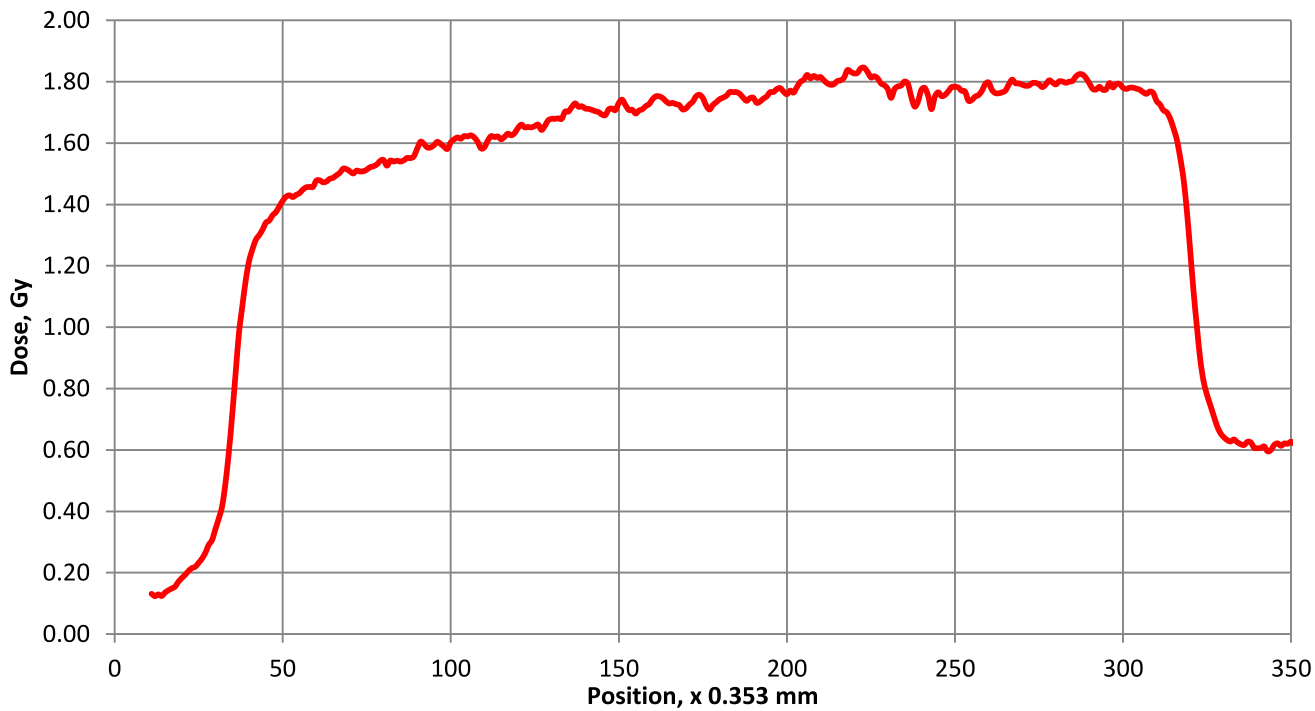
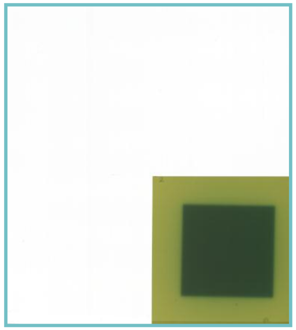
Single Channel – Lateral Effect

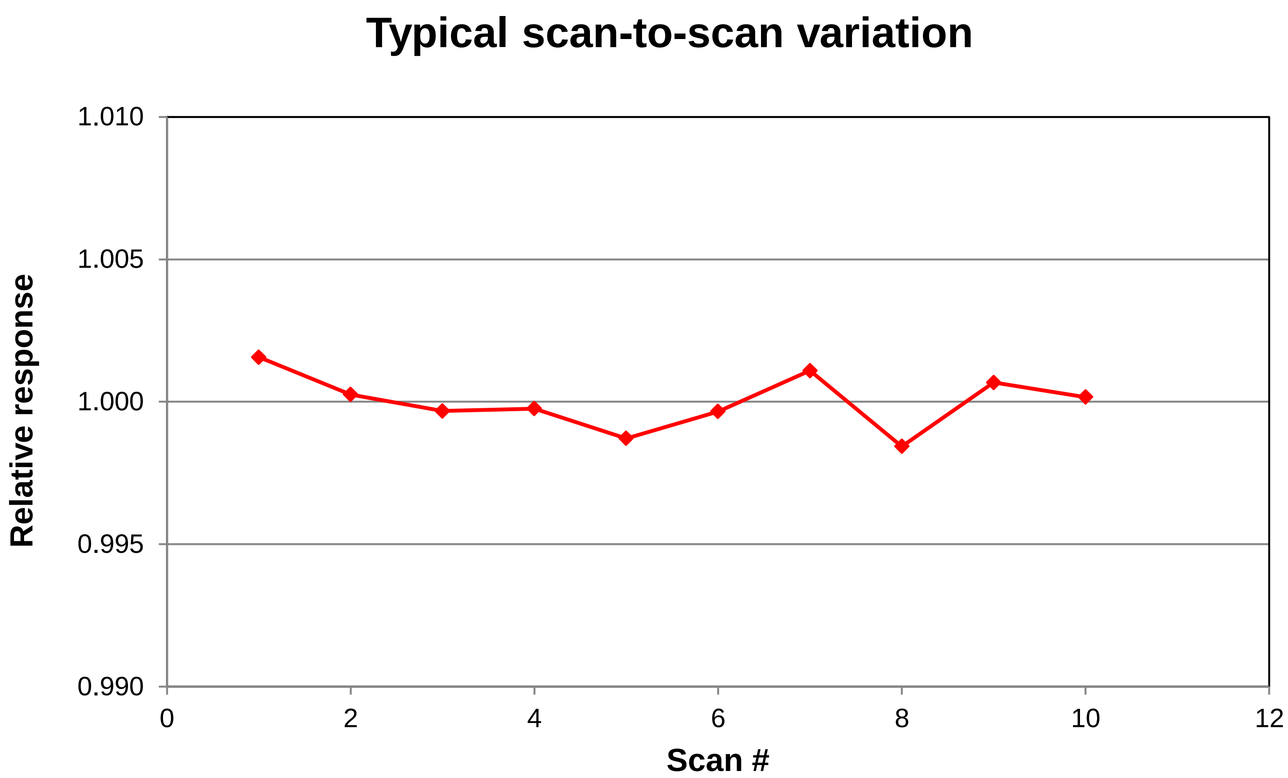




Dose map profile Red (single channel method)

Dose at lateral scanner edges overstated!

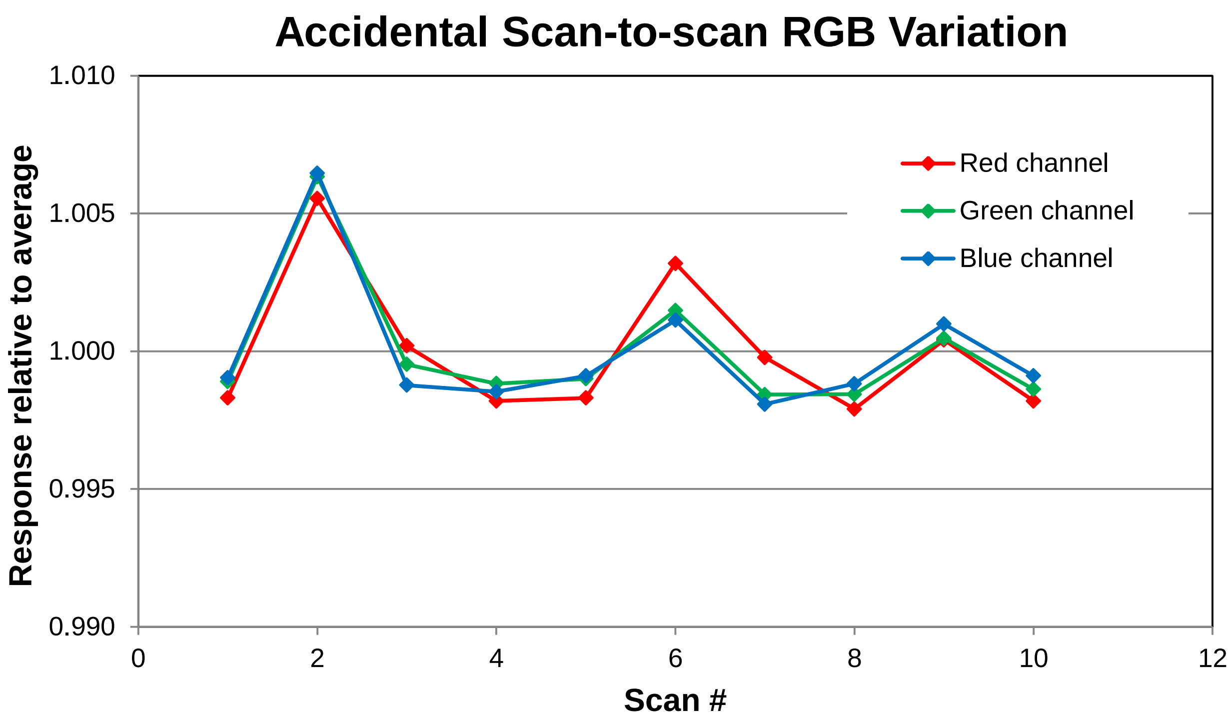
Measuring – Scanner Variation



<0.2% color variation ➡ 0.2 – 1.0% dose variation

(dose range 0 - 500cGy)

Measuring – Scanner Variation



>0.5% color variation ➡ 0.5 – 2.5% dose variation

(dose range 0 - 500cGy)

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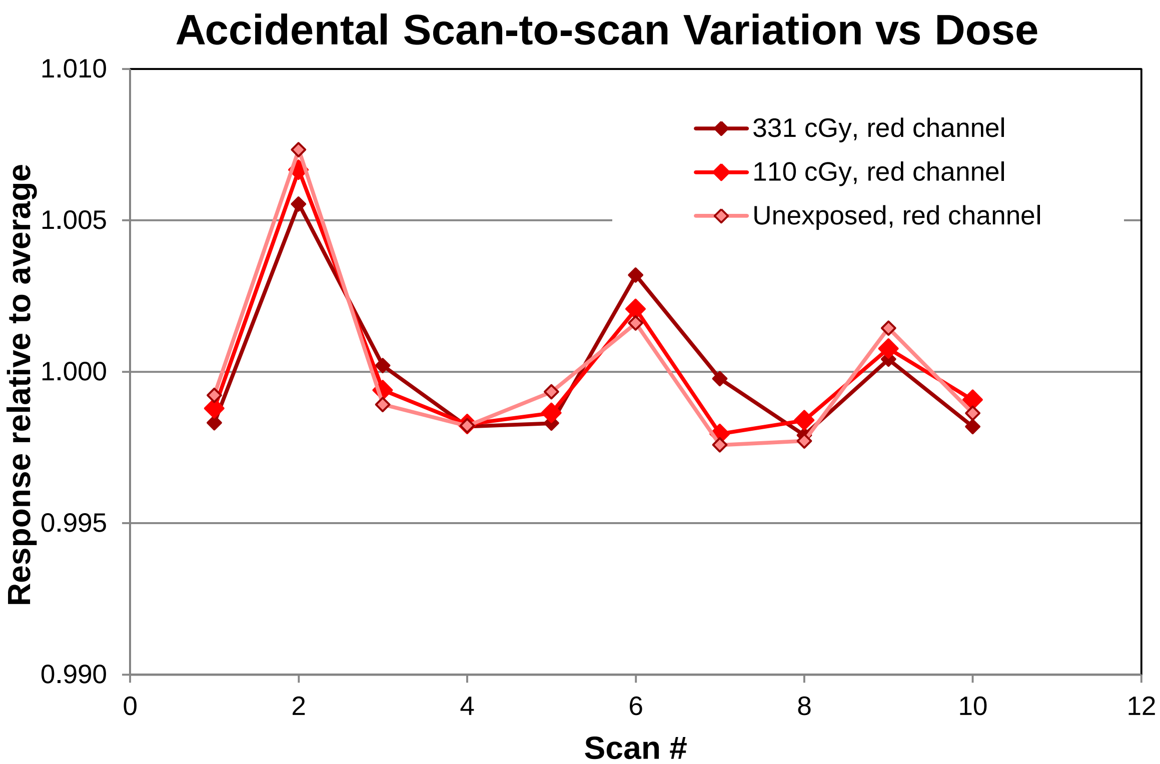
Measuring – Scanner Variation



Synchronic change with dose (Red channel)

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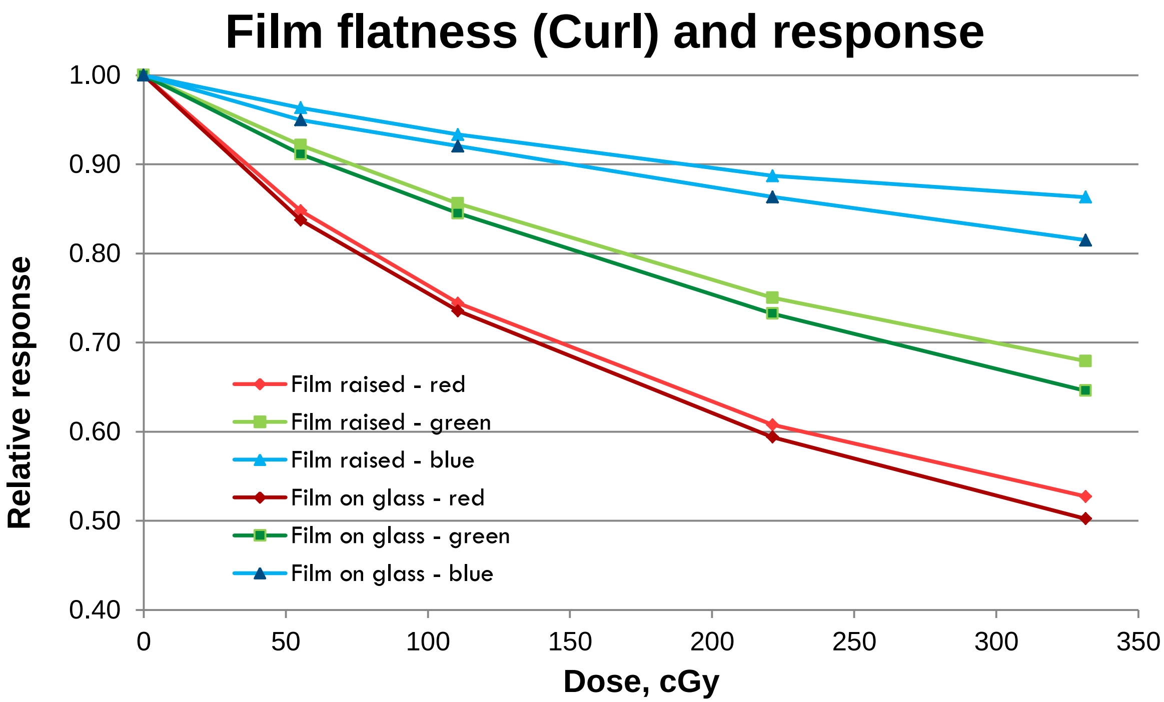
Measuring – Film Flatness



Callier effect - Light change from collimated to diffused

Avoidable !

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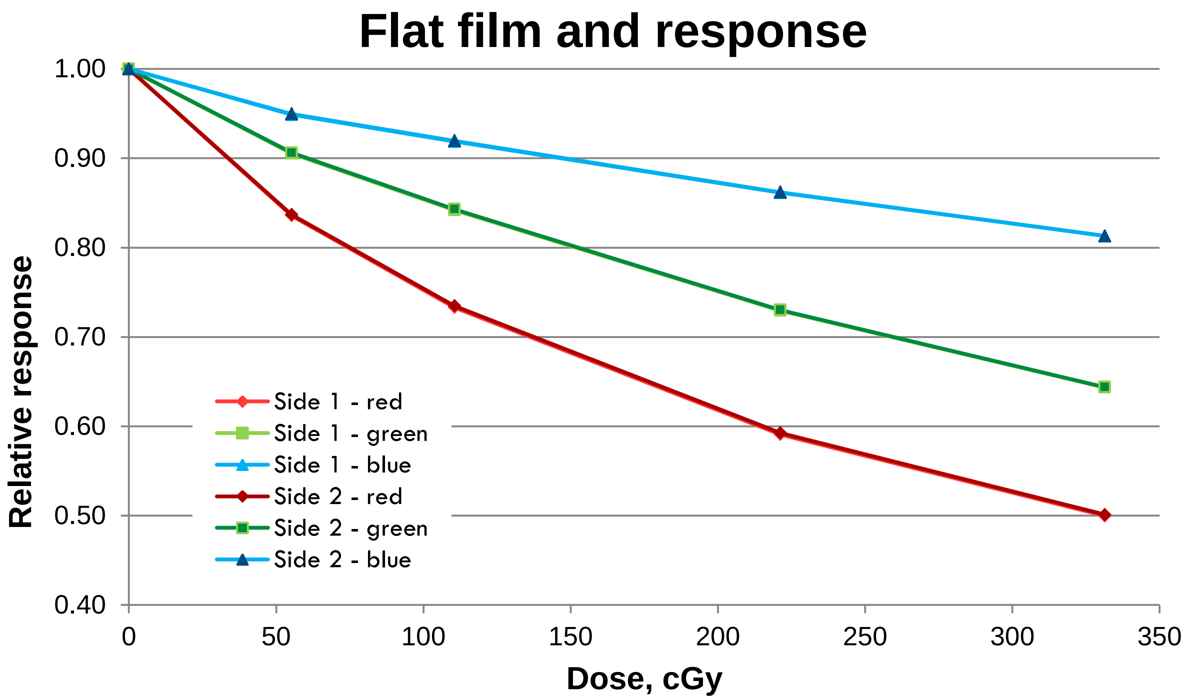
Measuring – Film Flatness

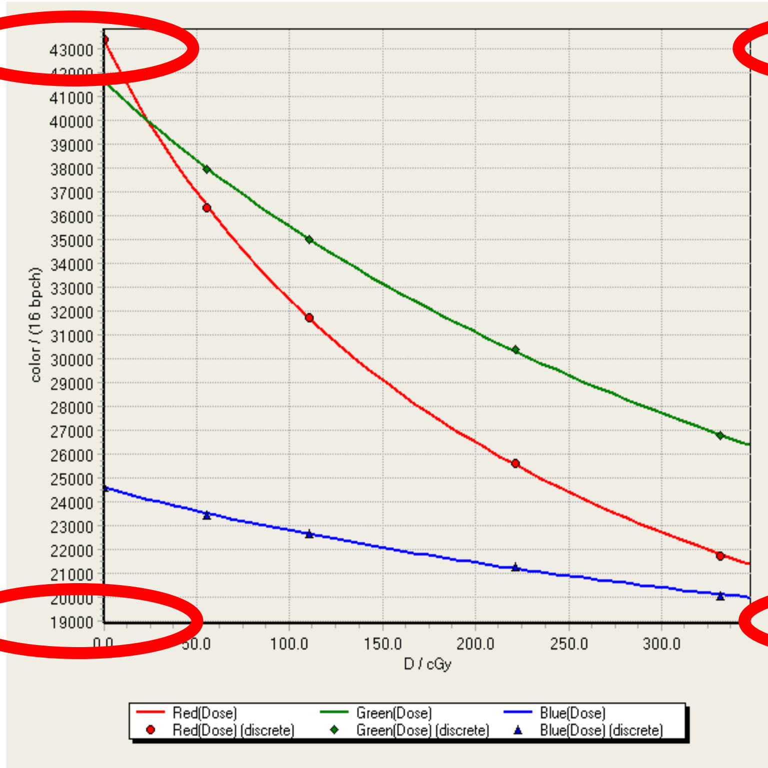
Glass/plastic sheet

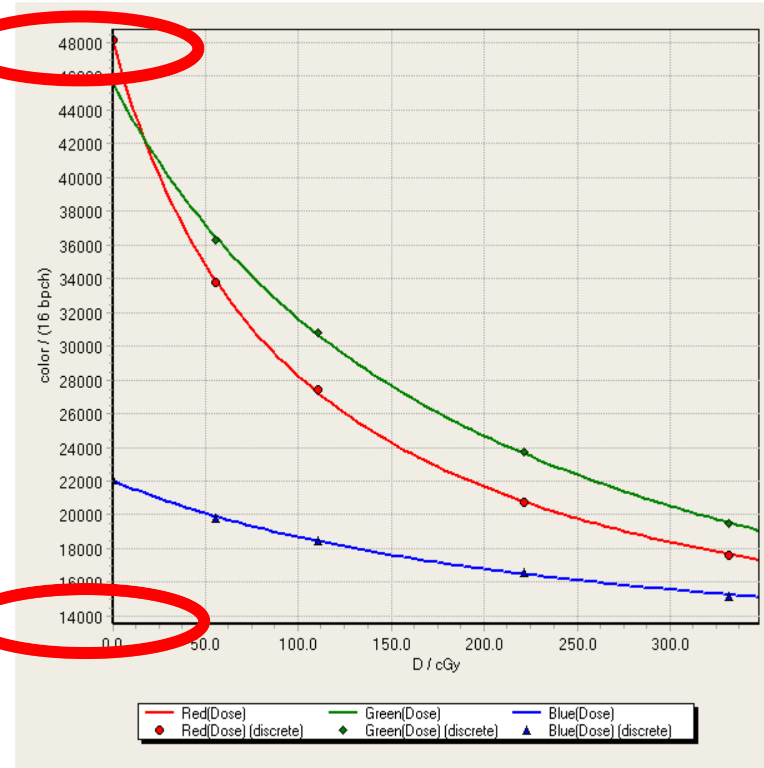


Rescan solves the problem

Multi-channel dosimetry recognizes such disturbances!

Measuring – Scanner effect Transmission *vs.* Reflection





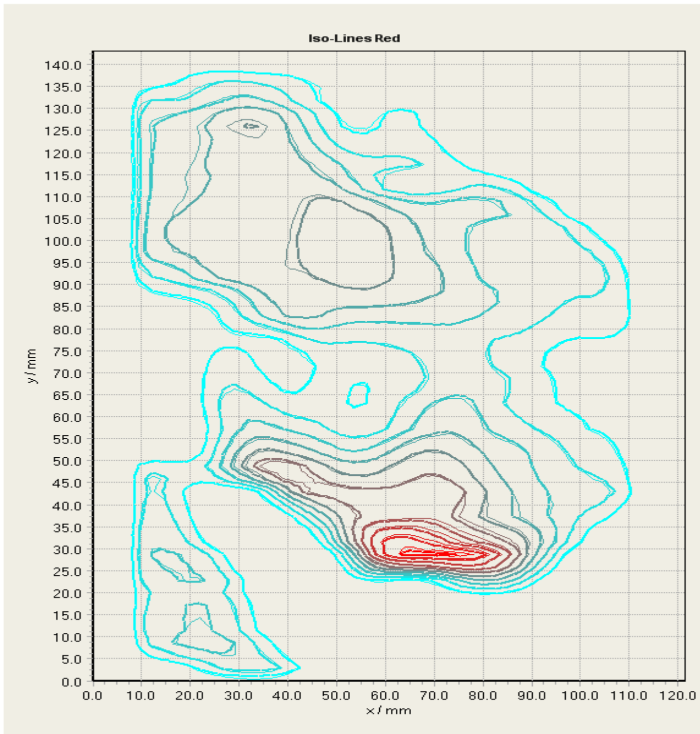
Transmission

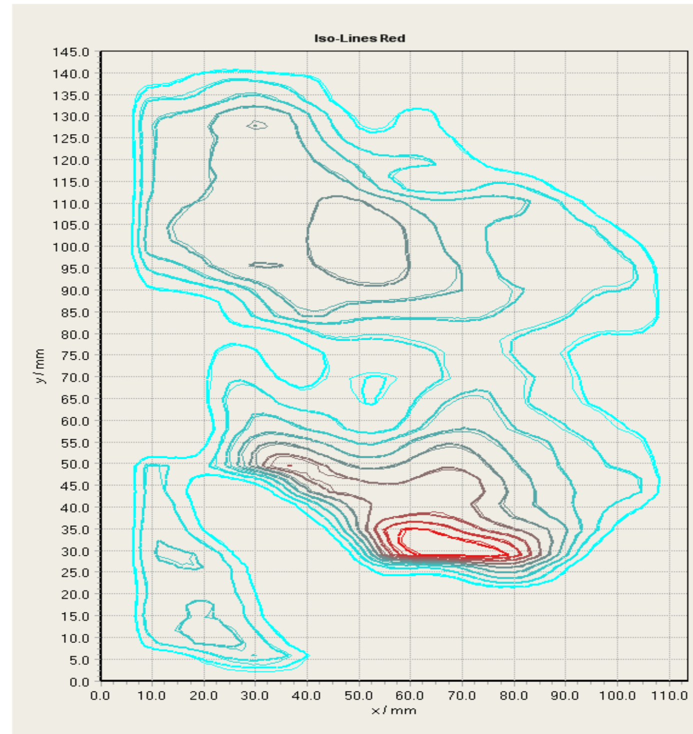
Flatter calibration curves
wider dose range

Reflection

Steeper calibration curves
smaller dose range

Measuring – Scanner effect Transmission *vs.* Reflection





Transmission

Gamma function 2%/2mm:

R: 98.3%; G: 97.8%; B: 98.1%

Reflection

Gamma function 2%/2mm:

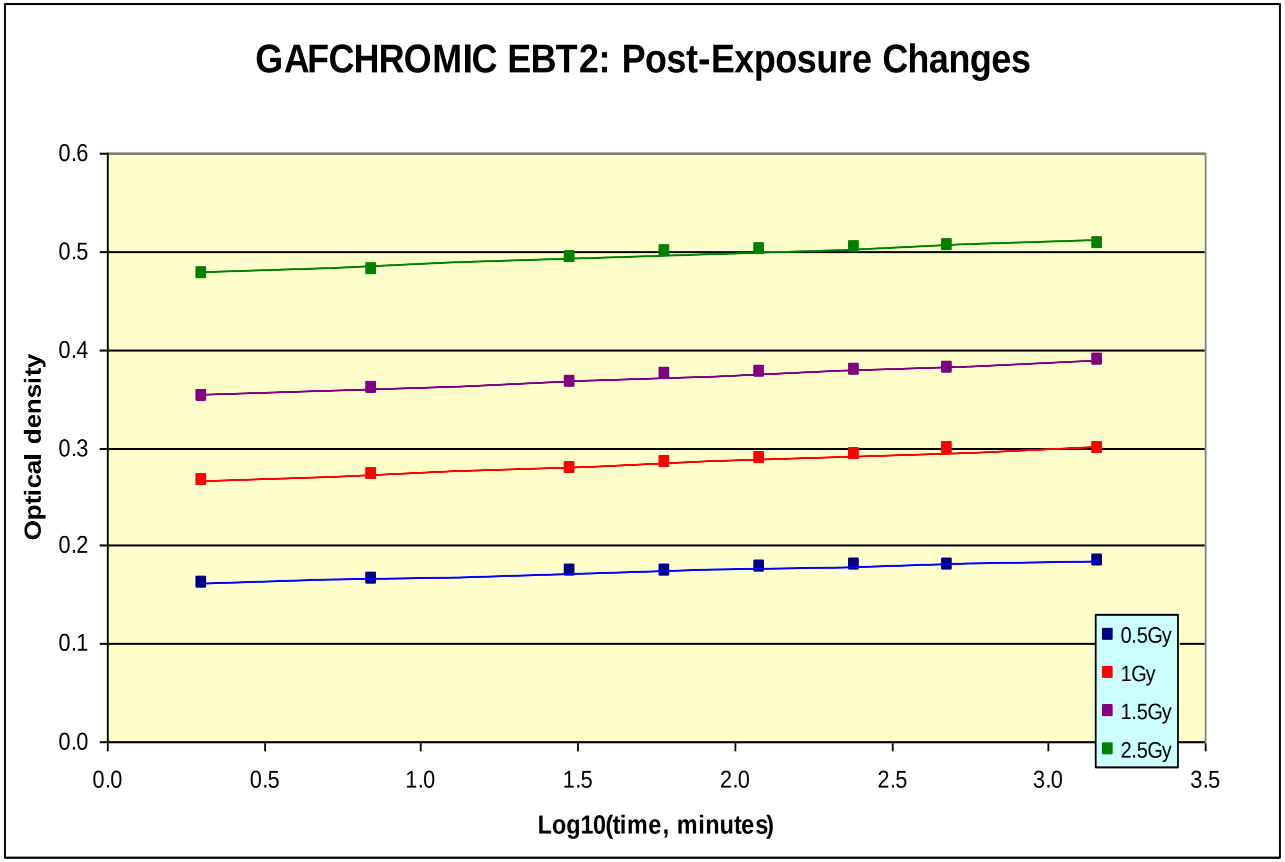
R: 98.3%; G: 98.9%; B: 98.7%

Both deliver similar results – choose and be consistent!

Measuring – Scanner effect Transmission *vs.* Reflection

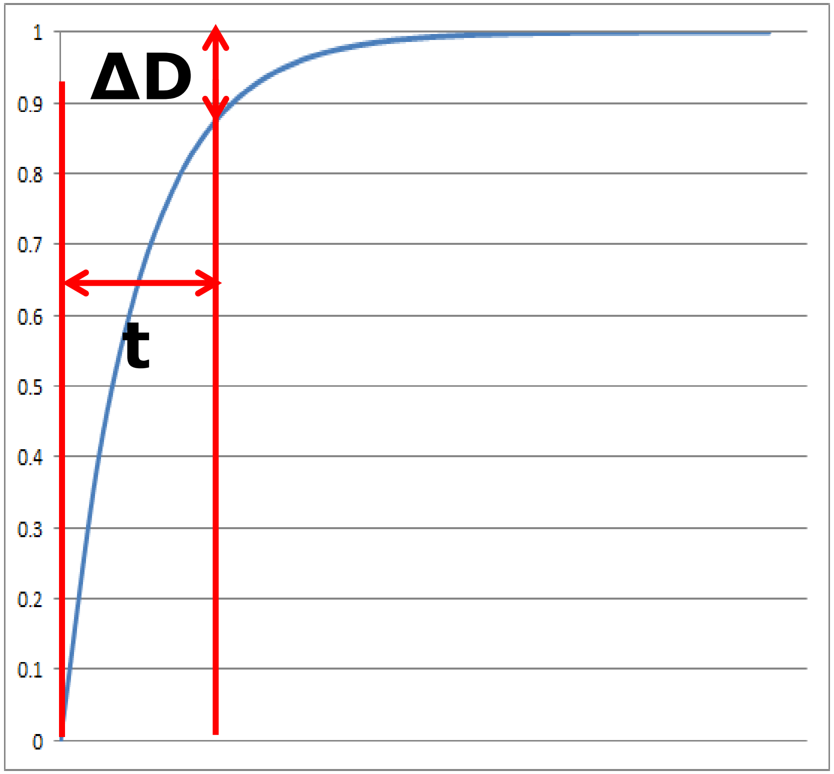
Property	Transmission	Reflection
Low dose response		++
Dynamic range	++	
Lateral response artifact	+	
Scan-to-scan consistency	=	=
Film flatness		+
Humidity dependence		+

Measuring – Post Exposure Time



Logarithmic growth approaching asymptotic value

Measuring – Post Exposure Time



Absolute aging

Compensate by waiting t = 24 h

ΔD(t) < 0.5%

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Measuring - Other Factors

- Limit exposure to light
  don't expose to UV
- Results temperature dependent
  reversible
- Don't expose to high temperature >60°C
  non-reversible
- Results humidity dependent
  reversible, watch gradients!

Conclusion ?

Film is a hassle!

Advantages, but

- Post-exposure waiting
- Film artifacts
- Scanner artifacts
- Many ‘constant’ conditions

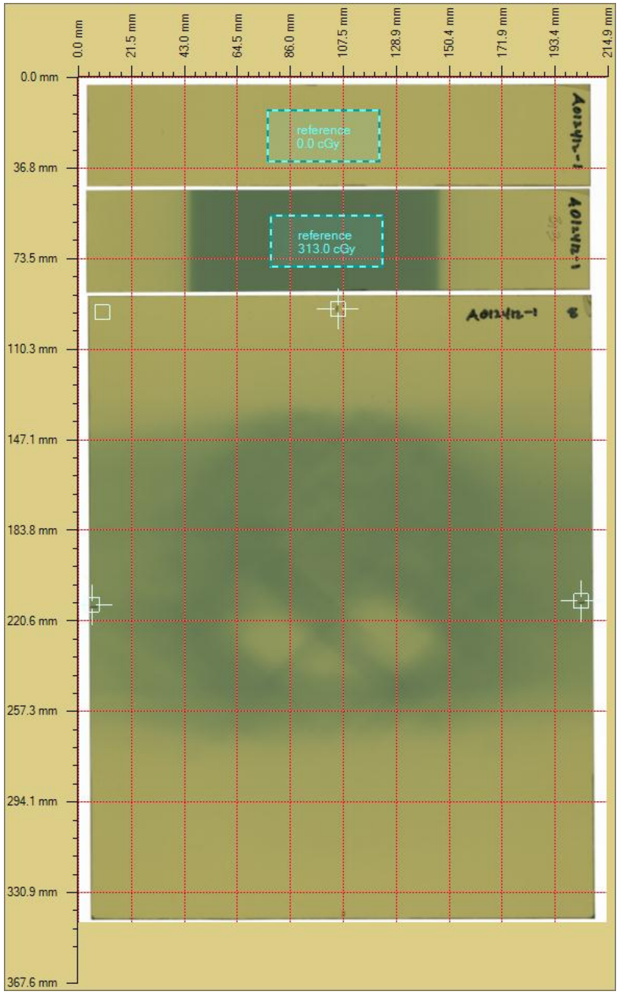
One-scan Protocol

Basic Idea

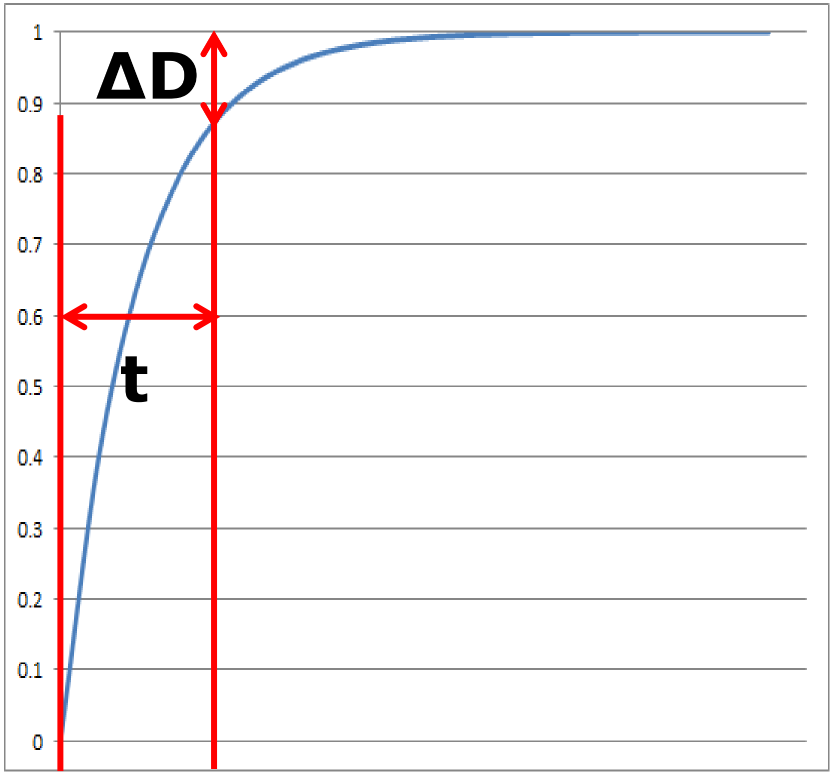
- All data measured in a single scan
- Do calibration + evaluation
  with same scan = same conditions
- Using reference strips with same post exposure age

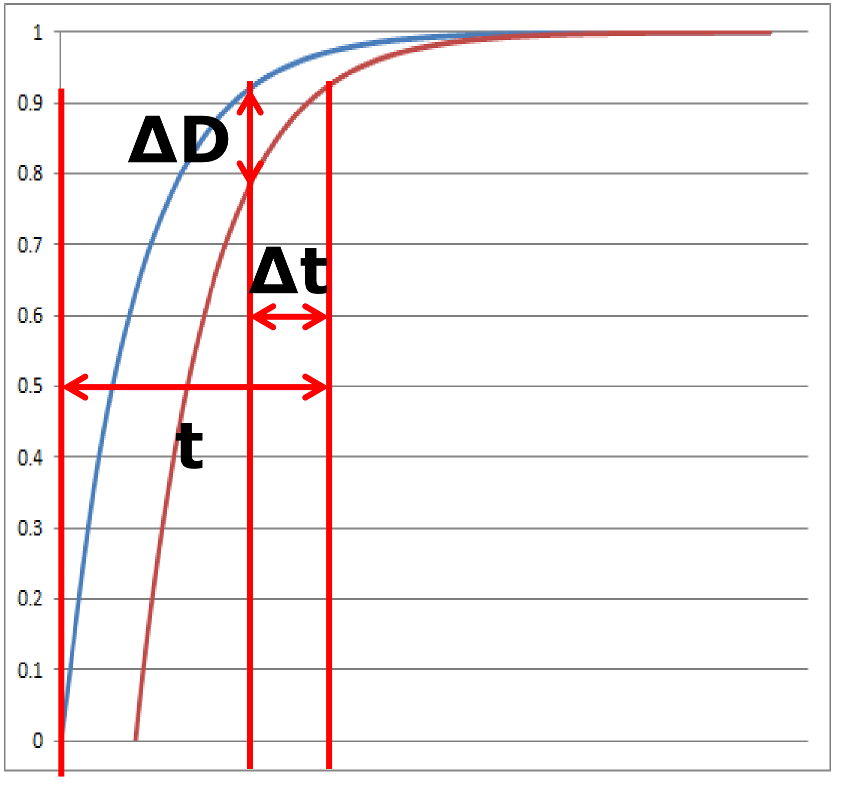
Problem

- How to fit everything into One Scan (many calibration points)?
- How to calibrate (single exposure)?



One-Scan - Post Exposure Age





Absolute aging
wait t = 24 h
ΔD(t) < 0.5%

Relative aging
wait t = 4 Δt
ΔD(t) < 0.5%

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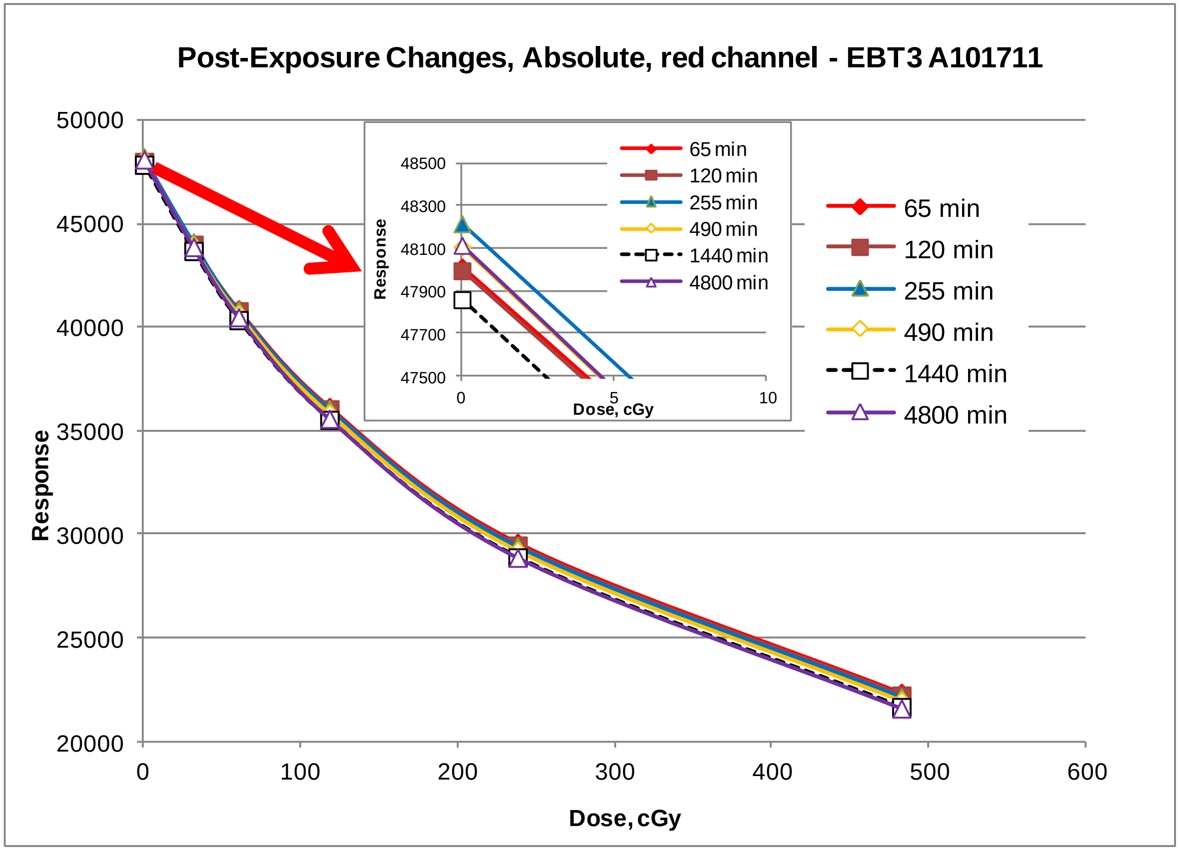
One-Scan – Post Exposure Age

Expose application and reference films in a narrow time window

Wait before scanning, min.	Exposure window, min.	Dose error
10	5	<1%
20	5	<0.5%
40	5	<0.25%

Calibration – Post Exposure Age



Curves look similar – convertible?

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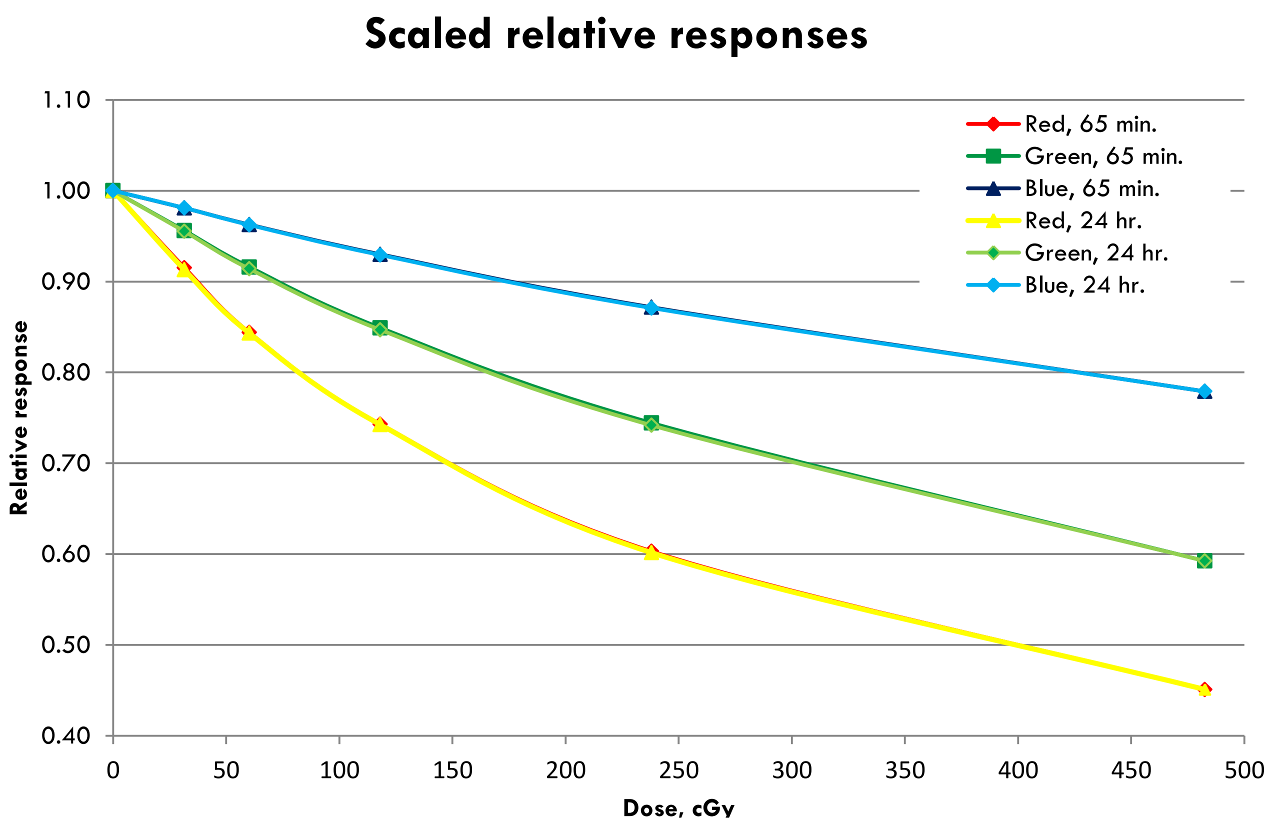
Calibration – Post Exposure Age



Color scaling

Color(0) = const

Color(D_{max}) = const

All calibration curves have same Shape !

Can be converted by shifting + stretching

Calibration – Curve Shape

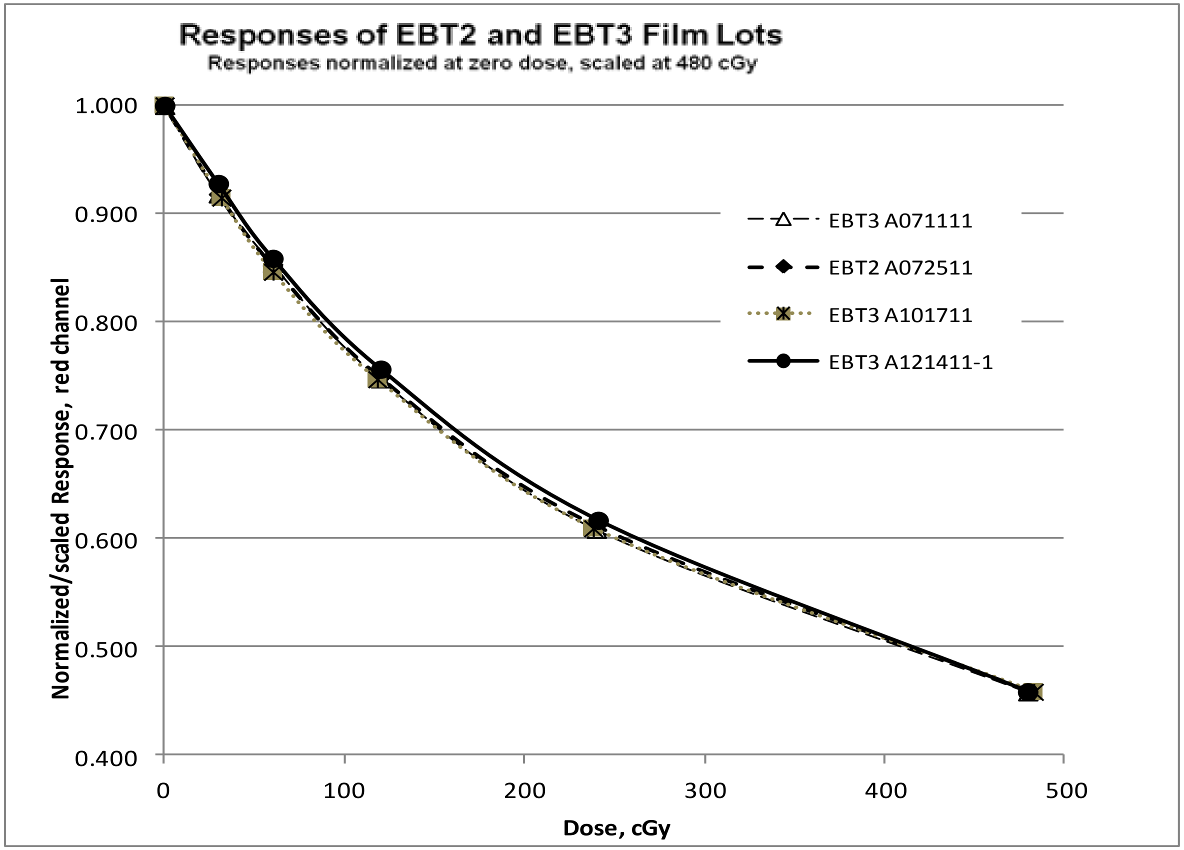
Experimental comparisons:

- Different scanners
  Epson 10000XL, V700, 1680
- Different scan temperatures
- Different humidity levels
- Different photon energies
- Different orientations
  landscape and portrait

Calibration curves are Shape invariant!

Curves can be converted by 2 point rescaling

Calibration – Curve Shape



Calibration curves of different EBT lots are NOT Shape invariant!

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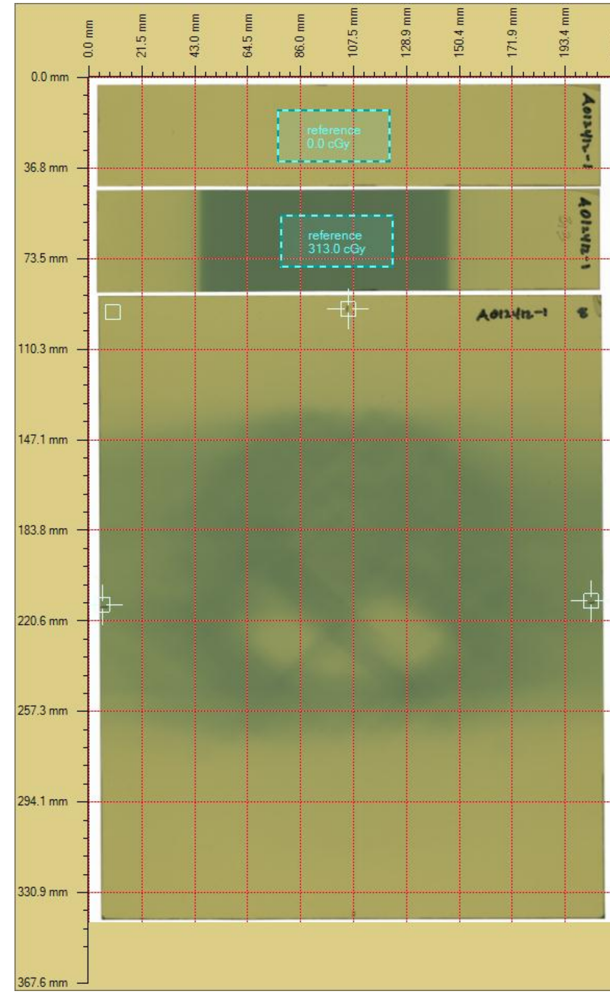
One-scan Protocol

Procedure

- Set up and expose treatment plan
- Expose reference film (same lot) with flat field ~80 - 100% D_{max}
- Single scan of patient film, reference and unexposed strip
- Use reference films to re-scale calibration

Lewis, Micke, Yu, Chan
Med. Physics, 39 (2012) 10, pp. 6339.



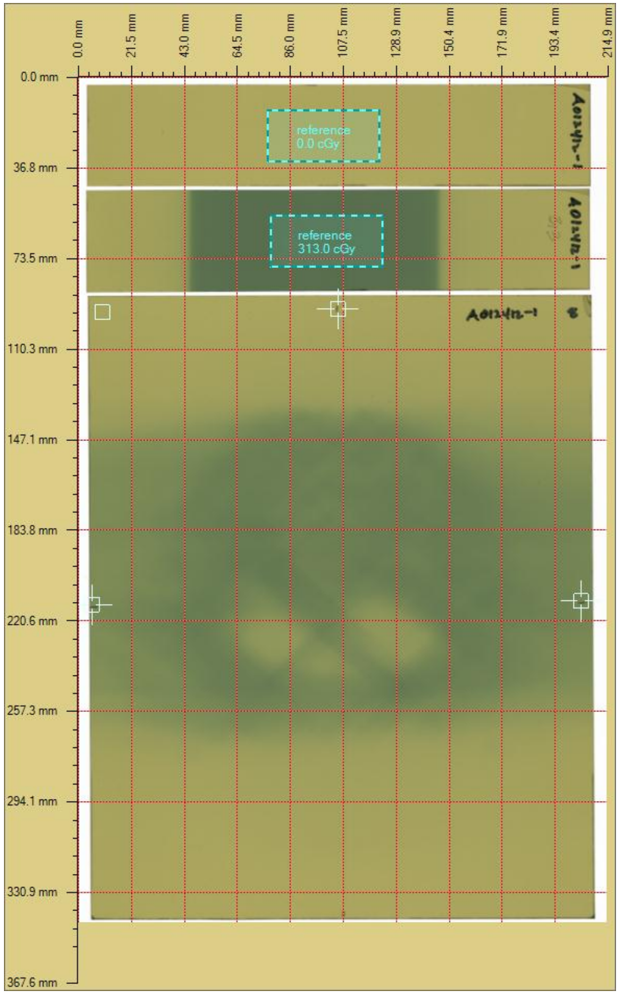
One-scan Protocol

Compensates

- Any scan to scan variation
- Ambient conditions
  temperature, humidity
- Mitigates Energy dependence

Does Not compensate

- Local disturbances
  Film non-uniformities, curl,
  Newton ring pattern, noise
- Lateral scanner effect
- Calibration errors (curve shape)



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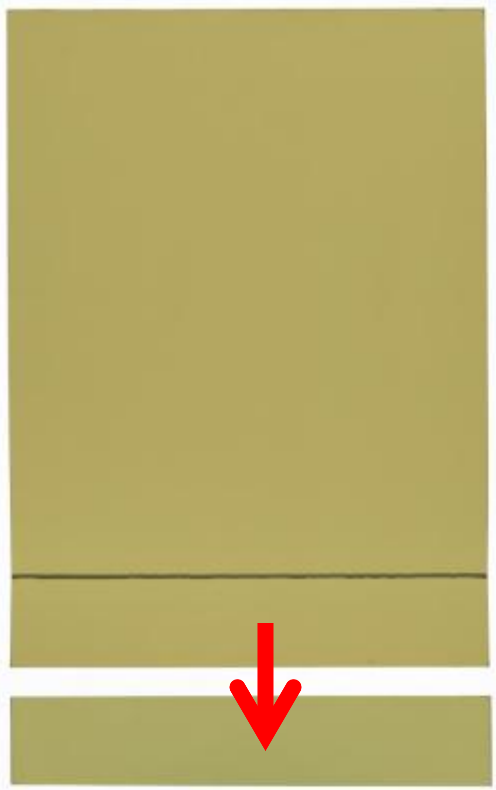
One-Scan Protocol - EBT3 Plus

- Configuration same as EBT3
- Attached reference strip
  - Strip properties same as patient film as close as possible
- Perforated Sheet
  easy to detach reference strip
  - Saves film cutting
  - Standardized strip size
- EBT3+ available November 2012



Conclusion …

Film is

a ~~hassle~~!

Advantages, but

- ~~Post-exposure waiting~~
- Film artifacts
- ~~Scanner artifacts~~
- ~~Many 'constant' conditions~~

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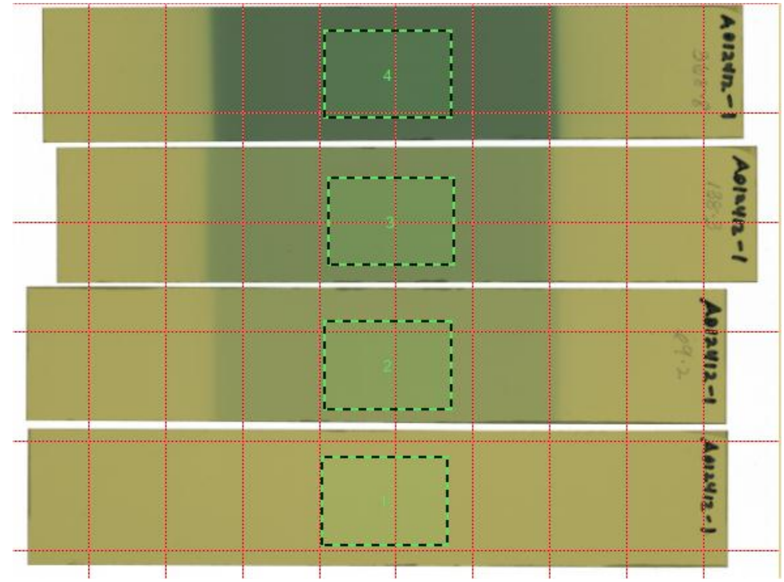
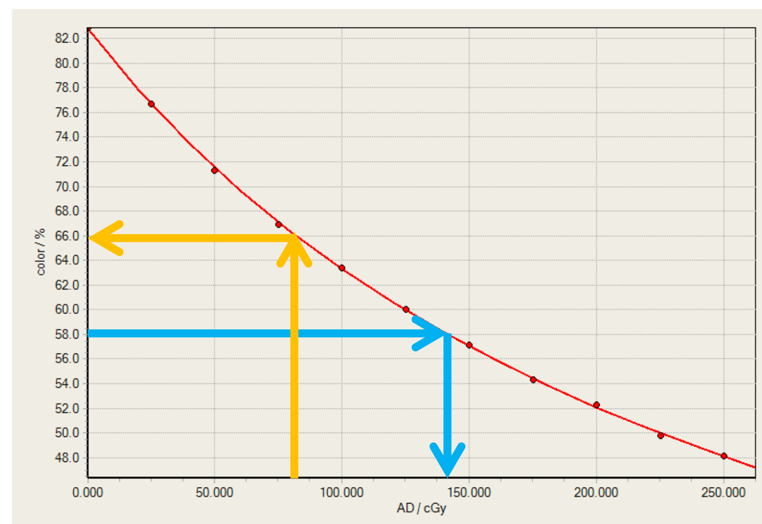
Single Channel Film Dosimetry

- Calibration Curve X=R
  $R_{ave} = R_{ave}(D) \leftrightarrow D_R = D_R(R_{ave})$
- Color channels X=RGB
  $D_X = D(X_{ave})$
  correlates (measures)
  average system response
  linac+film+scanner+protocol
- Unique mapping between
  X value and dose $D_X(X)$





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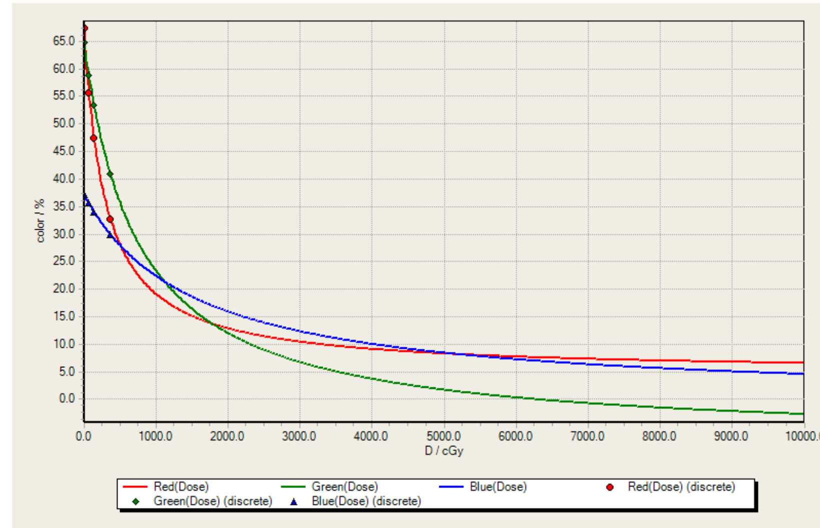
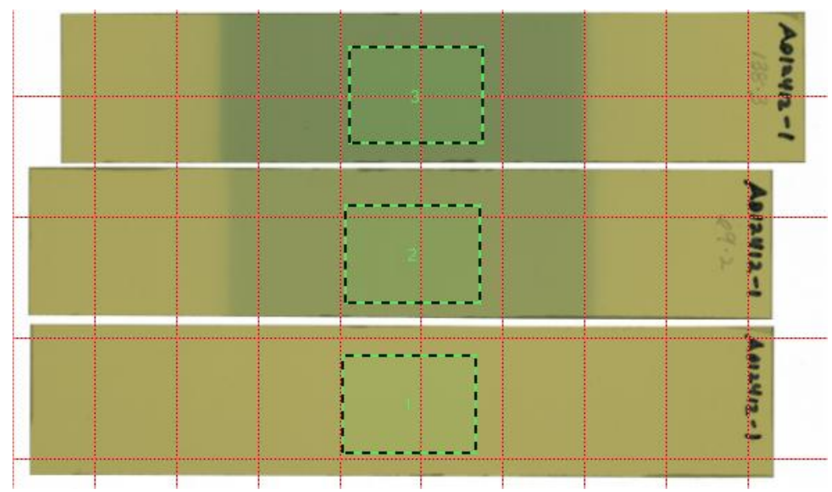
Single Channel Film Dosimetry

- *Rational* function
  X(D) = A + B / (D – C)
  use to fit calibration data
- Correct asymptotic

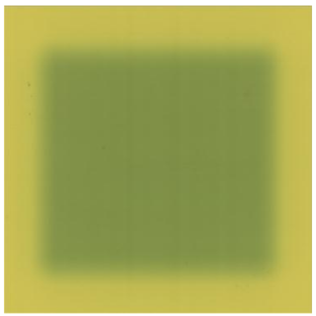
$$\lim_{D\to\infty} X(D) = A$$

- Easily invertible
  D(X) = C + B / (X – A)
- Only 3 parameters
  reduces calibration to
  2 exposures + blank film

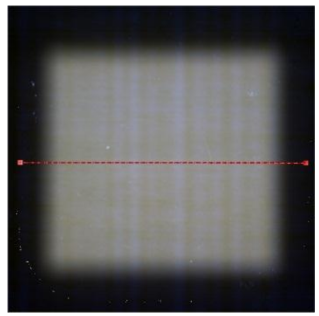


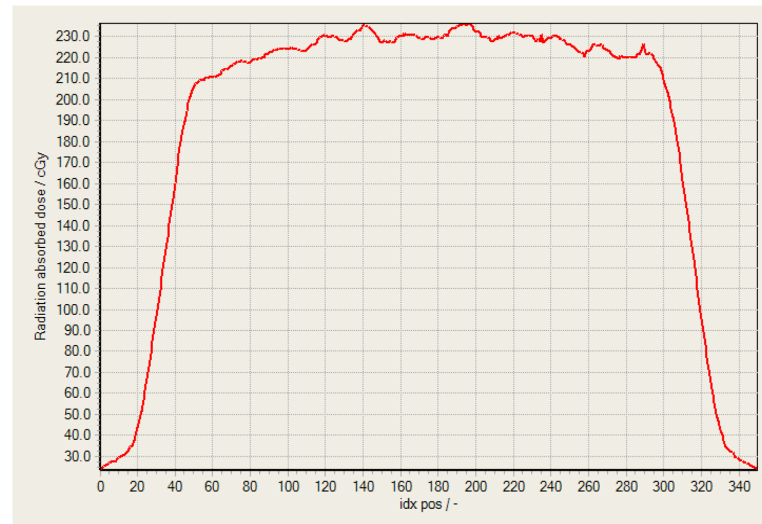


Single Channel Film Dosimetry



$D=D_X$





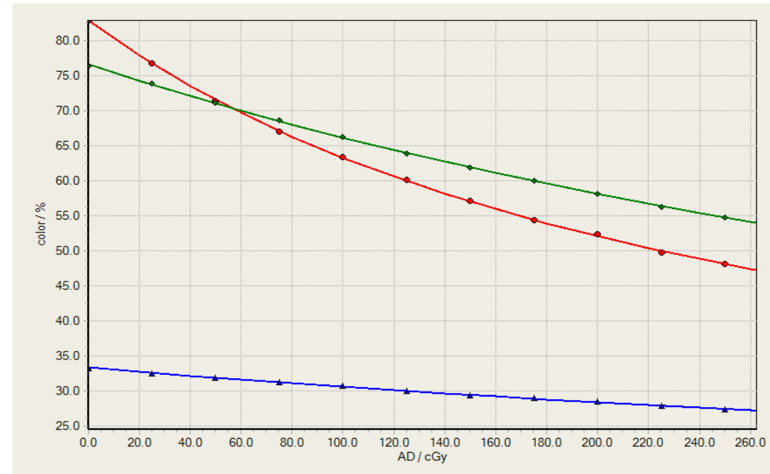
- Robust explicit (simple) calculation method any X value delivers dose $D_X(X)$
- Calibration data easy to correlate
- But, receptive to disturbances

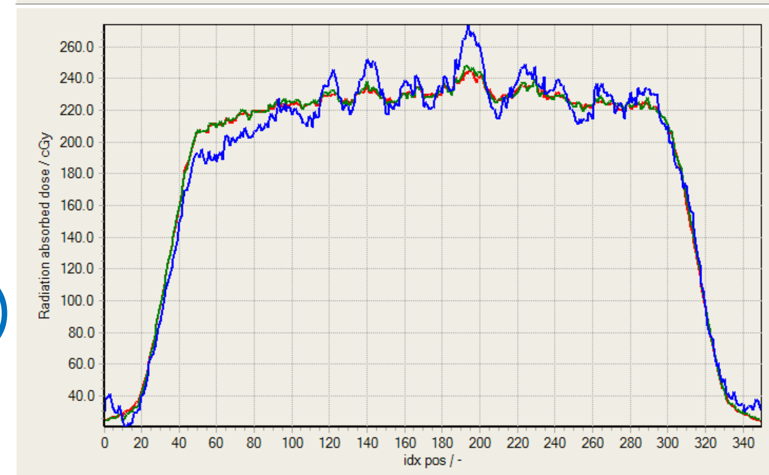
Single Channel Film Dosimetry

Problem:

Specific pixel does
not behaves like average

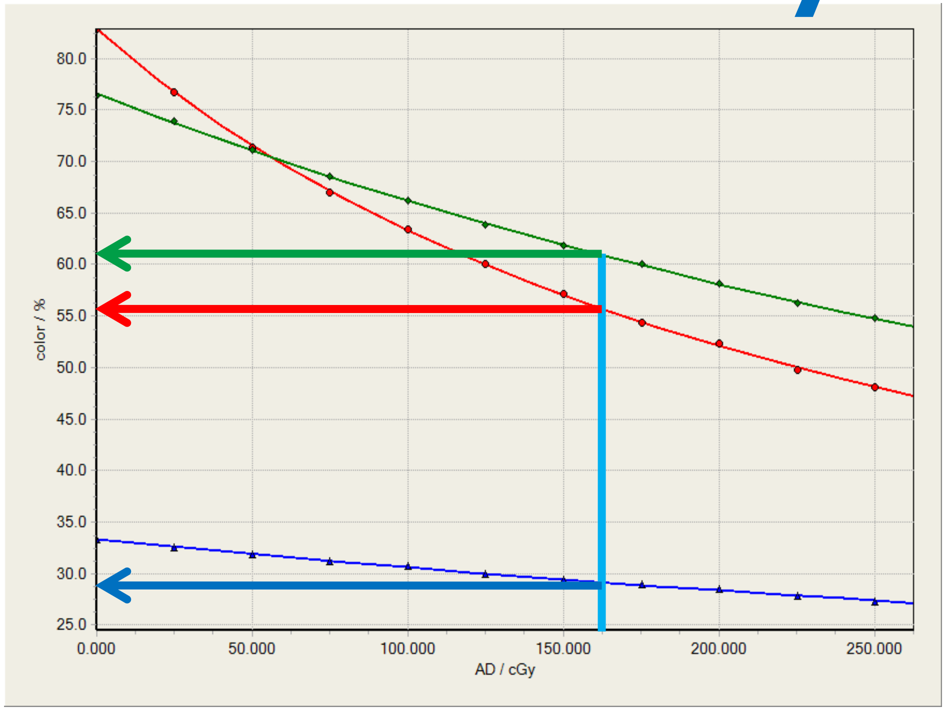
- Disturbance ΔX generates ΔD_X
  $X + \Delta X \leftrightarrow D(X) + \Delta D_X$
  - Film uniformity variations
  - Scanner non-linearities
  - Newton rings, noise, finger prints curling, …
- Any X value delivers dose $D_X(X)$
  - Each channel specific ΔD_X
  - No indication of 'big' ΔD_X
  - What dose D_X is best?





Multi-Channel Film Dosimetry

- RGB Calibration Curves
  - Dose induced color C
    C(D) = {R(D),G(D),B(D)}
- Dose exposure generates only 'certain' colors C
  - Not all C deliver dose value



- Observed color C_{scan} is superposed with disturbance ΔC
  - $C_{scan} = C(D) + \Delta C$
- Solution: Optimize dose D value, *i.e.* minimize ΔC
  - $| C_{scan} - C(D) | \rightarrow \min_D$

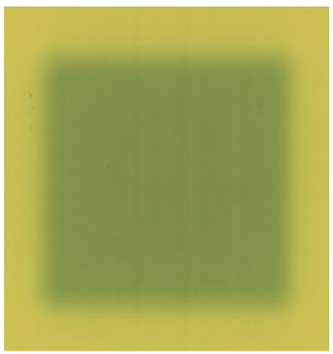
Triple Channel Film Dosimetry

- Model:
  Scanned optical density $d_{X,scan}$
  - $\mathbf{d_{X,scan}(D) = d_{X,D}(D) * \Delta d}$
    d_X = -log(X) for X = RGB
  - $d_{X,D}$ is calibration function (average behavior)
  - ! disturbance Δd independent of dose + X (wave length) !
    but Δd = Δd(thickness, scanner, noise, artifacts)
- Solution:
  - Minimized function ϕ *vs.* disturbance Δd:

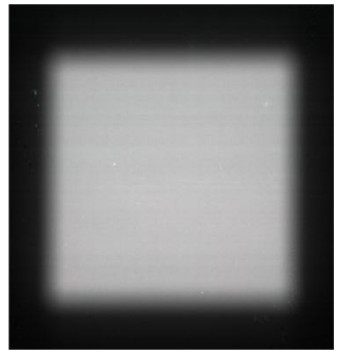
$$\phi(\Delta d) = (D_R - D_B)^2 + (D_B - D_G)^2 + (D_G - D_R)^2 \rightarrow \min_{\Delta d}$$

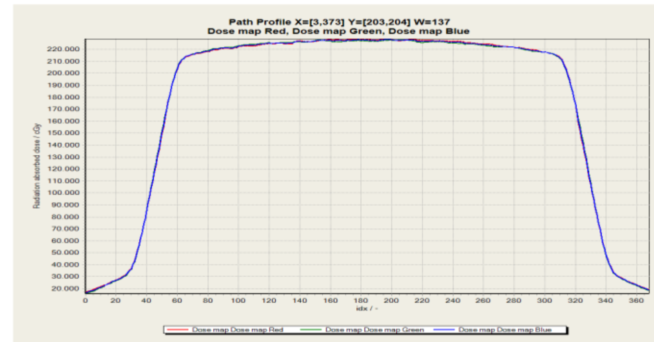
Triple Channel Film Dosimetry Example

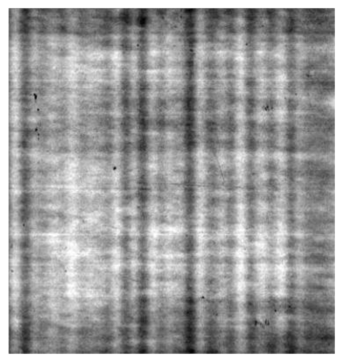
- Signal split into *dose dependent* and *dose independent* part

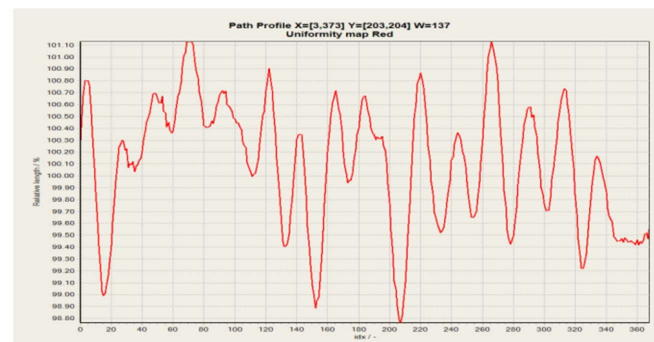


$D_{RGB} + \Delta d$







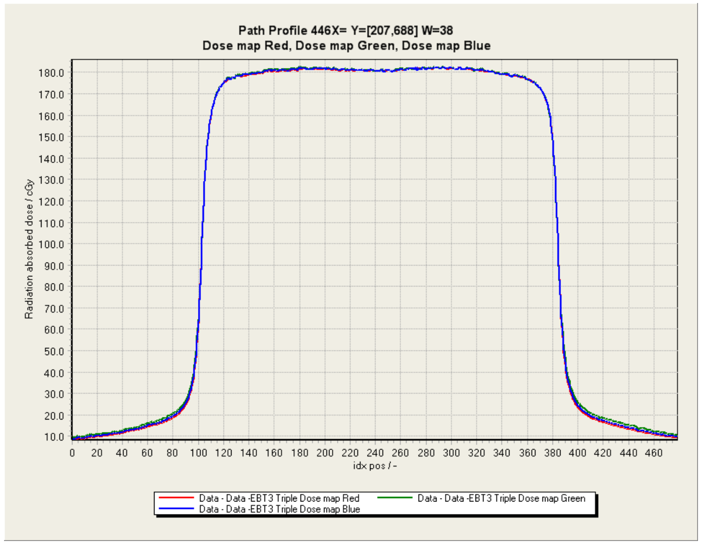


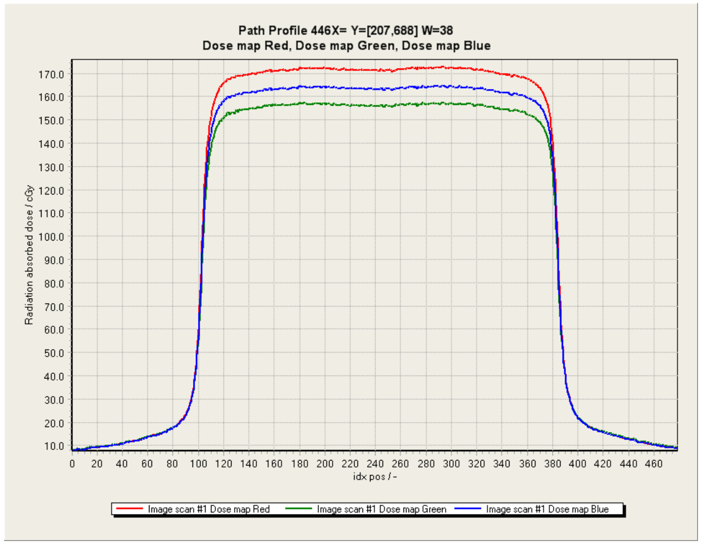
- Dose map (*dose dependent* part)
- Disturbance Δd map (*dose independent* part) includes film uniformity variations, noise etc.

Triple Channel Dosimetry
Film Consistency

Film consistent with Calibration Patches

- Film has same dose response for X=RGB
  i.e. same dose values D_X are calculable
- Offset between D_X measures calibration consistency

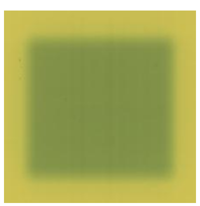




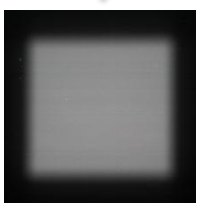
Example: Profiles original calibration patch and 90° rotated scan

Triple Channel Dosimetry Consistency Map

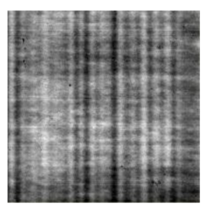
- Dose map
  – measurement result
- Disturbance map
  – removed error
- Consistency map
  – remaining dose error
  ideal case: noise only



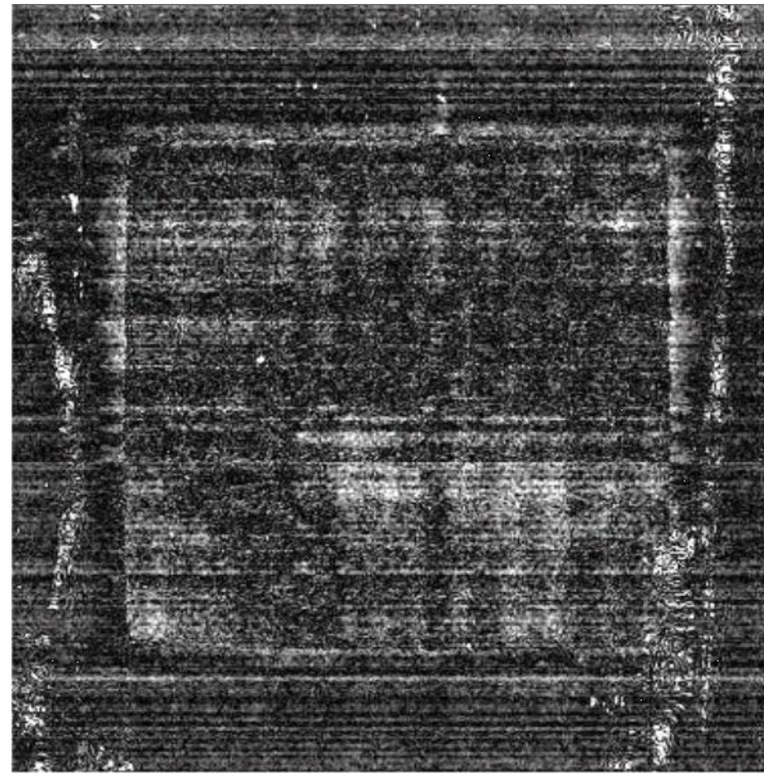
Film



Dose Map



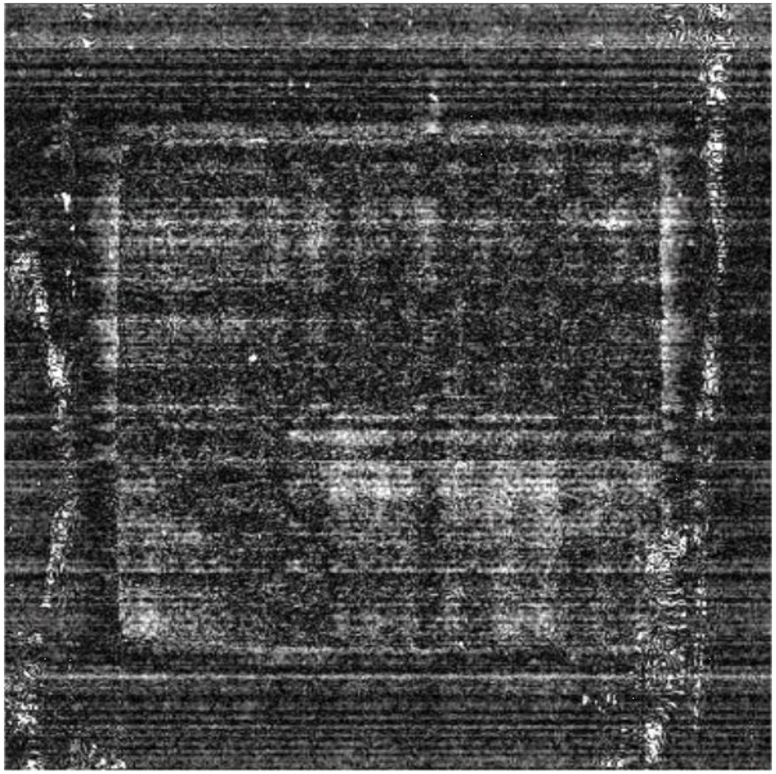
Disturbance
Map



Consistency Map
(dark = +, light = -, contrast maximized)
Example: dominated by scanner cogging

Multi Channel Calibration

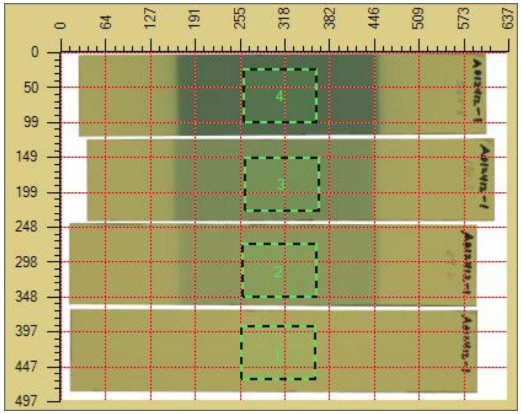
- **Optimize Calibration**
  - Lower consistency = better calibration
  - Offset in calibration points is **not** a quality criterion
- **Calibration goal**
  - Correlate calibration parameter for best (perfect) consistency
  - Calibration function C(D) = { R(D), G(D), B(D) } matches film dose spectrum



Perfect consistency ≡ 0

Multi Channel Calibration

- **Single channel calibration**
  average system response
  - **$x = x(D)$**
    x = RGB
    each channel fitted separately
- **Multi-channel calibration**
  - **$X(D) = A + B\,x(a + b\,D)$**
    X = RGB
    rescales calibration x
    a, b dose scaling, A, B color scaling
  - Correlation $D_R(R_{ref}) = D_G(G_{ref}) = D_B(B_{ref})$
    optimize consistency at reference points
  - Compensates calibration patch distortions
    if multi channel dose is used to rescale dose



Multi Channel Calibration

Two point recalibration

- 1 unexposed + 1 exposed film
  Minim cost possible
- *Dose* scaling (A=0, B=1)
  X(D) = x(a + b D) , X = RGB
- *Color* scaling (a=0, b=1)
  X(D) = A + B x(D) , X = RGB

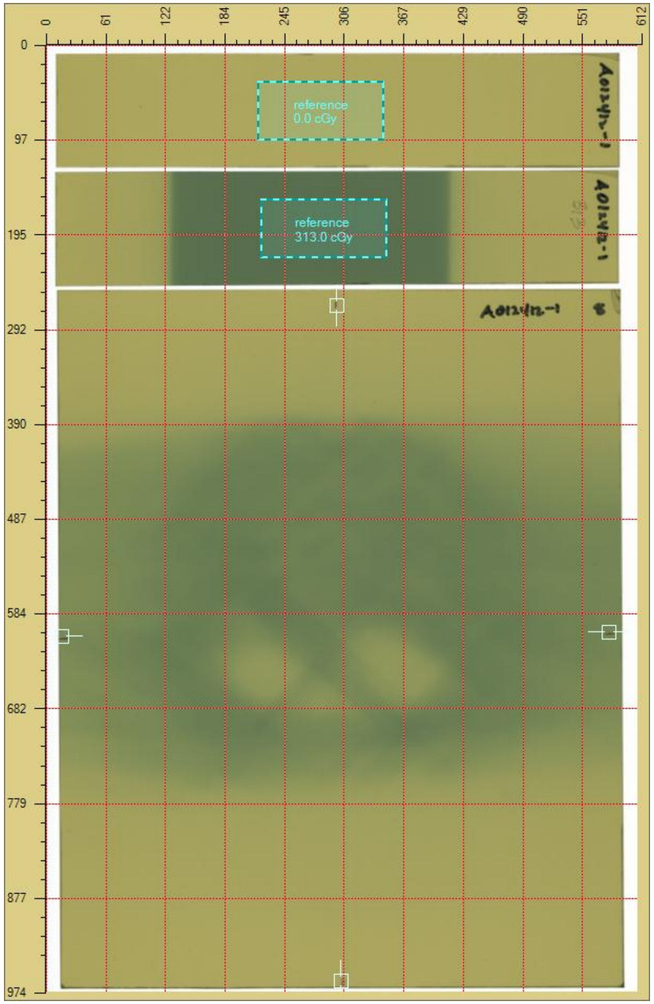
Assumption

- Calibration functions keep shape
  Shape(x) = Shape(X) , x, X=RGB

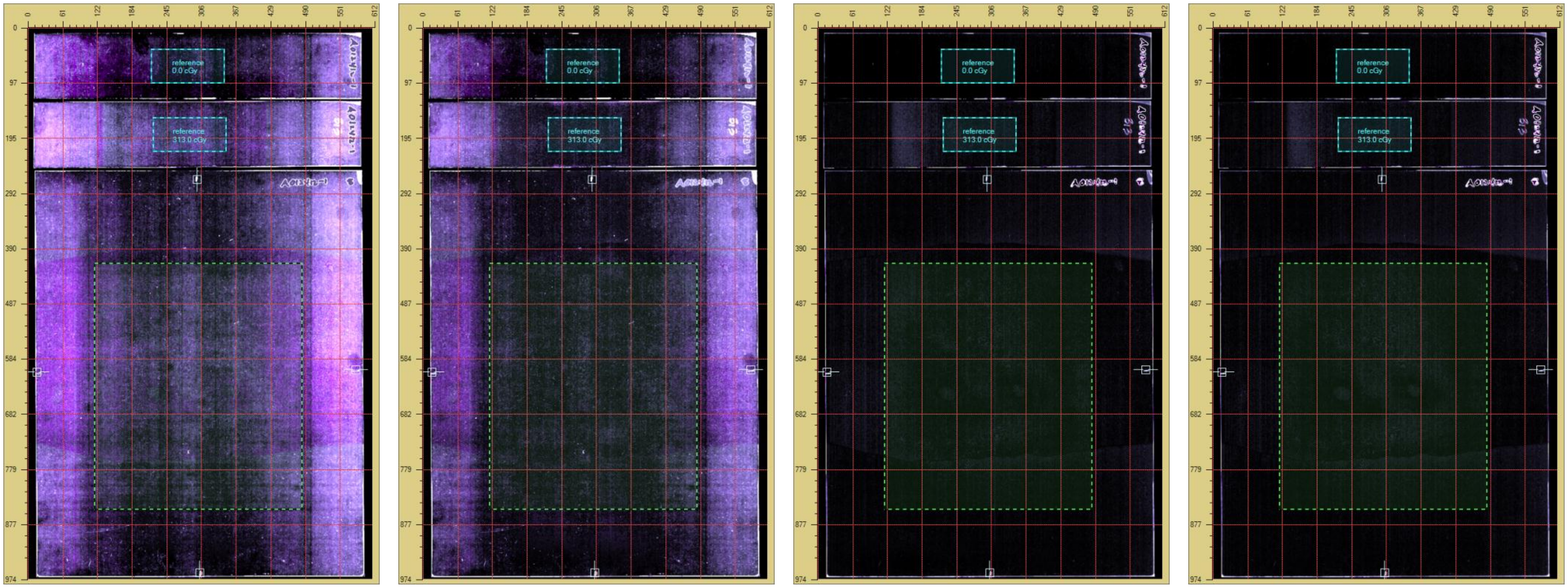
Single scan Evaluation

compensates for

- Ambient conditions: temperature, humidity
- Inter-scan scanner variations,
- Post exposure time, film aging



Consistency Comparison



Single Channel	Single Channel Recalibrated	Multi Channel	Multi Channel Recalibrated
10.2 cGy	3.6 cGy	1.3 cGy	1.2 cGy

Consistency measured across frame D_{max} = 243 cGy, D_{ave} = 139 cGy

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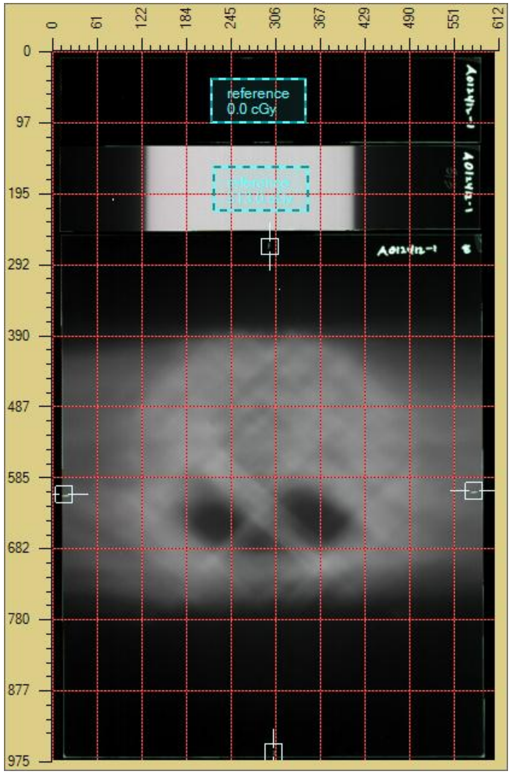
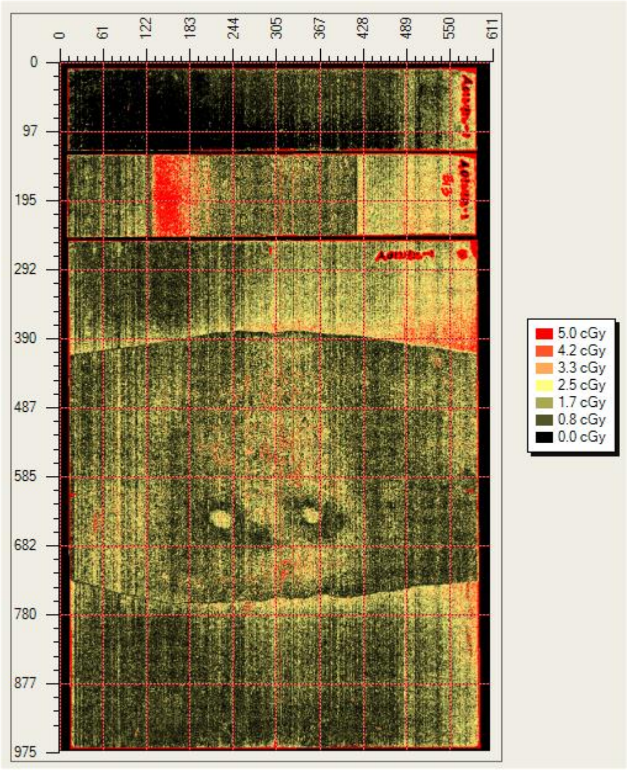
Triple Channel Dosimetry Dose Map Consistency

- Dose map error estimation known before comparison
- Detect 'abnormal' scans
  - 90° rotation, curling, Newton rings, 'top sheets' anomaly

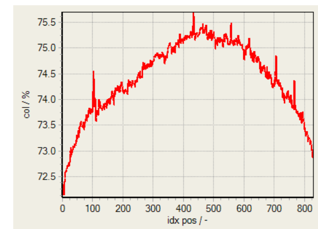




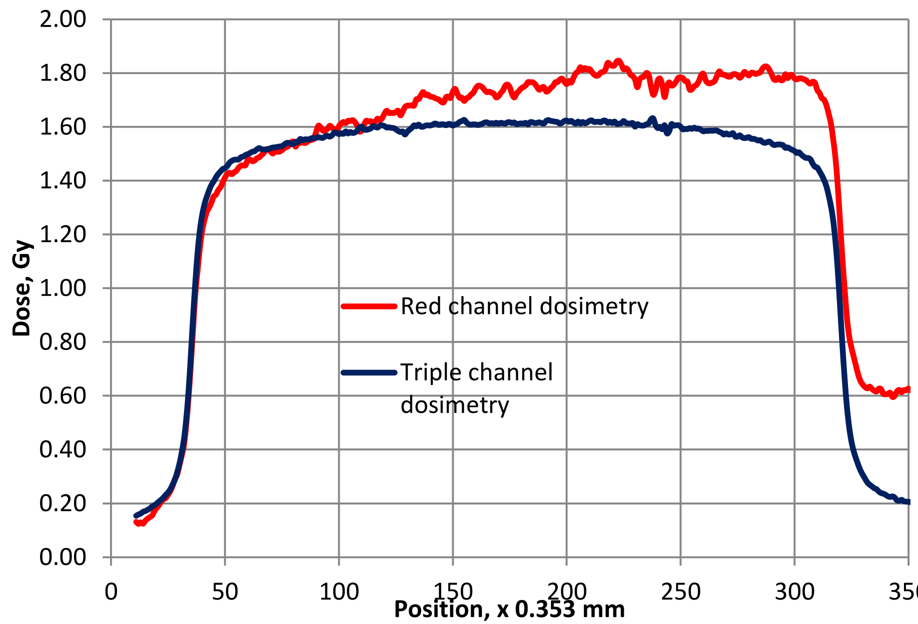
Example dose consistency map (iso-map) peak error ~2%

Triple Channel Dosimetry Lateral Scanner Non-Linearity

Scanner signal changes with lateral position (sensor direction)

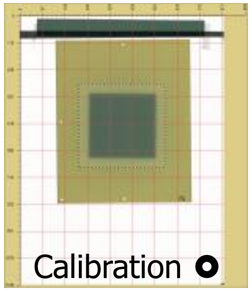


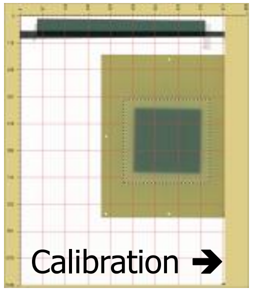
- EBT film polarization causes lateral effect
- Non-dose-dependent part of lateral effect is compensated
- Mitigation only (partial compensation)

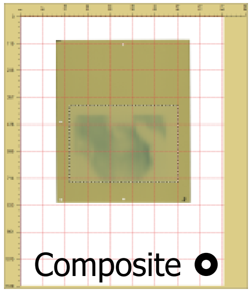


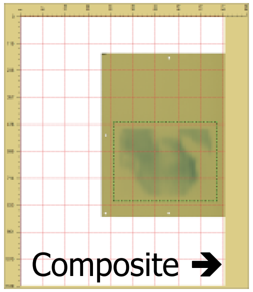
Lateral Scanner Non-Linearity
Single vs. Triple Channel

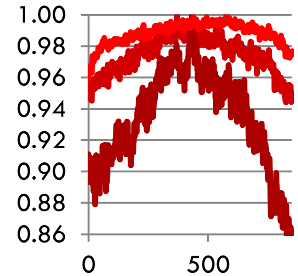
Gamma map Criterion	Calibration	Composite	Passing rate	
			Single Channel	Triple Channel
2% / 2mm	○	○	90%	96%
	➔	➔	87%	96%
	○	➔	98%	98%
	➔	○	94%	97%
1% / 1mm	○	○	58%	71%
	➔	➔	64%	69%
	○	➔	81%	85%
	➔	○	73%	78%
	○ = centered ➔ = right edge		absolute dosimetry (no dose re-scaling), <5% (<12cG) lowest dose ignored,	











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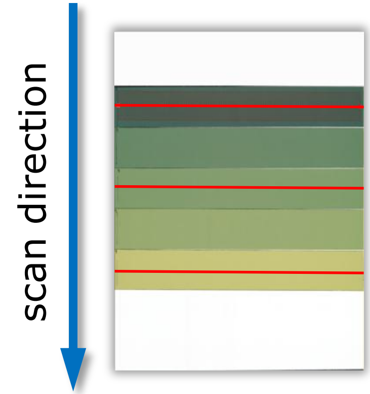
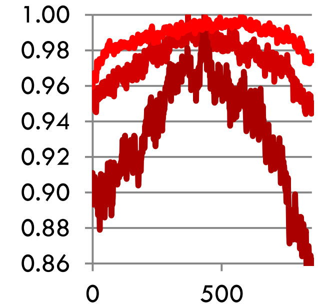
Lateral Scanner Non-Linearity Normalized Blank Scan

Lateral effect increases with dose

- Compensates only weakest occurrence of lateral effect
- Adding disturbances
  - Non-uniformity of blank film
  - Noise of blank scan
- Worsens consistency for exposed areas

! DO NOT USE !



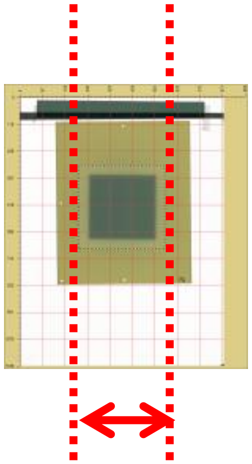


Calibration patch consistency comparison

dose <cGy>	Consistency <cGy>		Consistency <%>	
	None	Blank scan	None	Blank scan
202.0	**8.8**	**11.1**	**4.3**	**5.5**
151.5	**6.8**	**8.9**	**4.5**	**5.9**
101.0	**5.9**	**8.4**	**5.9**	**8.3**
50.5	**5.9**	**7.9**	**11.6**	**15.6**
0.0	**4.8**	**0.4**	Infinity	Infinity

Lateral Scanner Non-Linearity Normalized Blank Scan

Dose cGy	Usable Scanner Width Triple Channel Dosimetry	Usable Scanner Width Green + Blue Channel Dosimetry
250	full (26 cm)	
500	24 cm	
1000	18 cm	
2000	14 cm	full (26 cm)
3000	6 cm	20 cm
4000	5 cm	20 cm
Dose error < 1%		



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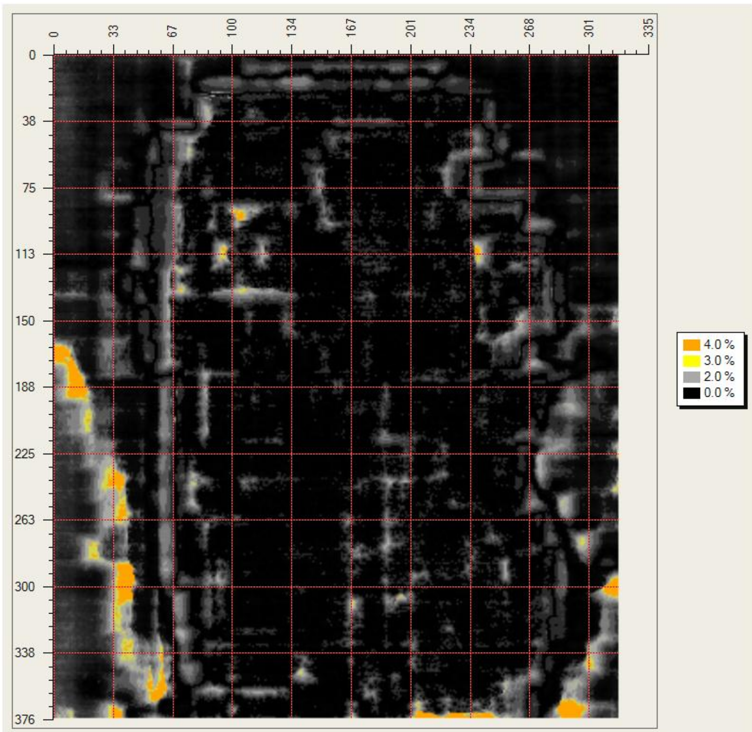
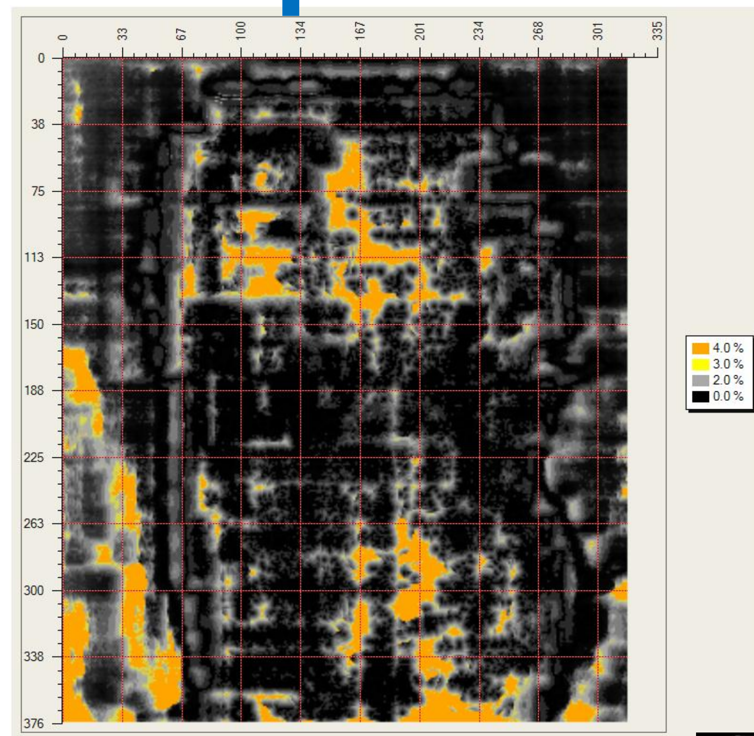
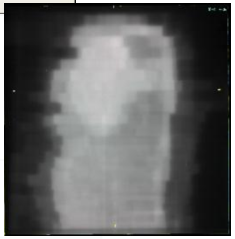
Triple Channel Film Dosimetry
Dose to Plan Comparison





Triple Channel Passing rate R – **97.15** %	Single Channel Passing rate R - **87.48** %

Gamma Map **2%/2mm** - IMRT example (part of FilmQA Pro installation)



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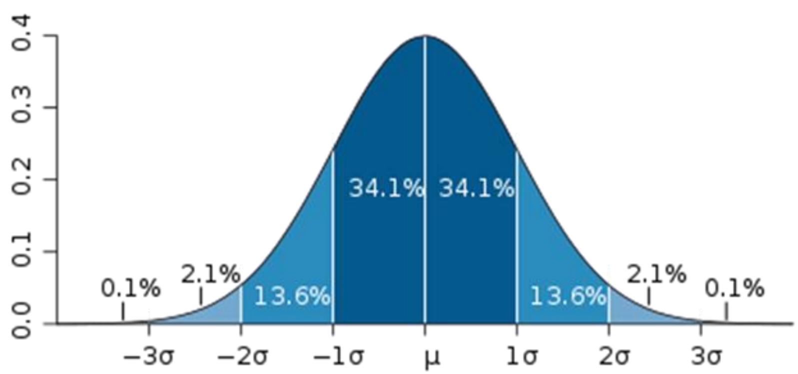
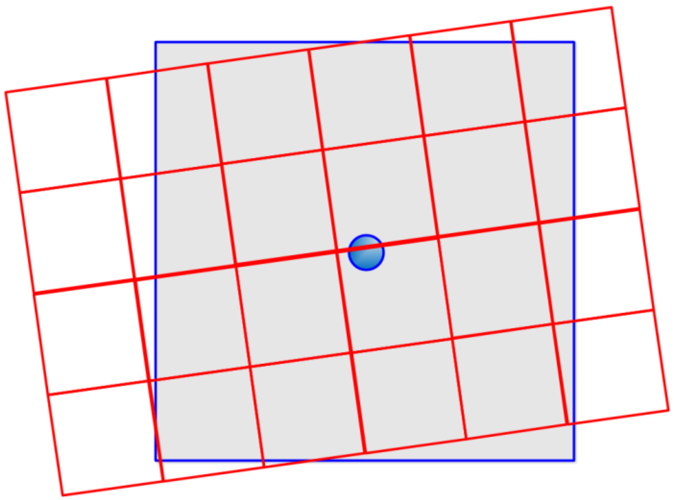
Triple Channel Film Dosimetry Dose to Plan Comparison

- Dose map error can dominate comparison
  - 1% achievable (*vs.* 3% with single channel method)
- Comparison Criteria 3%/3mm, 2%/2mm
  - Triple channel: 1% << 3%/2%, *i.e.* majority < tolerance
  - Single channel: 3% ~ 3% test, *i.e.* 50% > tolerance
- Passing rates improves more than dose accuracy

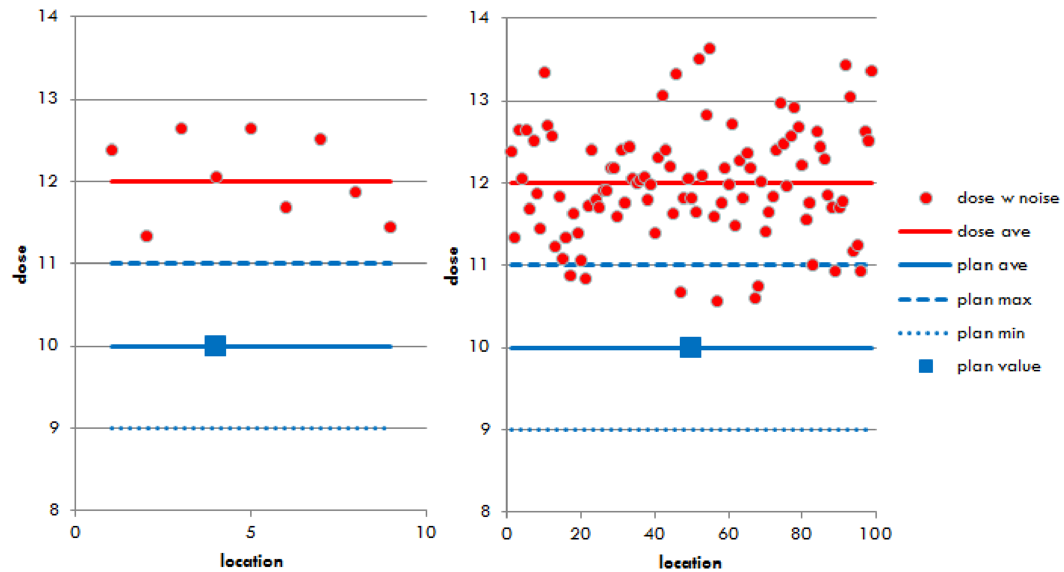


Gamma Map Comparison



Dose Map Pixel   Treatment Plan Pixel

plan pixel and
overlaid pixels of
registered dose map



same standard deviation
low sample number **fails**,
high sample number **passes**

➥ Use dose average across plan pixel
e.g. Projection of dose map to plan coordinate system
Filtering cannot fix this problem!

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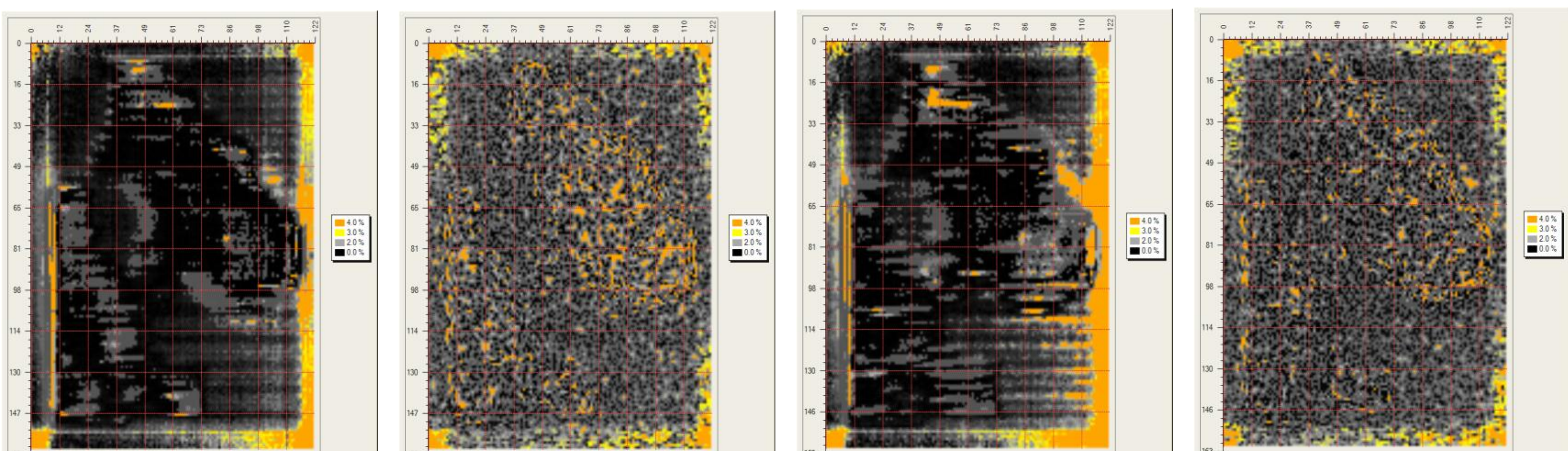
Single vs. Triple Channel Noise Dependence

Triple Channel	Passing rate			
Criterion	0% noise	0.5% noise	1% noise	2% noise
3% / 3mm	97%	96%	95%	95%
2% / 2mm	94%	96%	94%	87%
1% / 1mm	68%	70%	58%	41%

Single Channel	Passing rate			
Criterion	0% noise	0.5% noise	1% noise	2% noise
3% / 3mm	94%	95%	95%	94%
2% / 2mm	89%	92%	94%	91%
1% / 1mm	57%	65%	61%	48%



2% / 2 mm Gamma map comparison at 0%, 2% noise

White noise with various standard deviation added to EBT3 film scan, Gamma map with projection

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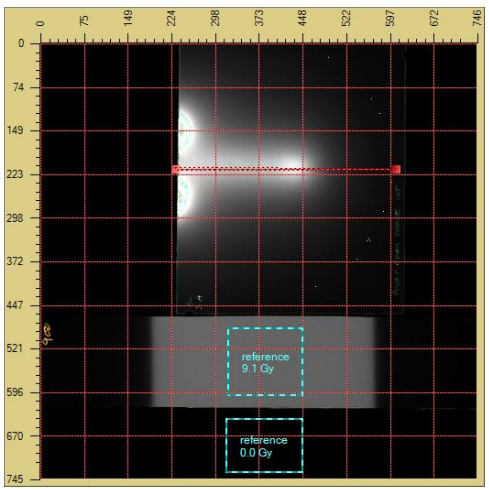
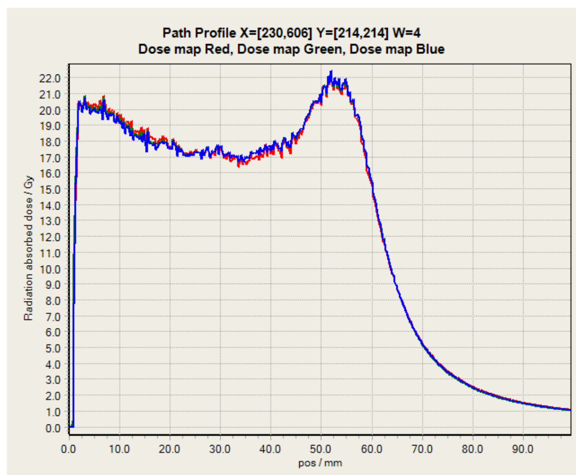
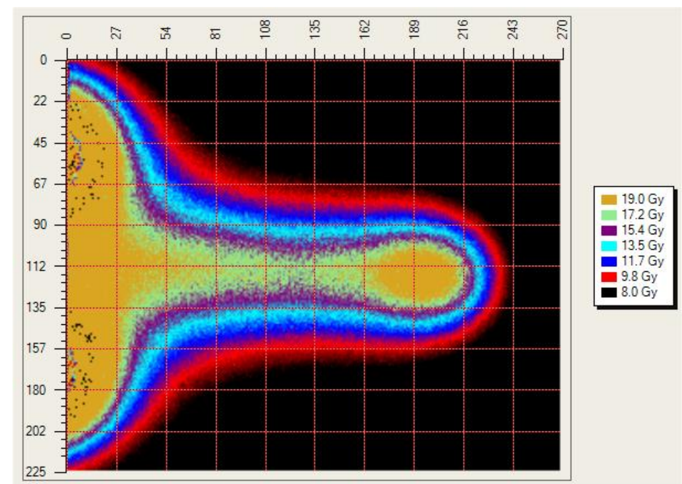
Triple Channel Film Dosimetry Dynamic Dose Range

- Same dose mapping method for all channels
- Range adaptation as needed
- Enables EBT's full dynamic range - Factor >1000
- ✘ Lateral effect increases substantially!







Example - Brachytherapy:
Calibration range 0 – 40 Gy, Dose map 22 Gy peak, Reference 9 Gy

Triple Channel, Single Scan Film Dosimetry

- Separate Dose and Dose-independent effects
  - Compensates for film thickness variation
  - Noise reduction without dose change
  - Mitigates scanner distortions
  - Background compensation, double exposure unnecessary
- Enables entire film dose range
  - Ebt2 dynamic range ratio >1000 (1 cGy - >40 Gy)
- Significant improvement of dose map accuracy
  - <1% achievable (*vs.* 3% with single channel method)
  - Optimized calibration per specific scan
- Indication of inconsistency between film and calibration, calibration inconsistencies

Conclusion !

Film is a ~~hassle~~ snap!

- **Fast results after minutes**
- **Accurate results <1%**
- **Simple operation**

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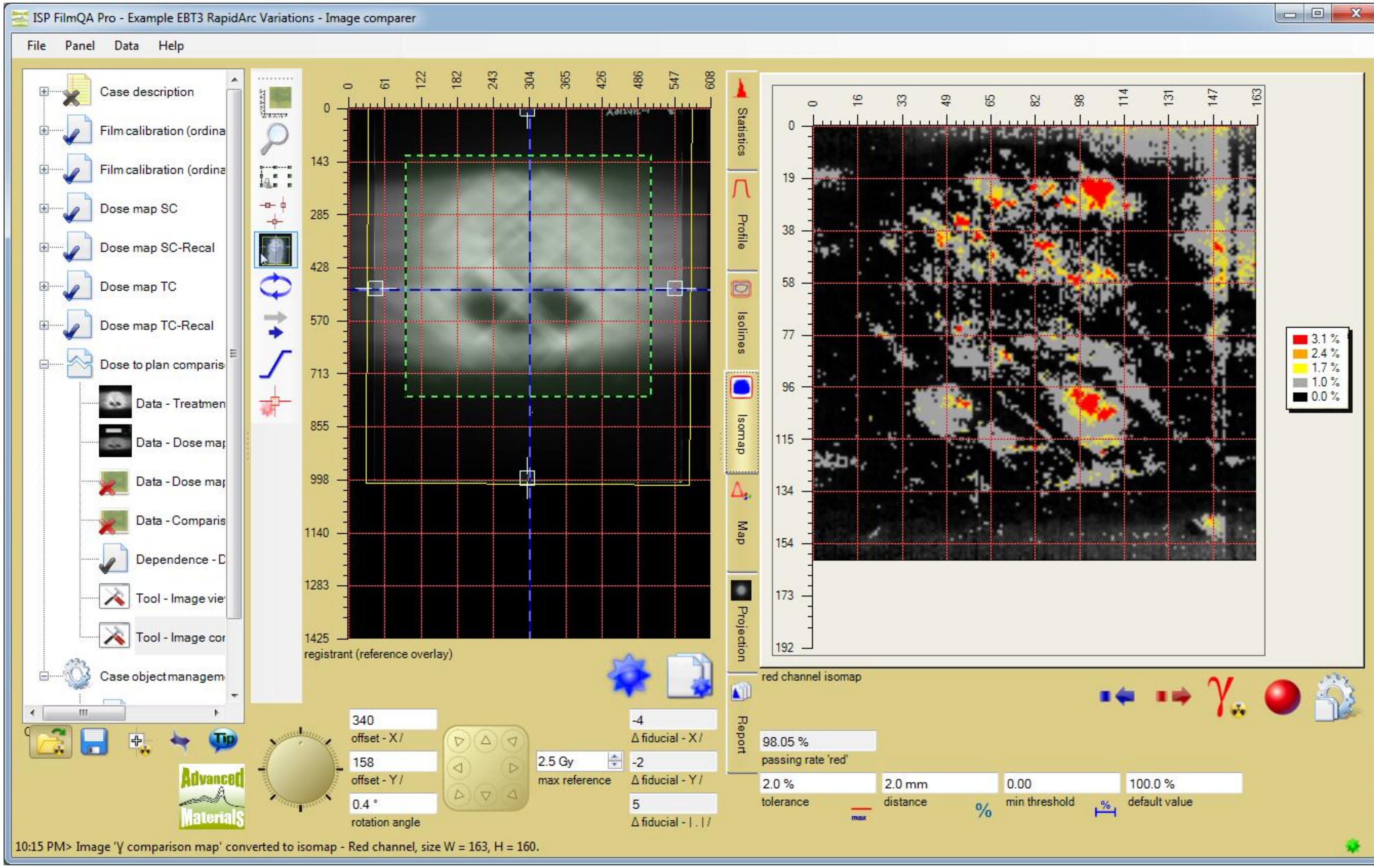

Micke, Lewis, Yu - Multi-channel Film Dosimetry with Non-Uniformity Correction, Medical Physics, 38 (2011) 5, pp. 2523.
Lewis, Micke, Yu, Chan - An Efficient Protocol for Radiochromic Film Dosimetry combining Calibration and Measurement in a Single Scan, Medical Physics, 39 (2012) 10, pp. 6339.

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