Multi-Channel Film Dosimetry Gamma Map Analysis

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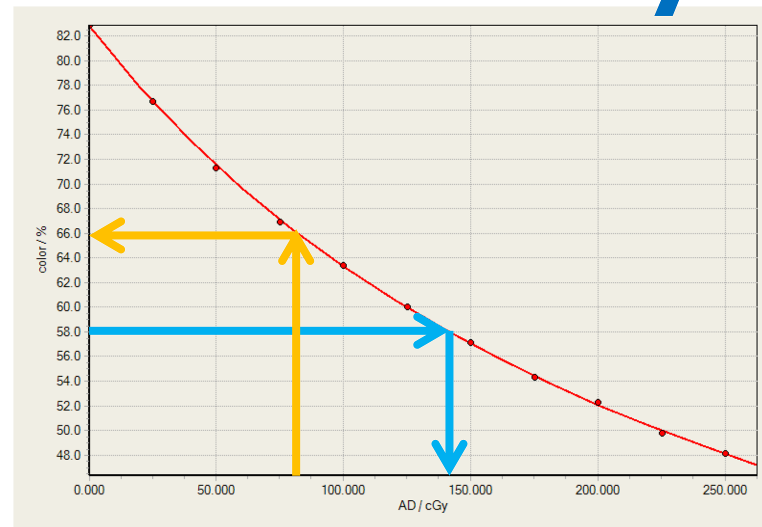
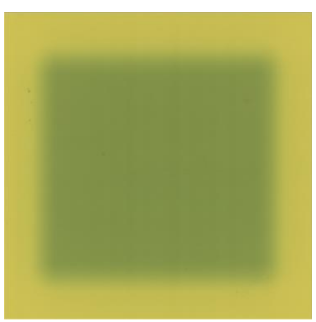
Ashland Inc. – Advanced Materials

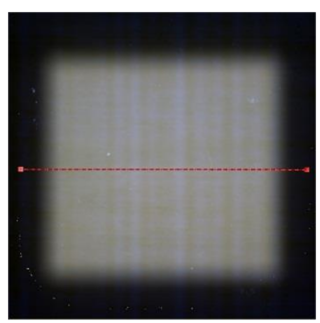
Ashland proprietary technology, patents pending

Single Channel Film Dosimetry

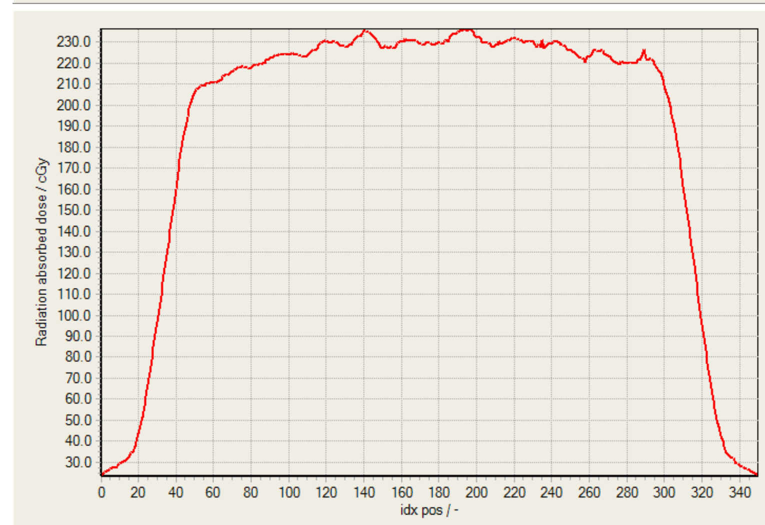
- Calibration Curve X=R
  $R_{ave} = R_{ave}(D) \leftrightarrow D_R = D_R(R_{ave})$
- Color channels X=RGB
  $D_X = D(\ X_{ave}\ )$
  correlates average response of film-scanner system
- Robust method
  any X value delivers dose $D_X(X)$







$D=D_X$



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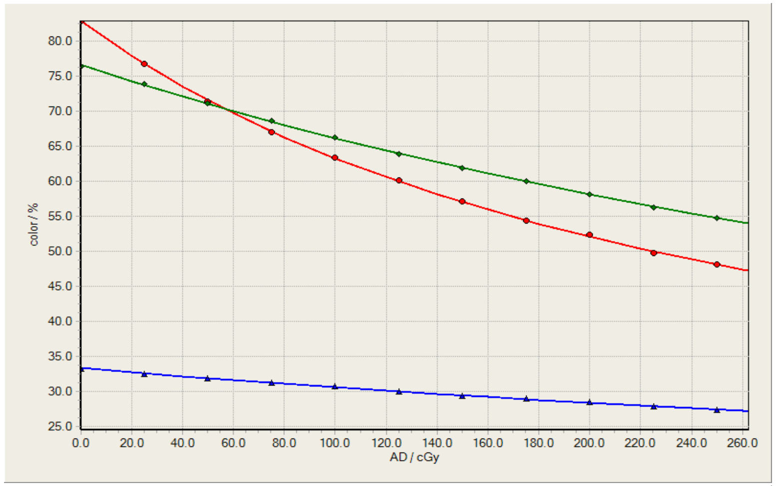
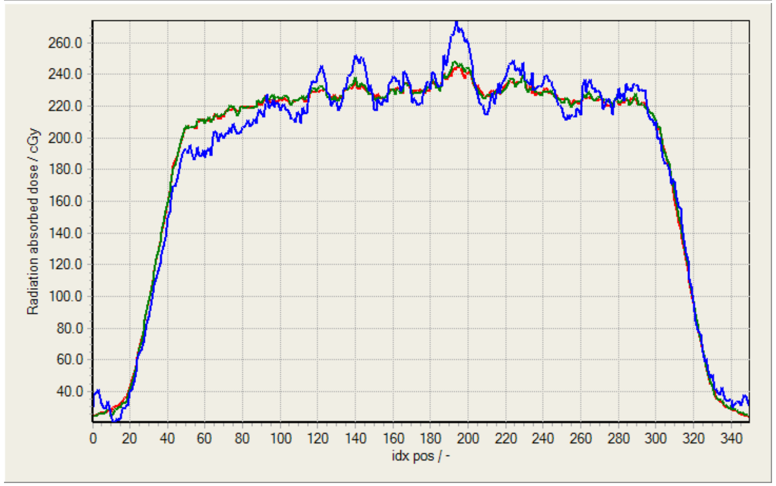
Single Channel Film Dosimetry

Problem:

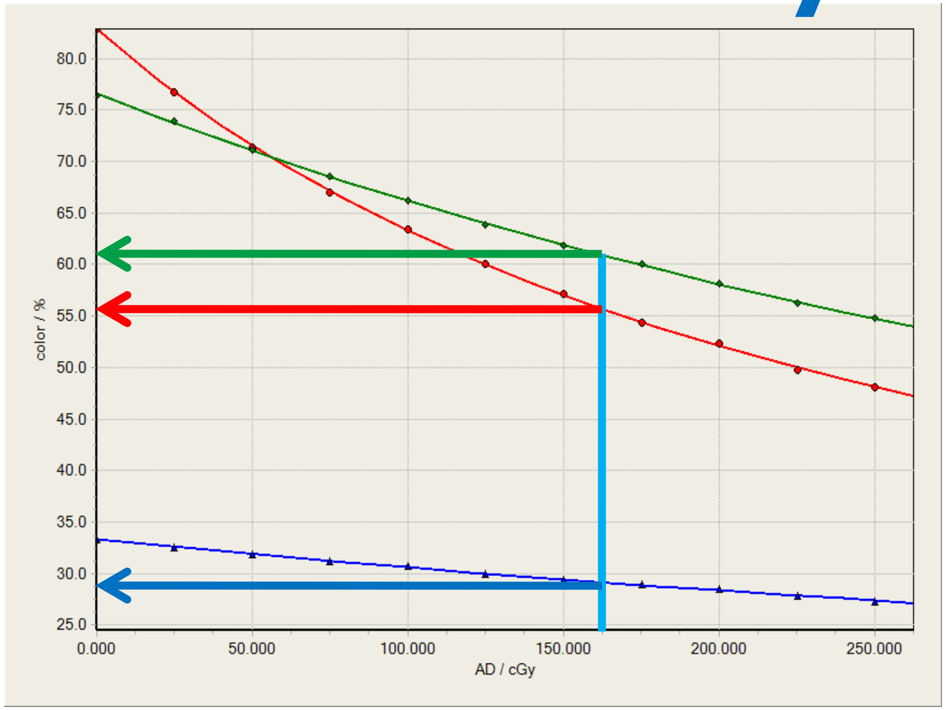
Specific pixel does
not behaves like average

- Disturbance ΔX generates ΔD_X
  X + $\Delta X \leftrightarrow$ D(X) + ΔD_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 $d_{X,scan}$
  - $\mathbf{d_{X,scan}(D) = d_{X,D}(D) * \Delta d}$

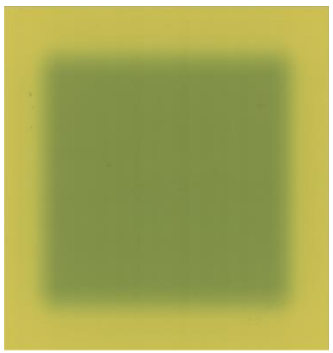
    $d_X = -\log(X)$ for $X = RGB$
  - $d_{X,D}$ is calibration function (average behavior)
  - ! disturbance Δd independent of dose + X (wave length) !

    but $\Delta d = \Delta d(\text{thickness, scanner, noise, artifacts})$
- Solution:
  - Minimized function ϕ *vs.* disturbance Δd:

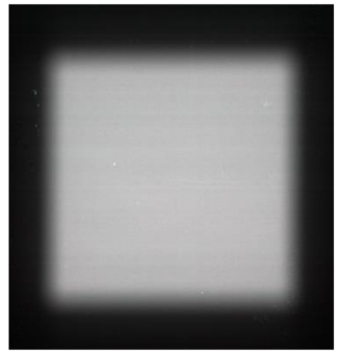
    $$\phi(\Delta d) = (D_R - D_B)^2 + (D_B - D_G)^2 + (D_G - D_R)^2 \rightarrow \min_{\Delta d}$$

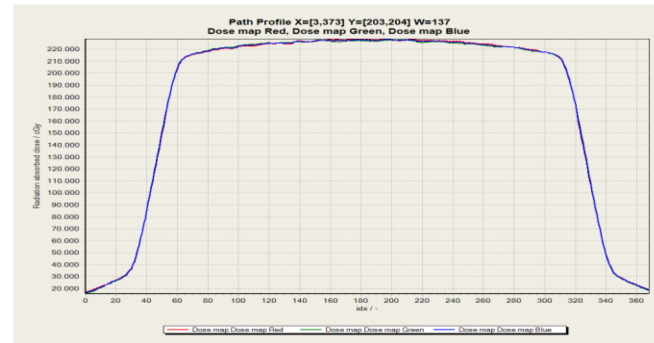
Triple Channel Film Dosimetry Example

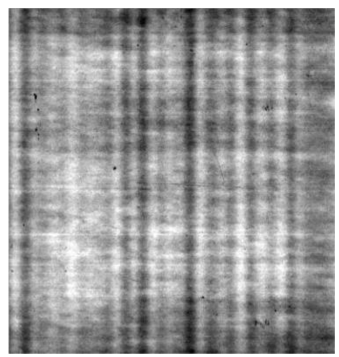
- Signal split into *dose dependent* and *dose independent* part

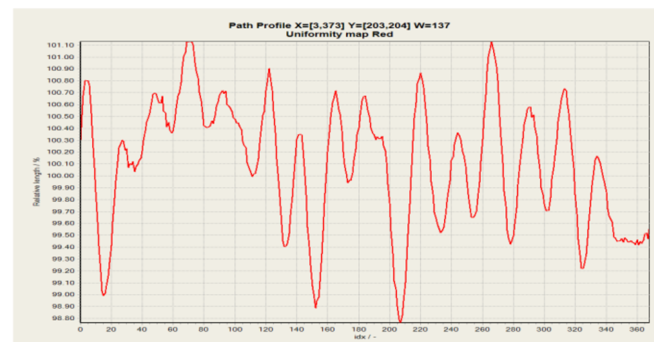


D_{RGB}+ Δd







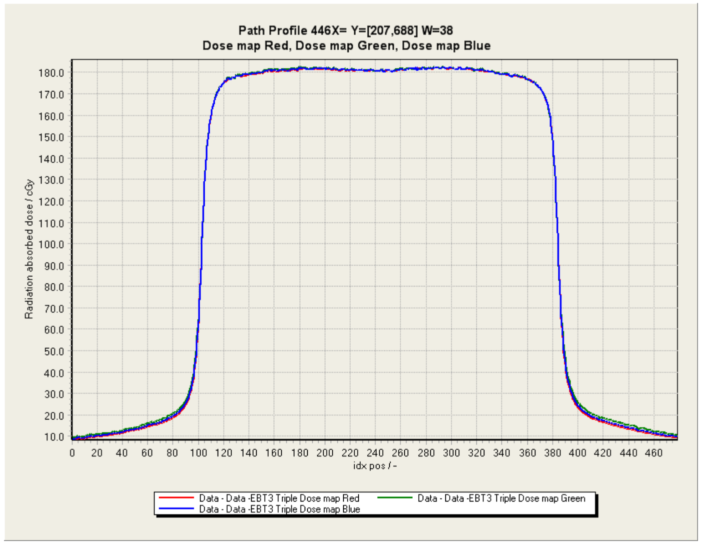


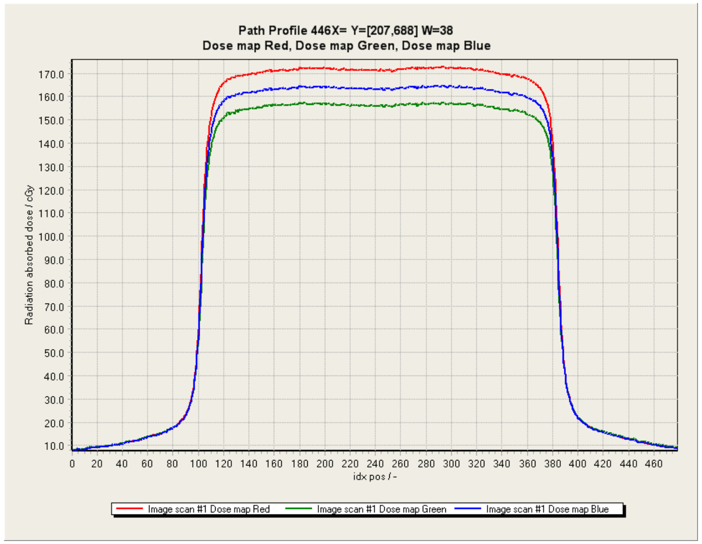
- Dose map (D dependent part)
- Disturbance Δd map (D independent part) includes film uniformity variations, noise etc.

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

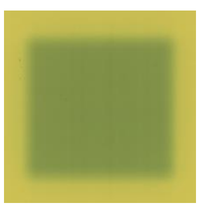




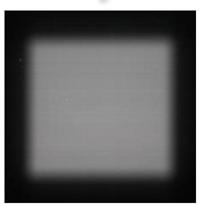
Example: Profiles original calibration patch and 90° rotated scan

Triple Channel Dosimetry Consistency Map

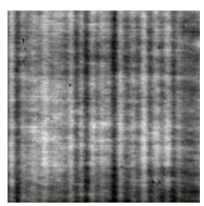
- Dose map
  – measurement result
- Disturbance map
  – removed error
- Consistency map
  – remaining error
  ideal case: noise only



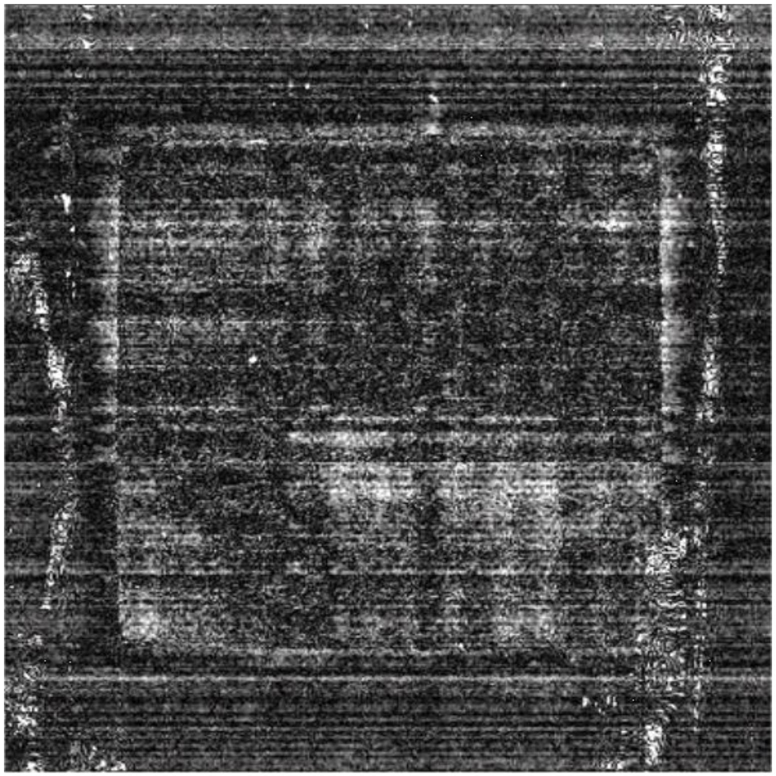
Film



Dose Map



Disturbance Map



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

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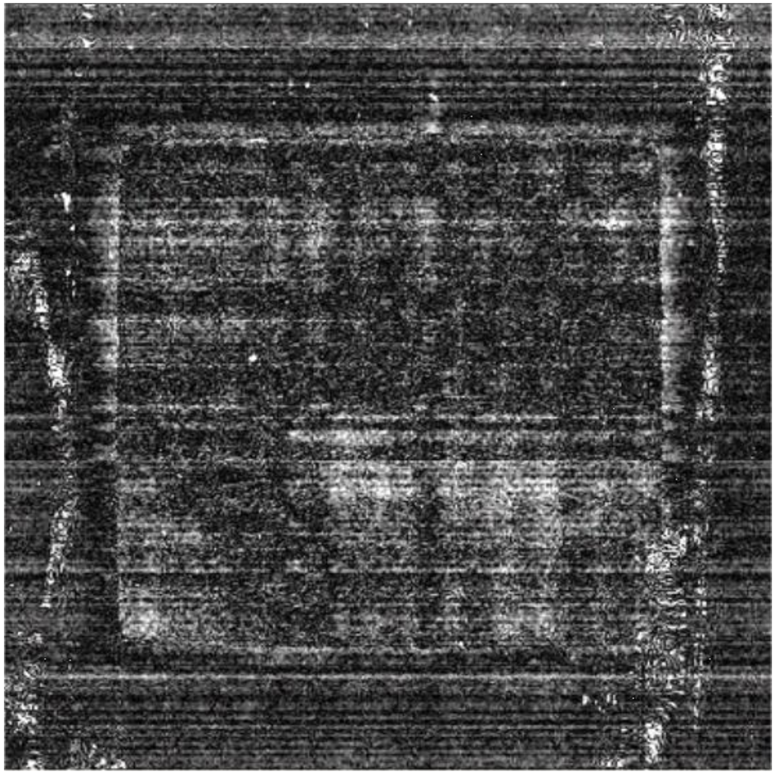
Multi Channel Calibration

Optimize Calibration

- Lower consistency = better calibration
- Offset in calibration points is **not** a quality criterion

Calibration goal

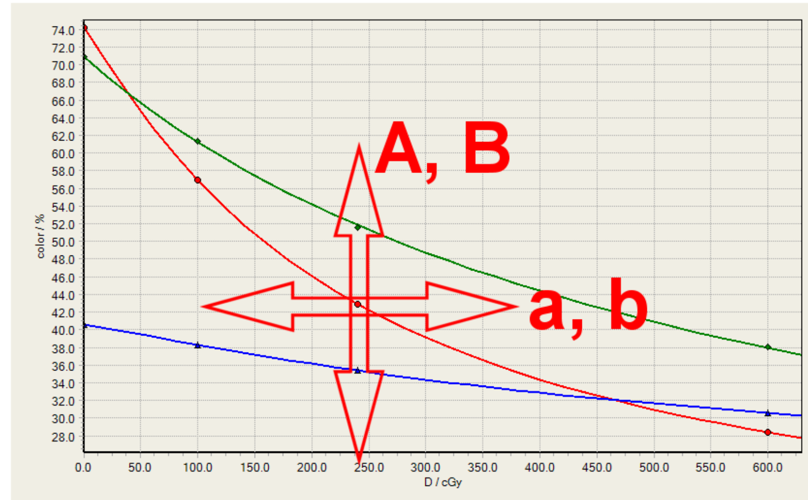
- Correlate calibration parameter for best (perfect) consistency
- Calibration function C(D) = { R(D), G(D), B(D) } matches film dose spectrum

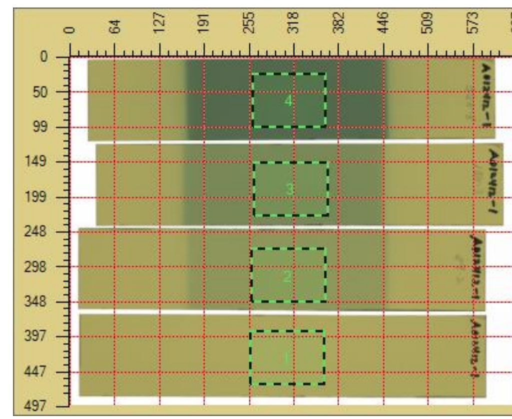


Perfect consistency ≡ 0

Multi Channel Calibration

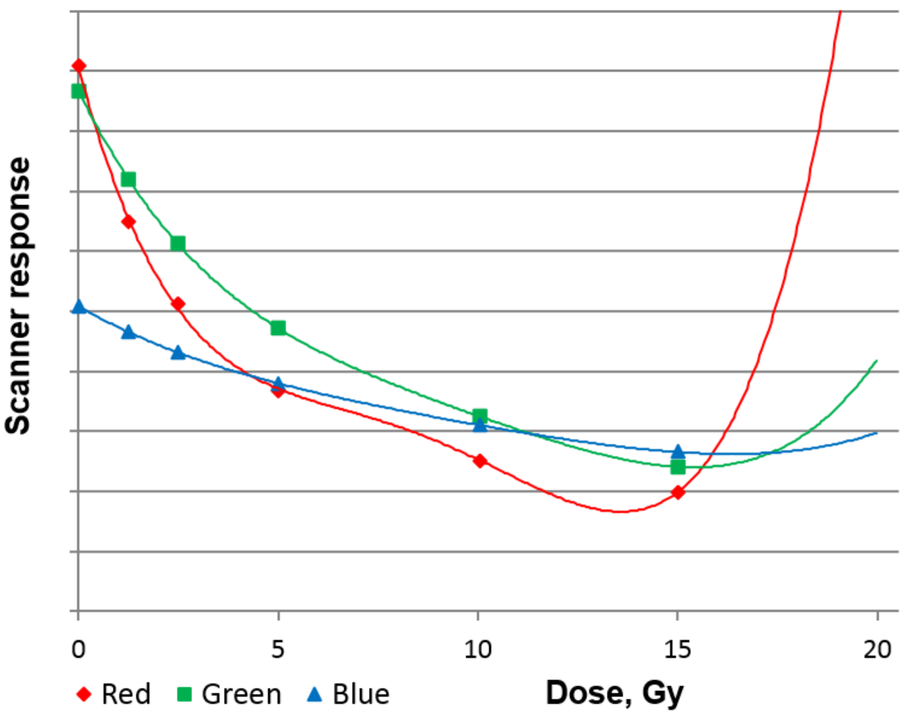
- **Single channel calibration**
  average system response
  - **$x = x(D)$**
    x = RGB
    each channel fitted separately
- **Multi-channel calibration**
  - **$X(D) = A + B\,x(a + b\,D)$**
    X = RGB
    rescales calibration x
    a, b dose scaling, A, B color scaling
  - Correlation $D_R(R_{ref})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





Polynomial Calibration

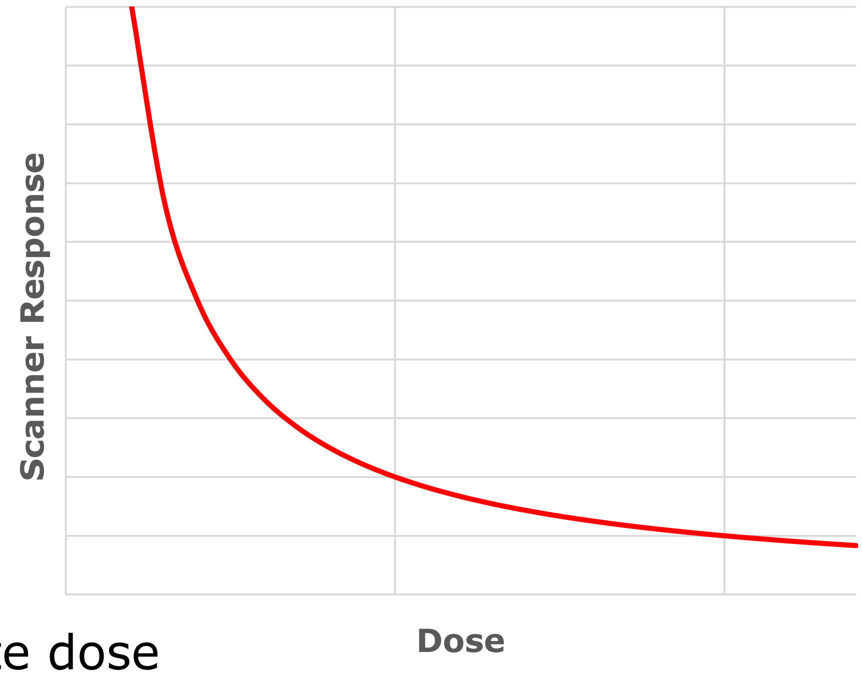
- **Polynomial fit**
  - $x(D) = \sum A_i D^i$
  - Least square solution
    $\sum(x_i - x(D_i))^2 \rightarrow min\ (A_i)$
    many parameters, oscillations



- **!Do Not Use!**
  - Many parameters
    (many calibration points)
  - Non-Monotonic function
    (physical incorrect!)
  - Non-Invertible function
    (optimization consistency at reference points costly)
  - Uncontrolled behavior between calibration point
    (additional calibration points to correct)

Rational Calibration

- **Primary Calibration**
  fits only function **Shape**
  - **Example**: Reciprocal function
    $x = 1 / D$
    no parameters, 'pure' shape



- **Recalibration**
  - **$X(D) = A + B / (C + D)$**
    rescales calibration x to absolute dose
  - **Rational function** with 3 parameters
    (only 3 dose points stipulate calibration)
  - Monotonic function (always physical correct)
  - Invertible function (dose *vs.* color) **$D_X = -C + B / (-A + X)$**

Multi Channel Calibration

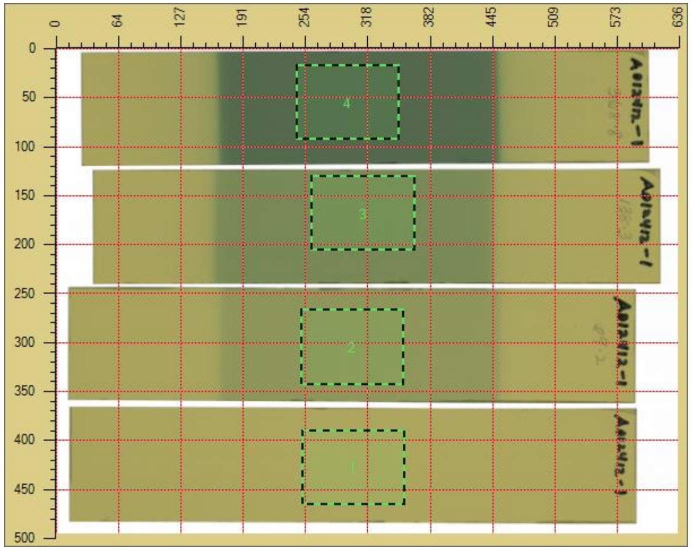
Model functions

- **Use Rational functions**

  Reciprocal $X(D) = A + B/(C+D)$

  Linear $X(D) = (A+BD)/(C+D)$

  Quadratic $X(D) = (A+BD+CD^2)/(E+D)$



Optimize Consistency

- Enforce

  $D_R(R_{calib}) = D_G(G_{calib}) = D_B(B_{calib}) = D_{calib}$

  for all calibration pixels X_{calib} (>10000 equations)

- Optimize calibration regions
- Select best model function
- **Do Not** $D_R(R_{ave}) = D_G(G_{ave}) = D_B(B_{ave}) = D_{calib}$

  for all calibration dose points (<10 equations)

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Multi Channel Calibration

Two point recalibration

- 1 unexposed + 1 exposed film
  Minimum 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

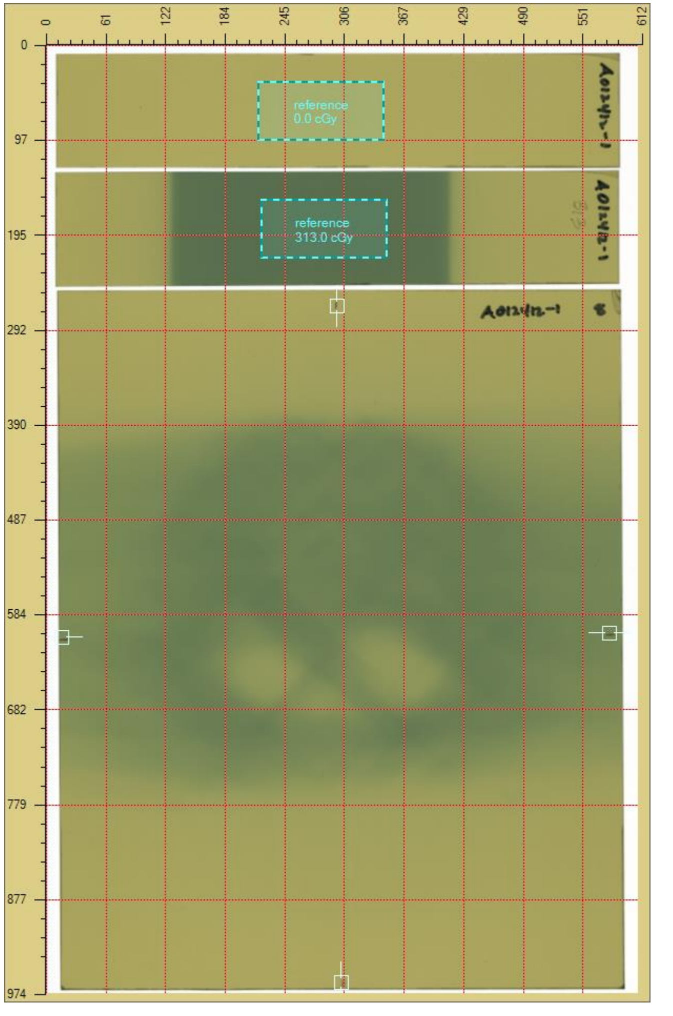
Assumption

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

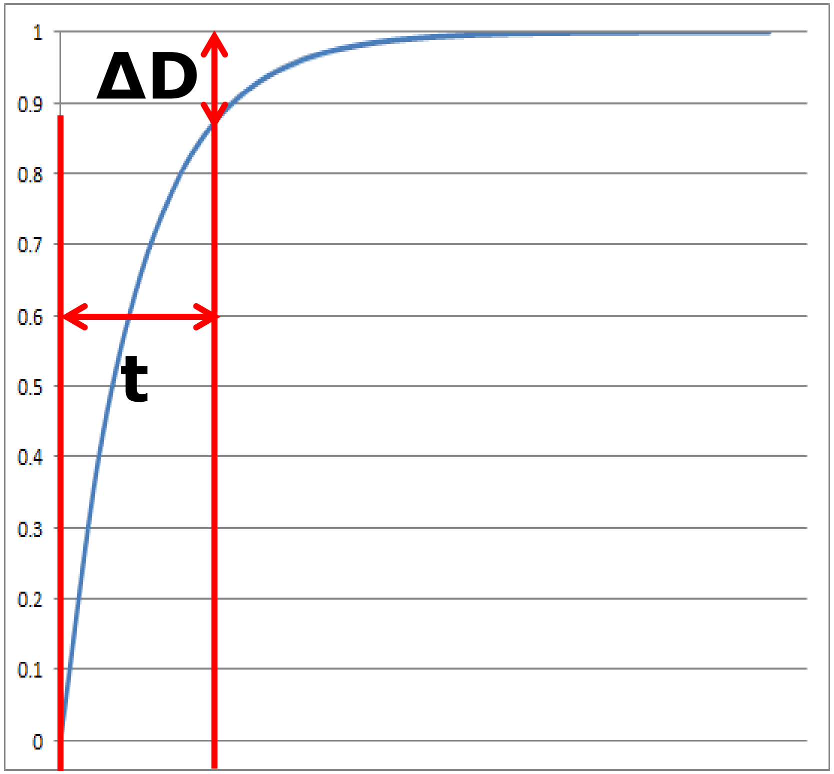
Single scan Evaluation

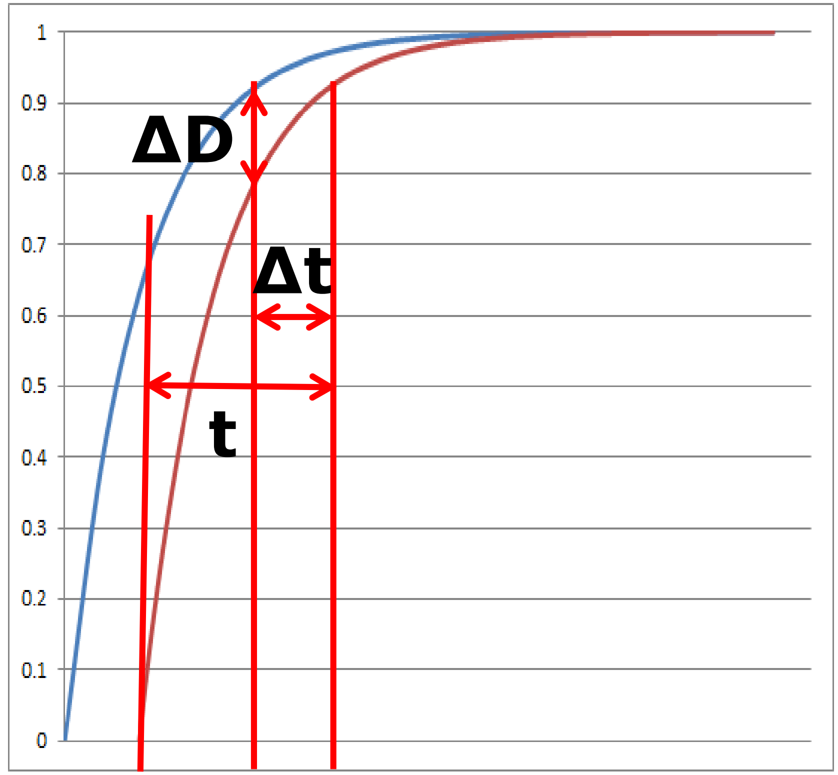
compensates for

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



Rescaling - Post Exposure Age





Absolute aging
wait t = 24 h
$\Delta D(t) < 0.5\%$

Relative aging
wait t = 4 Δt
$\Delta D(t) < 0.5\%$

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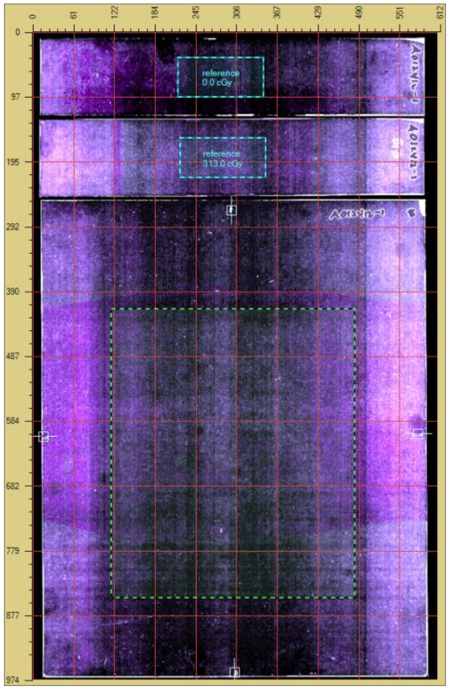
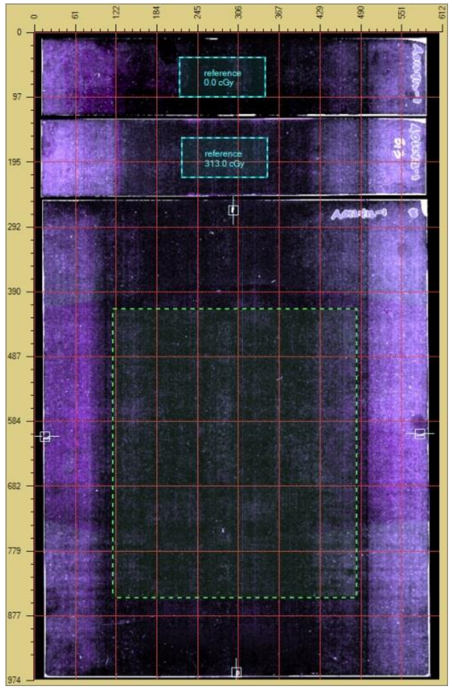
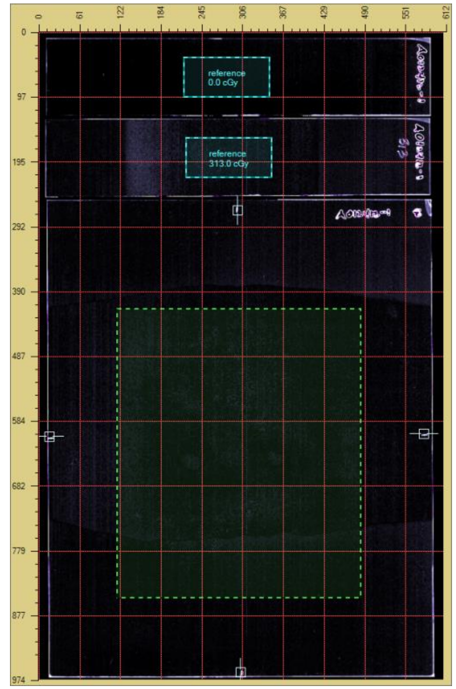
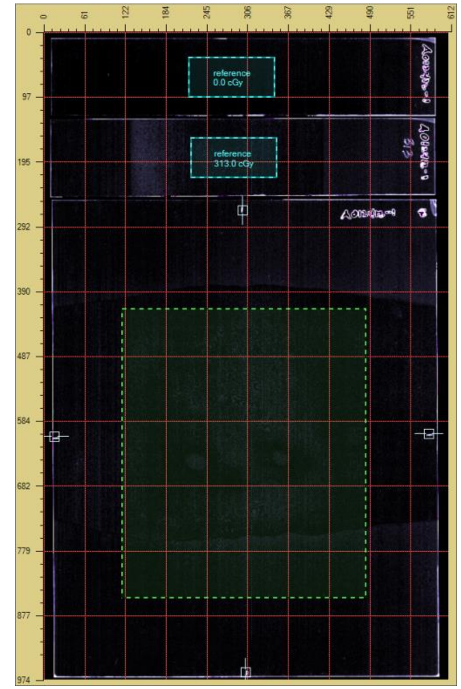
Consistency Comparison









Single Channel	Single Channel Recalibrated	Multi Channel	Multi Channel Recalibrated
10.2 cGy	3.6 cGy	1.3 cGy	1.2 cGy
4.2%	1.5%	0.53%	0.49%

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

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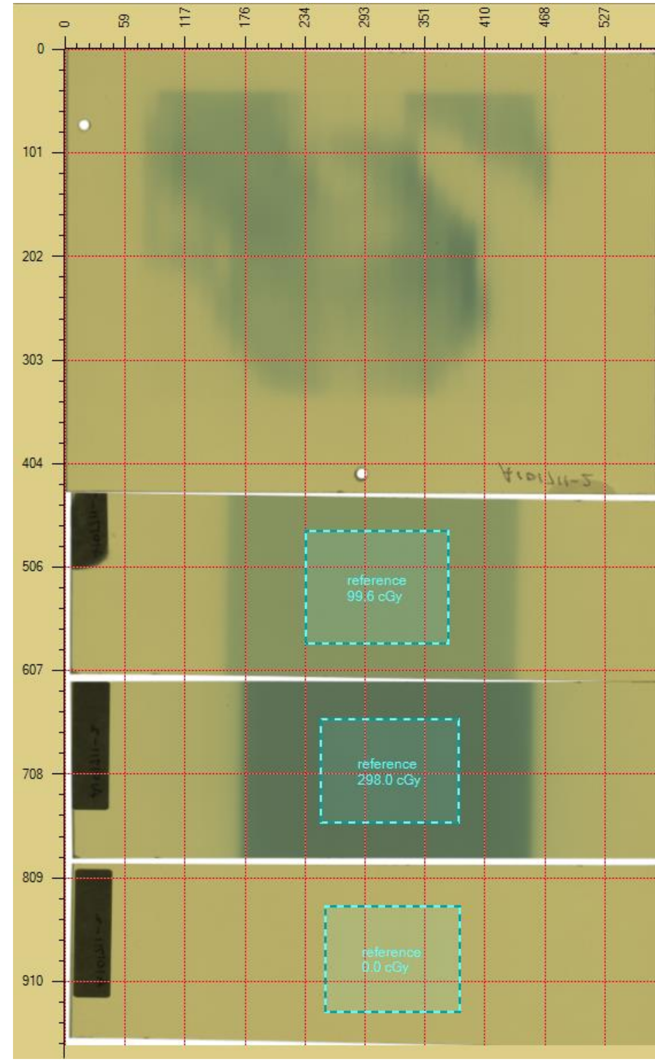
Multi Channel Calibration

- **Triple point recalibration**
  - 1 unexposed + 2 exposed film
    Higher cost
  - X(D) = A + B x(C D) (3 point rescaling)
  - X(D) = A + B x(D^C)
    X = RGB
- Requires 2 exposures
  - Enforces perfect consistency at references
  - Recalibration includes rescaling and shape correction
- Single scan Evaluation compensates for
  - All two point recalibration benefits
  - Shape changing properties
    i.e. any primary calibration can be used



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Multi Channel Calibration

Single point recalibration

- 1 unexposed
  it's **free** and always possible
- *Dose* shift ($A=0$, $B=1$, $b=1$)
  $X(D) = x(a + D)$, $X = RGB$
- *Color* shift ($a=0$, $b=1$, $B=1$)
  $X(D) = A + x(D)$, $X = RGB$

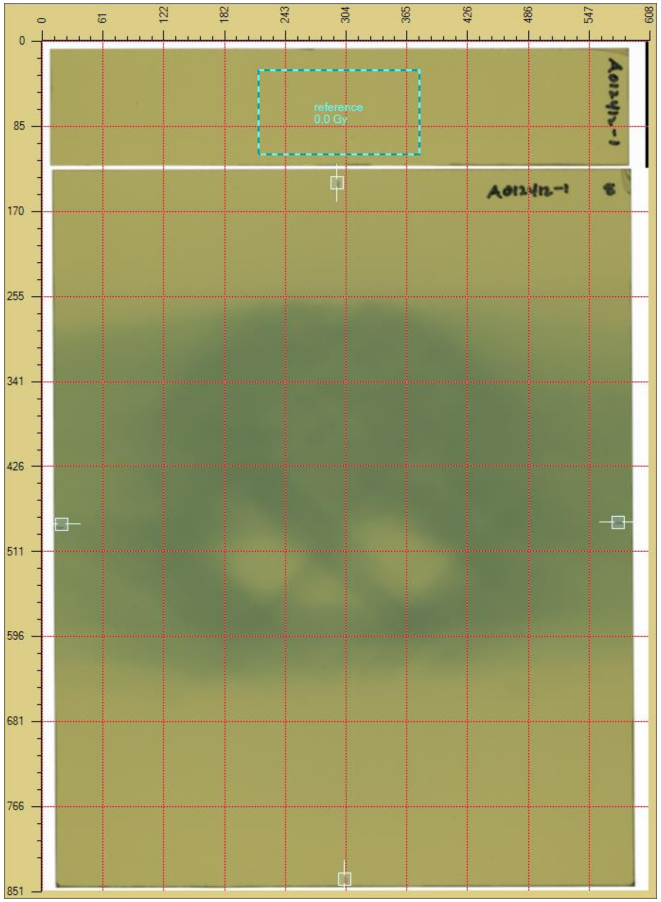
Assumption

- Calibration functions keep shape
  $Shape(x) = Shape(X)$, $x, X = RGB$
  disturbance caused by offset only

Single scan Evaluation

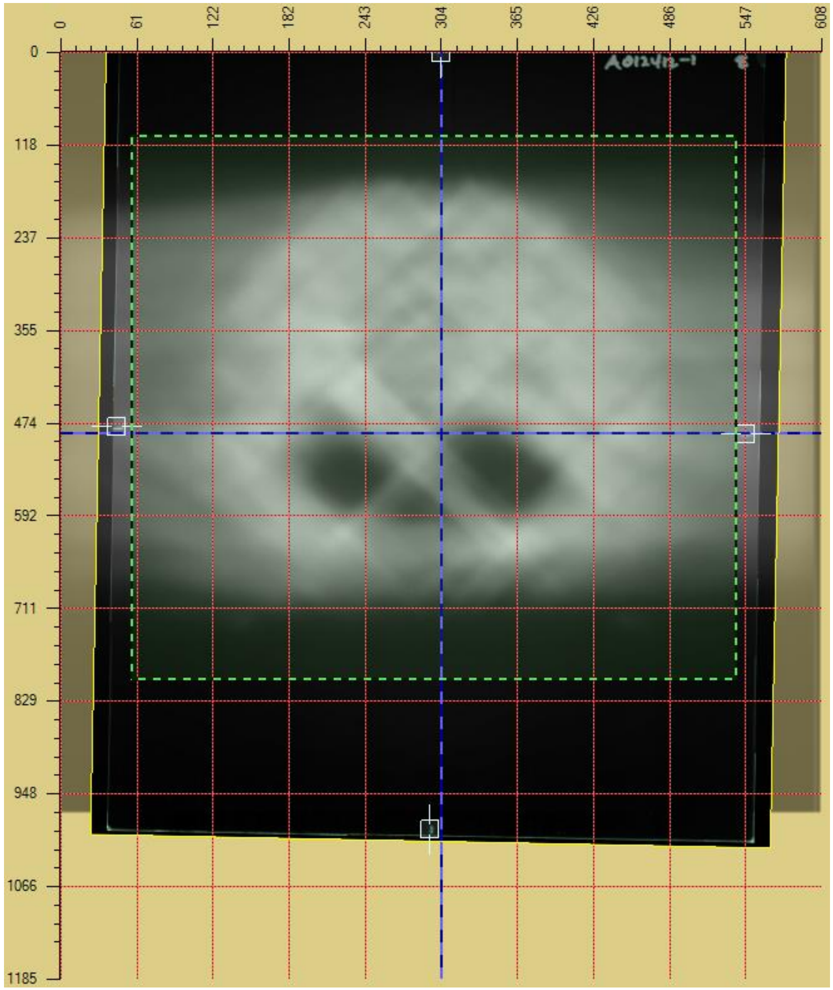
compensates for

- Offset generating disturbances



Multi Channel Calibration

Recalibration Comparison Triple Channel Method			
Recalibration points	0 points	1 point	2 points
Passing rate 3%/3mm	99.6	99.8%	99.9%
Passing rate 2%/2mm	95.6%	96.3%	97.1%
Passing rate 1%/1mm	44.5%	48.6%	49.6%
Example range: D_{max} = 243 cGy, D_{ave} = 139 cGy			



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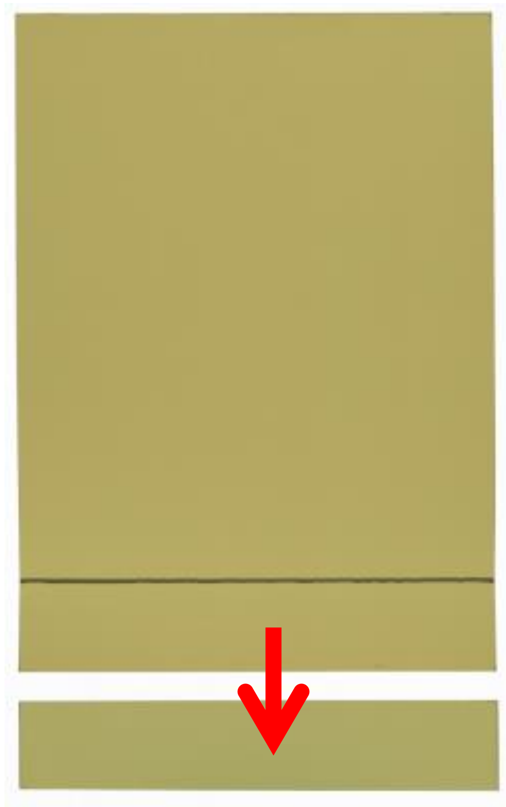
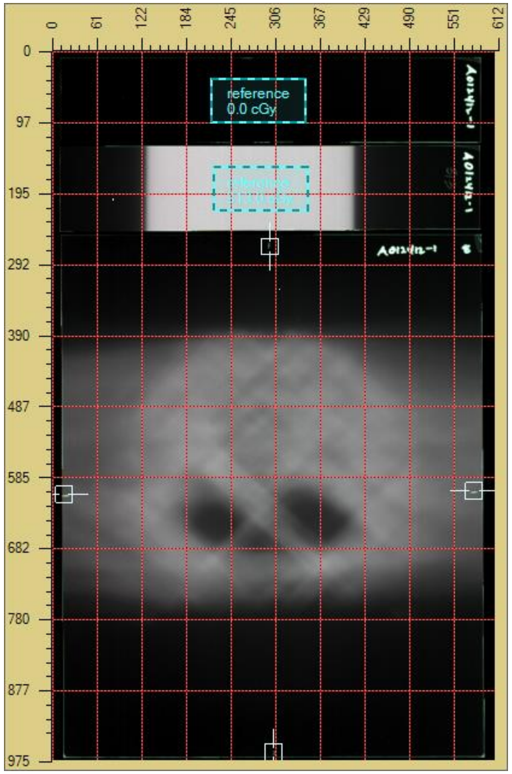
One-Scan Protocol - EBT3+

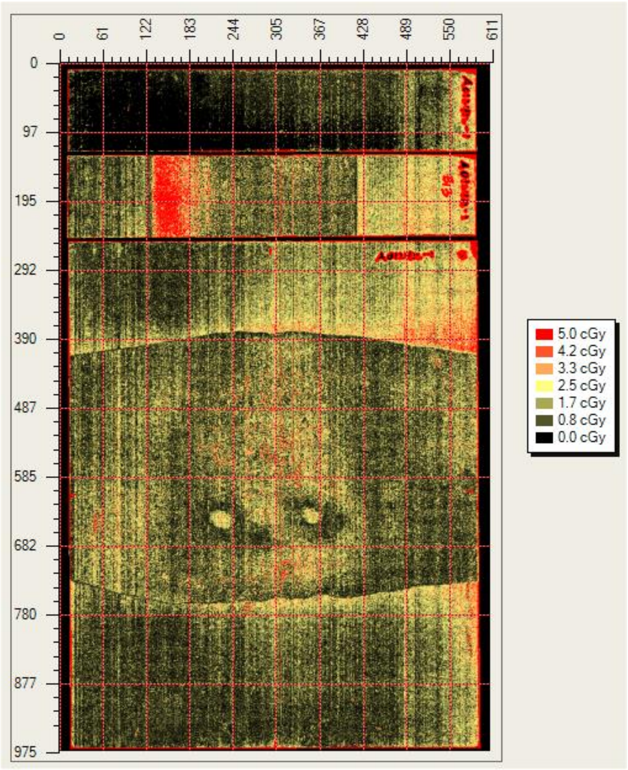
- Configuration same as EBT3
- Attached reference strip
  - Strip *properties as close as possible* to patient film
- Perforated Sheet
  easy to detach reference strip
  - Saves film cutting
  - Standardized strip size
- EBT3+ available since 2012



Triple Channel Dosimetry Dose Map Consistency

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

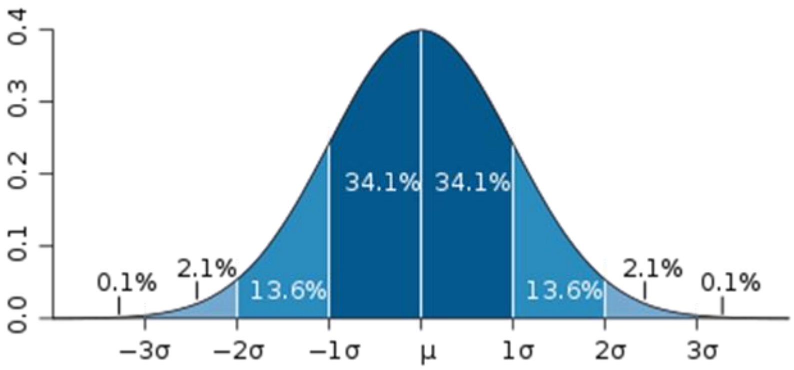




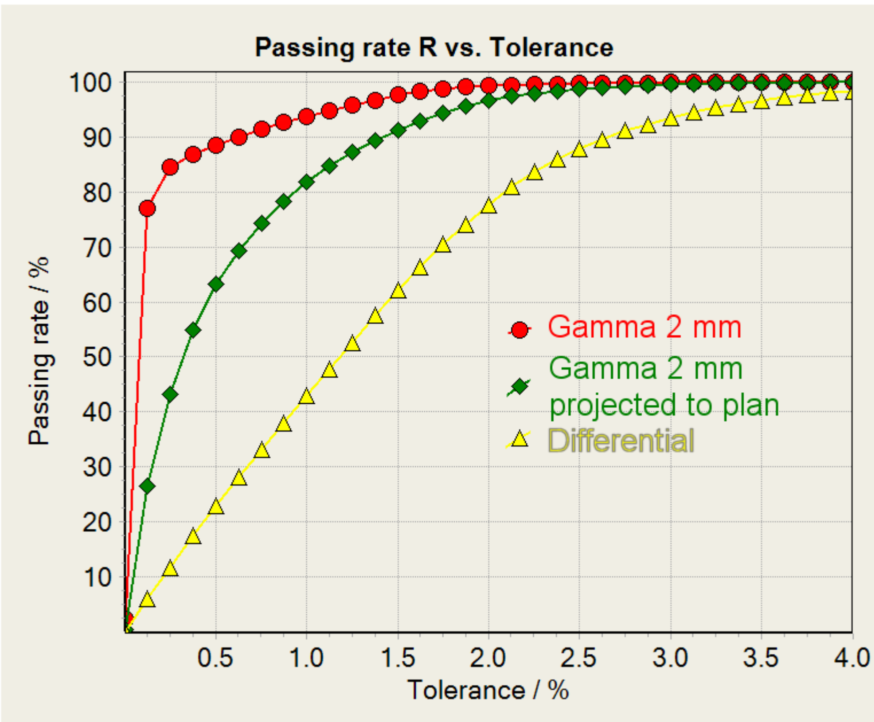
Example dose consistency map (iso-map) peak error ~2%

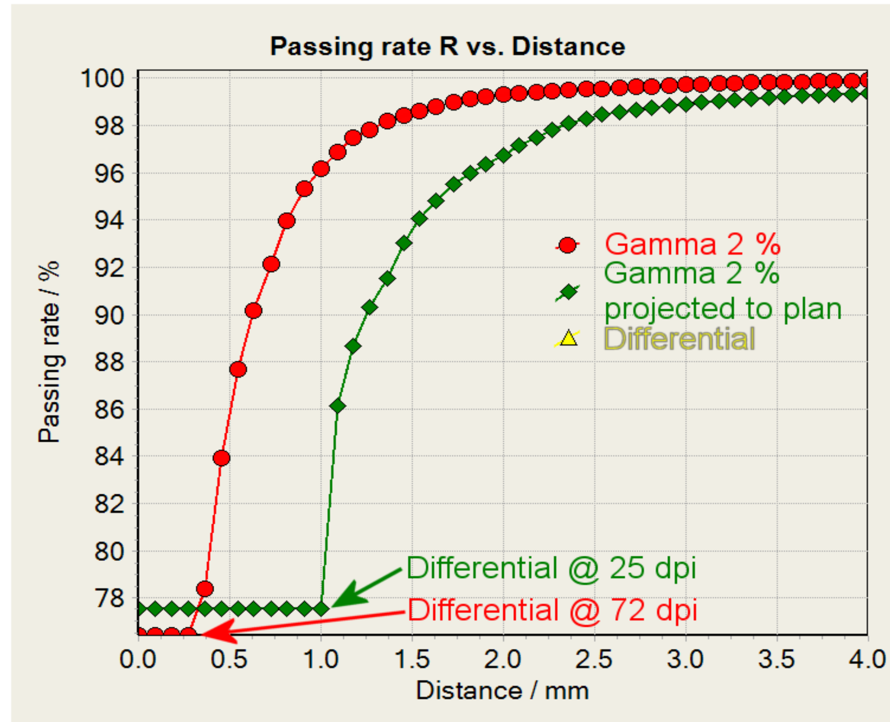
Triple Channel Film Dosimetry Dose to Plan Comparison

- Dose map error can dominate comparison
  - ~0.5% 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

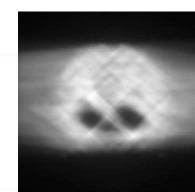


Gamma Map Comparison
Passing Rate Dependencies





Passing Rate vs. Tolerance **Passing Rate vs. Distance (DTA)**



Gamma Map **2%/2mm** - FilmQA Pro RapidArc example
Distance dependence chart suggest **Resolution** dependence

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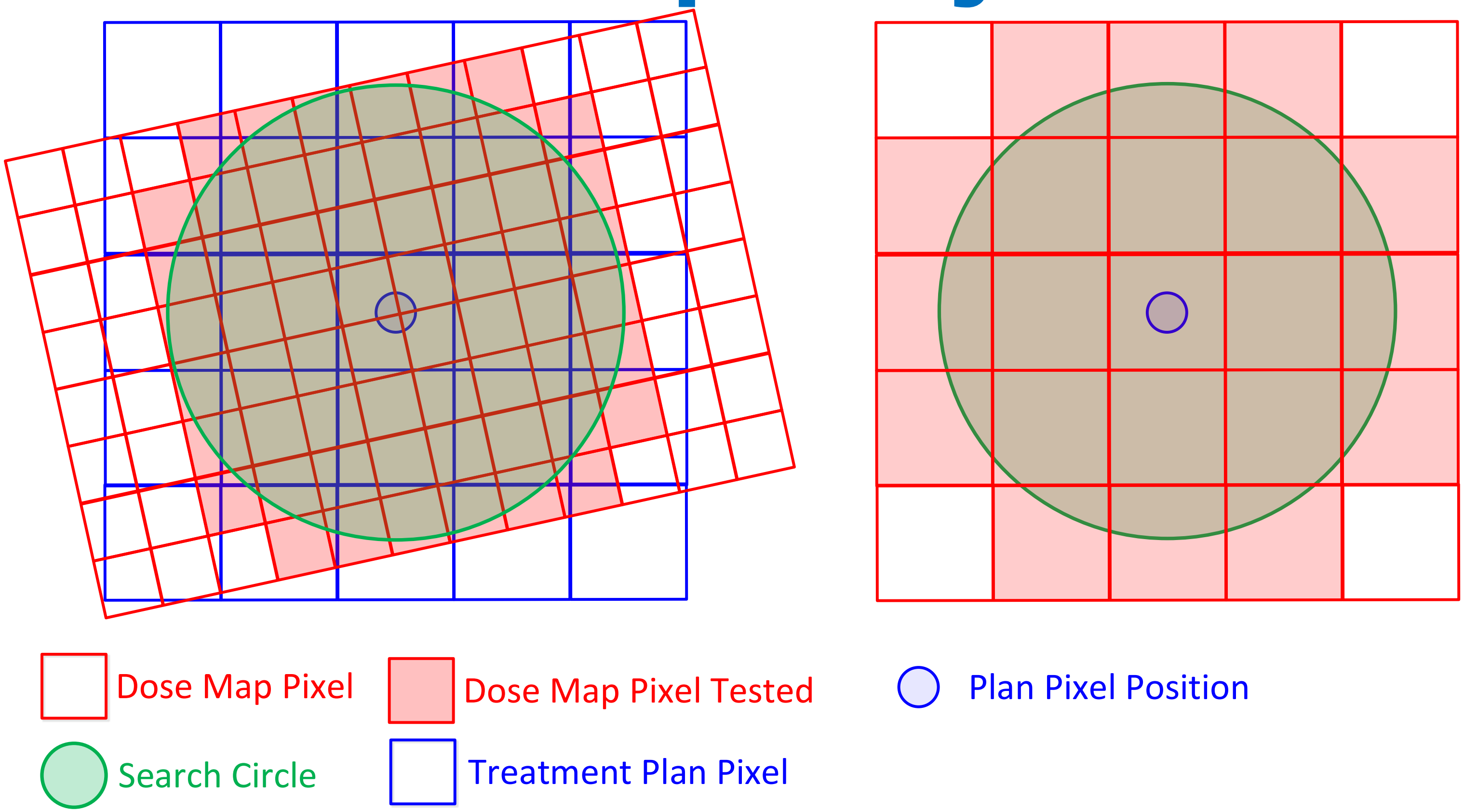
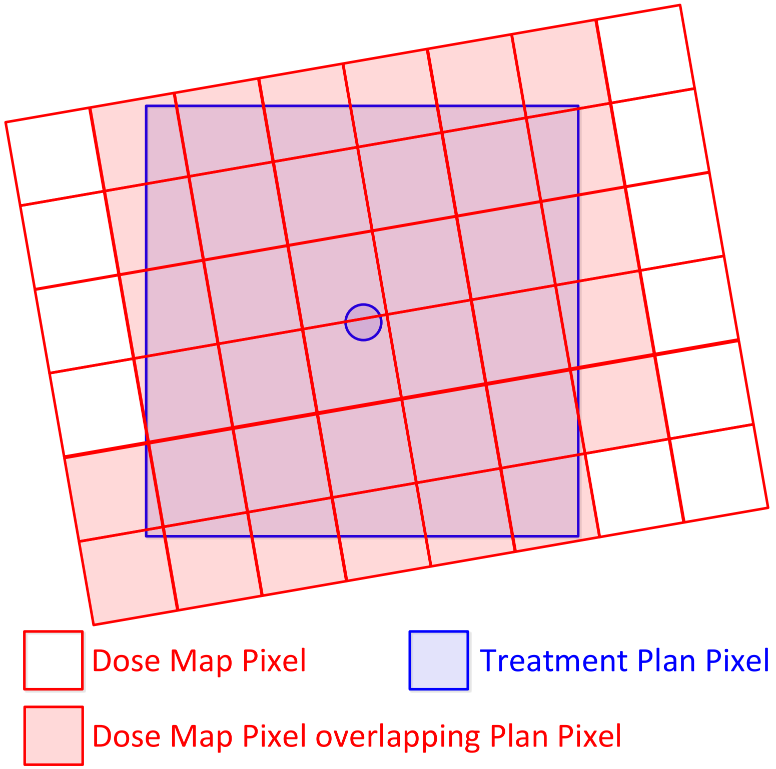
Gamma Map Comaprison
Dose Map Projection



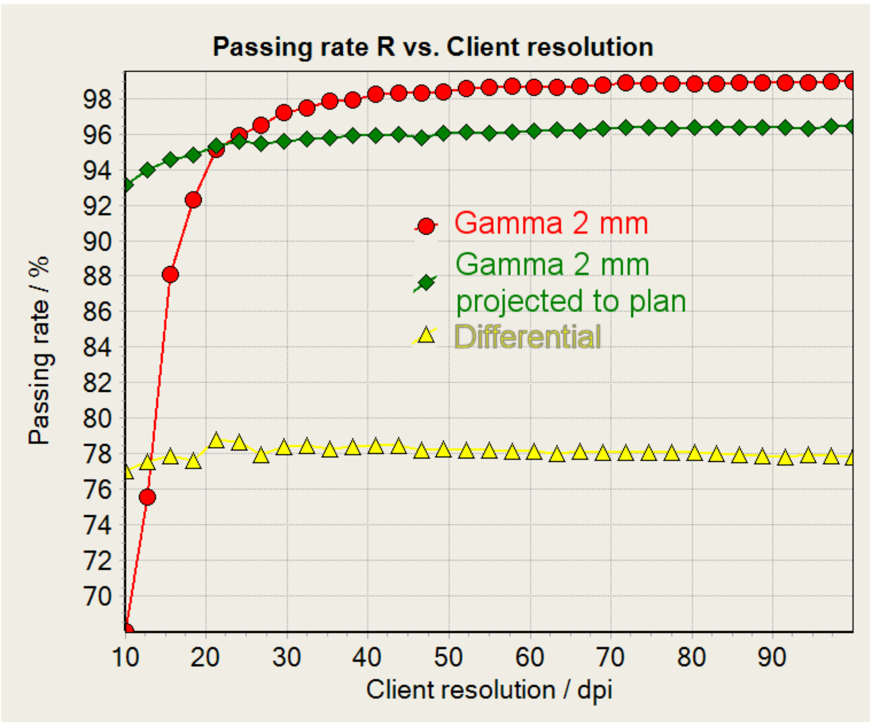
Gamma unprojected   Gamma projected

Triple Channel Film Dosimetry Dose to Plan Comparison

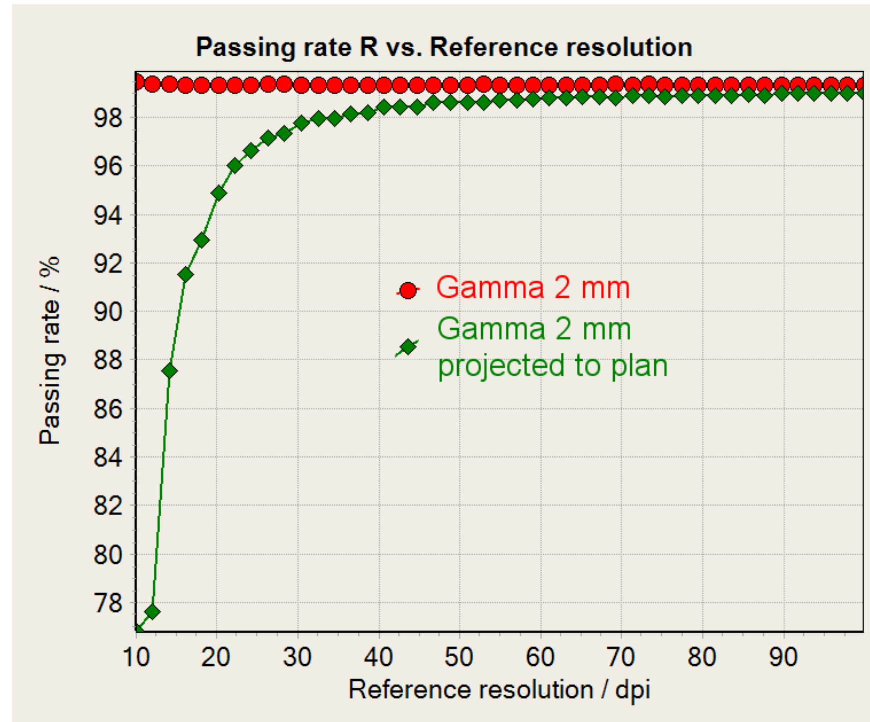


- Averaging Dose Pixels over Plan Pixel
- Result: Dose Map with Plan Resolution
- Direct Differntial Comparison

Gamma Map Comparison
Passing Rate Dependencies



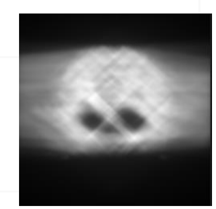
Passing Rate vs. Dose Map Resolution



Passing Rate vs. Plan Resolution

Gamma Map **2%/2mm** - FilmQA Pro RapidArc example

Passing rate R **99.3 %**



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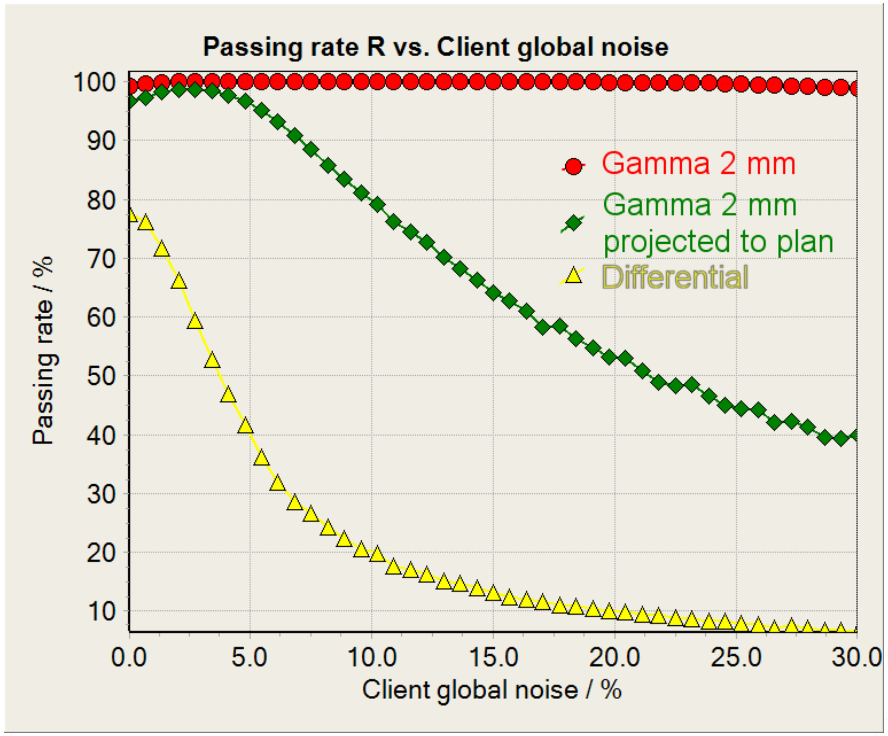
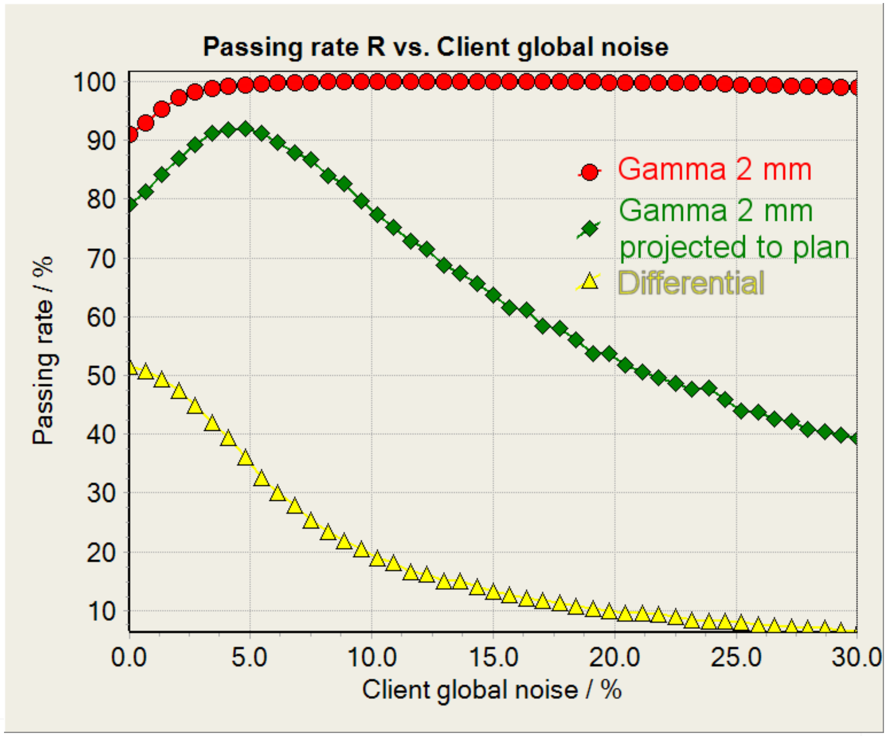
Gamma Map Comparison
Passing Rate Dependencies

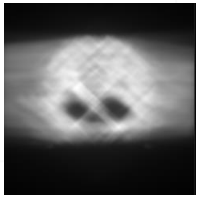


Passing Rate @ best location vs. Noise



Passing Rate @ 2 mm shift vs. Noise

Gamma Map **2%/2mm** - FilmQA Pro RapidArc example
Equi-distributed noise added, x axis shows maximum amplitude



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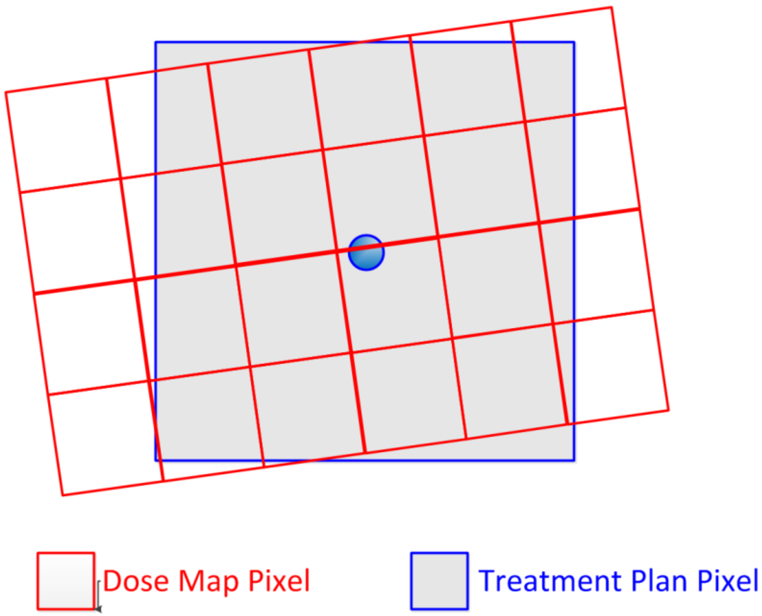
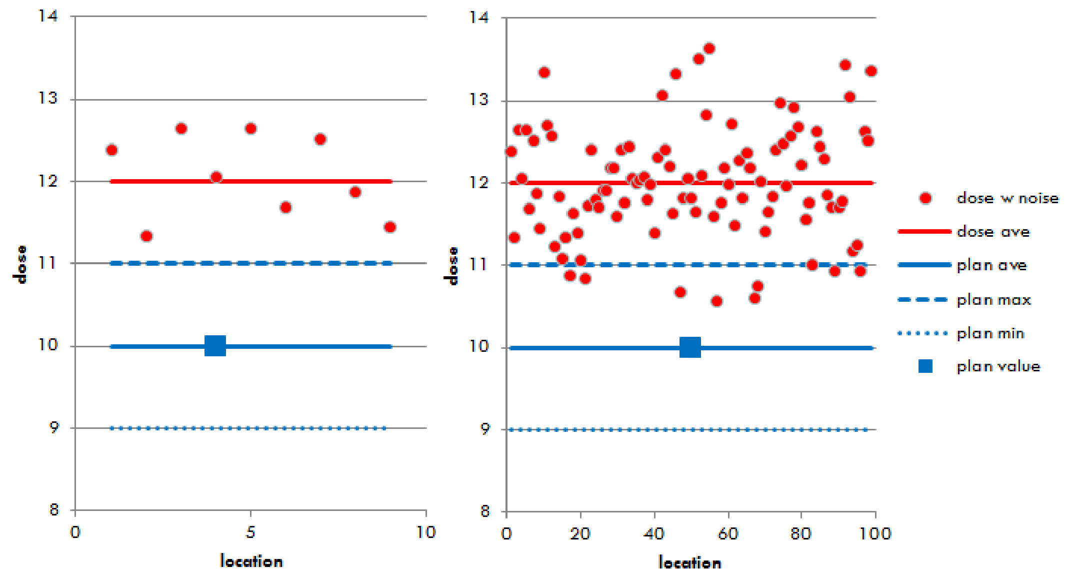
Gamma Map Comparison



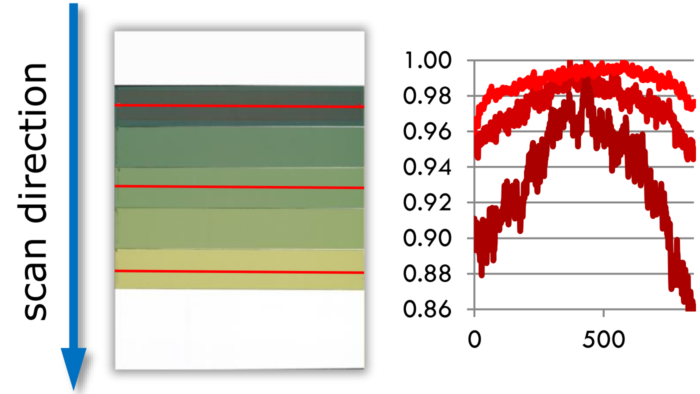


plan pixel and overlaid pixels of registered dose map

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!

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
- Improved Gamma passing rates reported due to noise

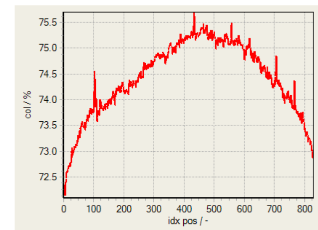
! DO NOT USE !

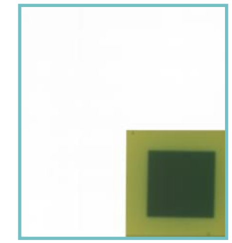
Calibration patch consistency comparison

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

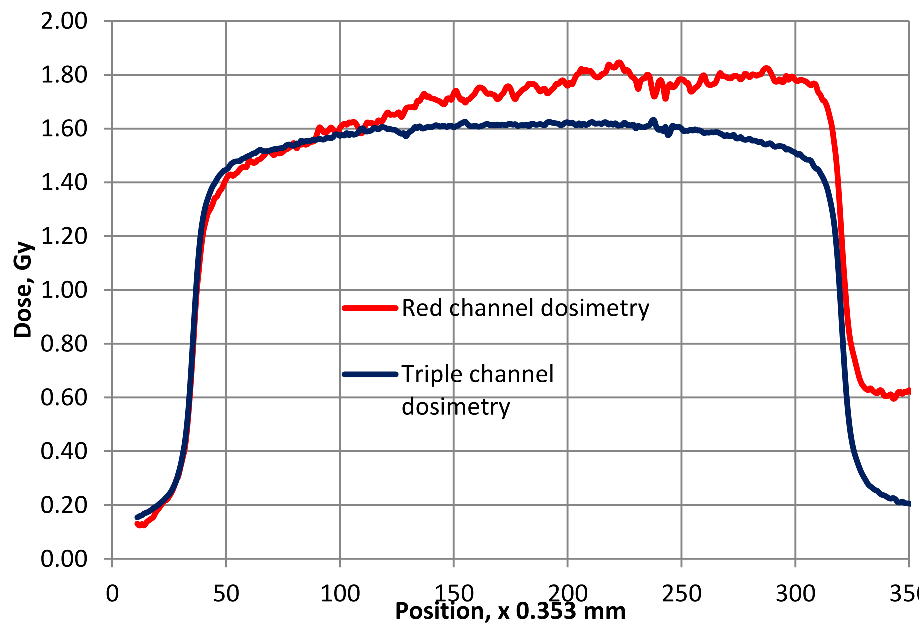
Triple Channel Dosimetry
Lateral Scanner Non-Linearity

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)



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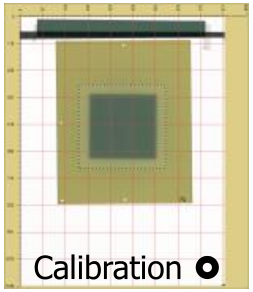
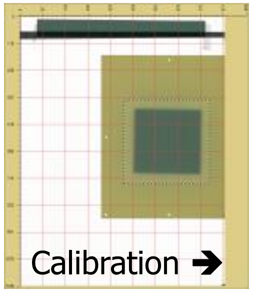
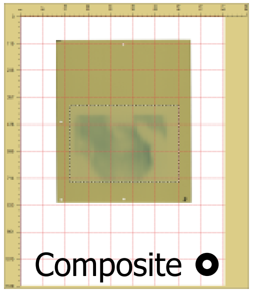
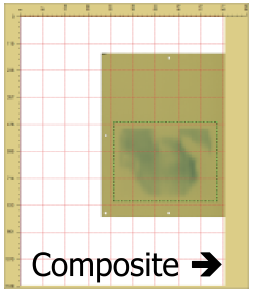
Lateral Scanner Non-Linearity
Single vs. Triple Channel

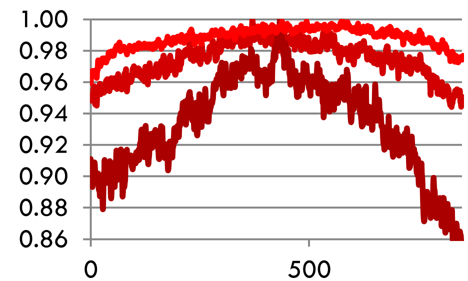
Gamma map Criterion	Calibration	Composite	Passing rate	
			Single Channel	Triple Channel
2% / 2mm	⊙	⊙	90%	96%
	→	→	87%	96%
	⊙	→	98%	98%
	→	⊙	94%	97%
	⊙ = centered → = right edge		absolute dosimetry (no dose re-scaling), <5% (<12cG) lowest dose ignored,	











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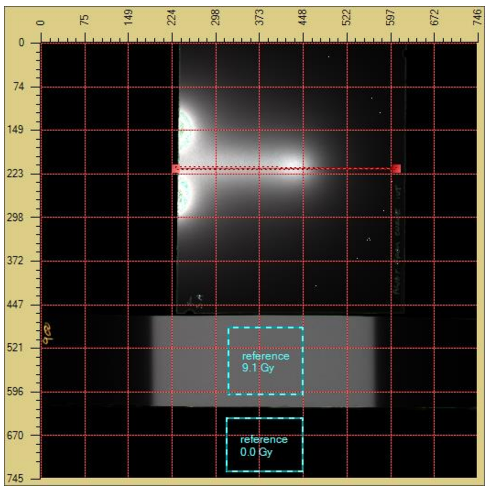
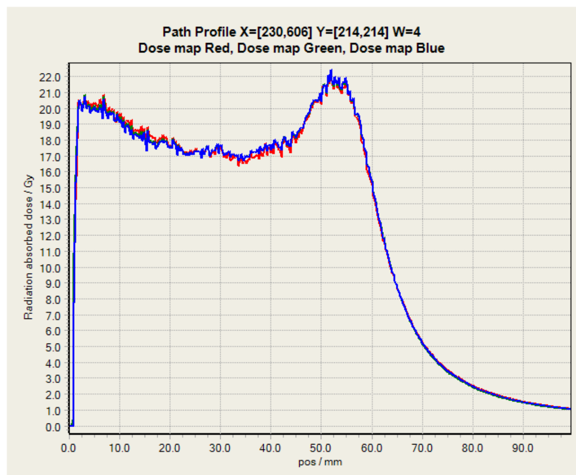
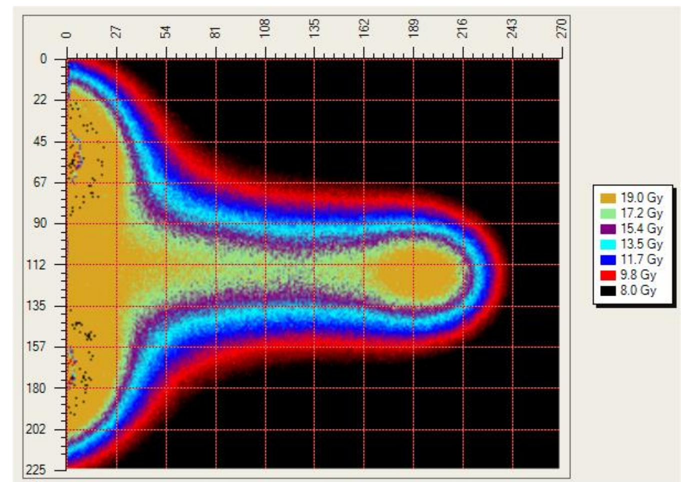
Triple Channel Film Dosimetry
Dynamic Dose Range

- 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

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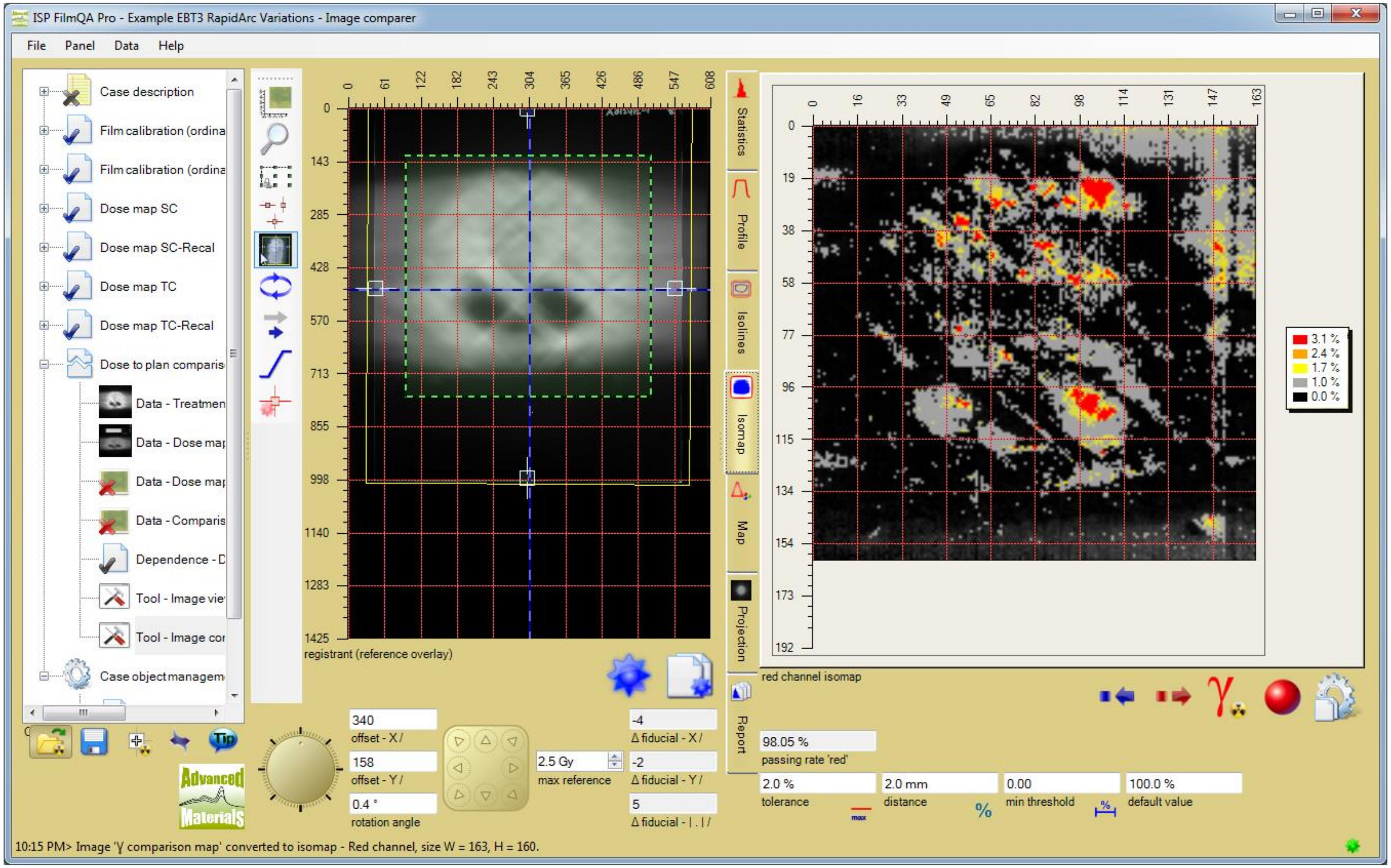

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Lewis, Micke, Yu, Chan - An Efficient Protocol for Radiochromic Film Dosimetry combining Calibration and Measurement in a Single Scan, Medical Physics, 39 (2012) 10, pp. 6339.