GafChromic Protocol

Multi-Channel Film Dosimetry + Gamma Map Analysis

Micke A.

Ashland Inc. – Advanced Materials

Ashland proprietary patented technology

GafChromic

A. Micke, Europe, February 2015
www.FilmQAPro.com

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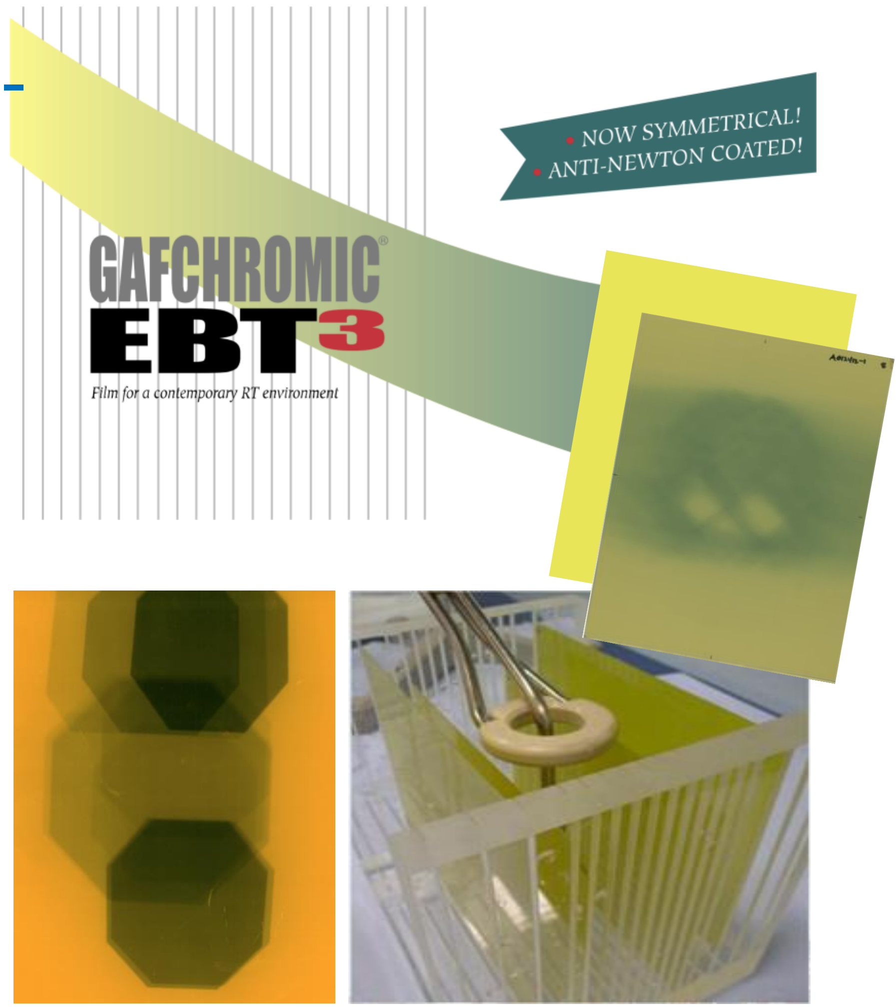
GafChromic Film for Dose Measurement

- **Radiotherapy** (MV photons-electrons-protons)
  - EBT2, EBT3, EBT3+, EBT3P (1 cGy to >40 Gy)
  - EBT-XD 4x EBT3 Dose (***New*** 2015)
  - MD-V3 10x EBT Dose
  - HD-V2 100x EBT Dose
- **Radiology** (kV photons)
  - XR-RV3 - 5 cGy to 15 Gy
  - XRQA2 – 1 mGy to 20 cGy



GafChromic Protocol

Advantages of GafChromic Film

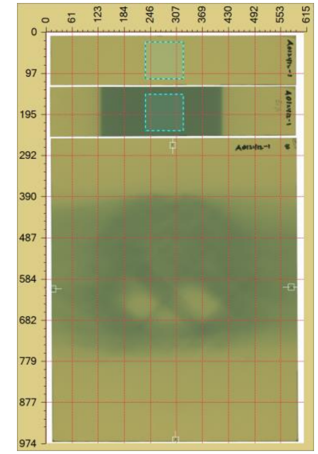
- High spatial resolution
- Wide dynamic dose range

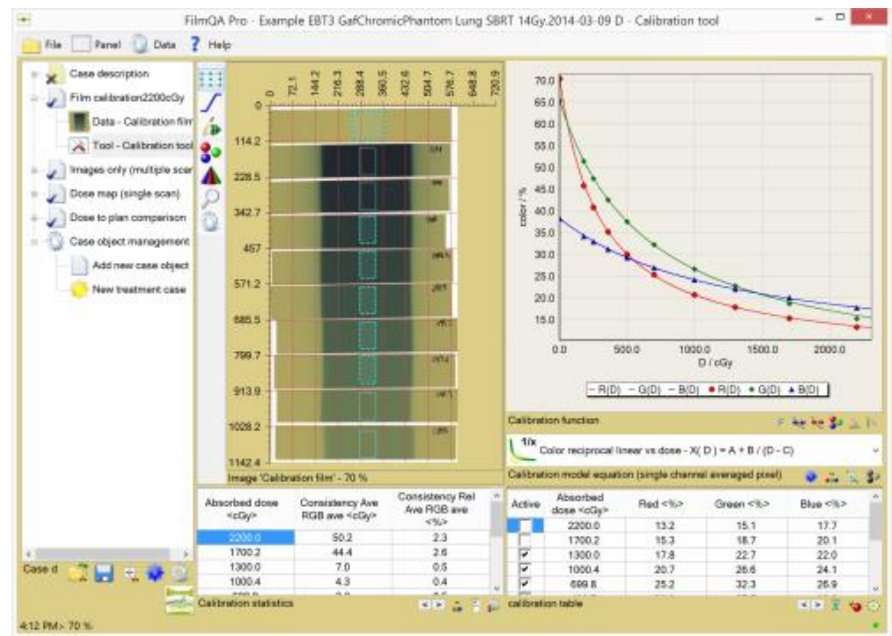
Achievements

- Accuracy of 0.5% dose error
- Efficient work flow
- Active error recognition

Protocol Elements

- GafChromic Film
- FilmQA Pro
- Multi-channel film dosimetry with rescaling
- Quick Phantom





GafChromic Protocol

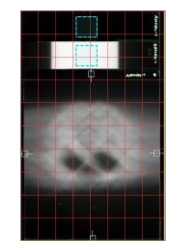
Exposure and Scanning Procedure

- Film handling using GafChromic Quick Phantom
- Avoidance of measurement disturbances

Primary Calibration

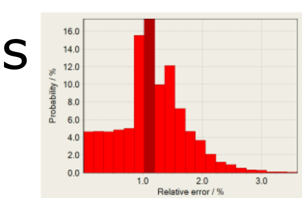
- Efficient way to generate calibration
- Adaptive calibration for specific measurements

Measurement Evaluation



- Multi-channel dosimetry with calibration optimization
- Dose error estimation and active measurement design

Dose Comparison



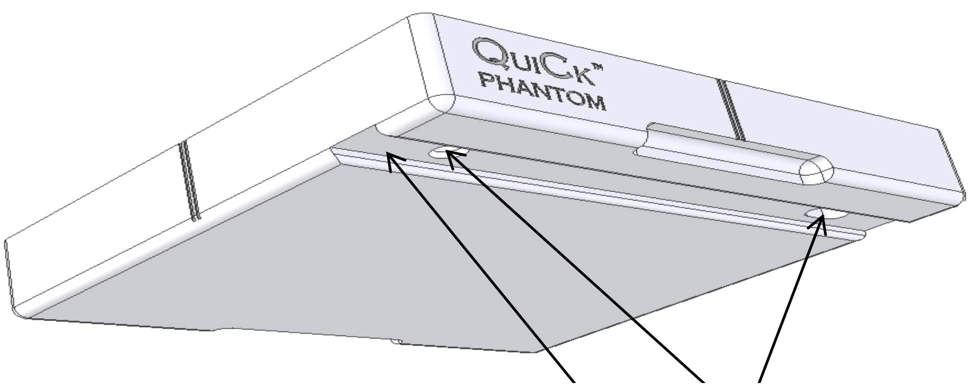
- Parameterized comparison with sensitivity analysis
- Feedback for measurement improvements

GafChromic Protocol

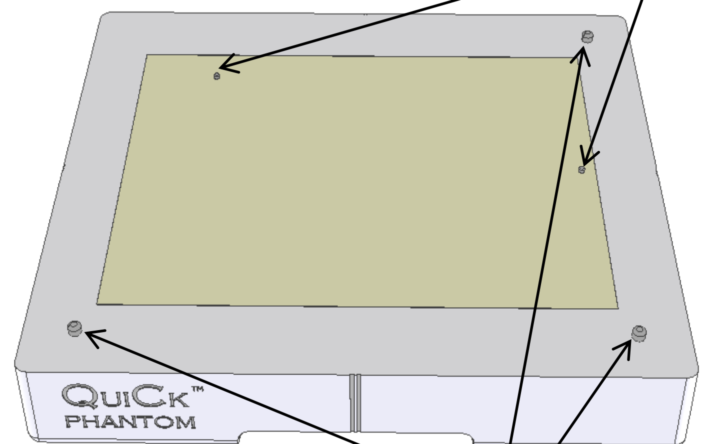
Exposure Procedure

GafChromic Quick Phantom

- Two Plastic Water® slabs
- Forced positioning on couch
- Automatic registration in FilmQA Pro
- Use with EBT3**P**



Groove and two holes to fit standard two Pin patient positioning index bar



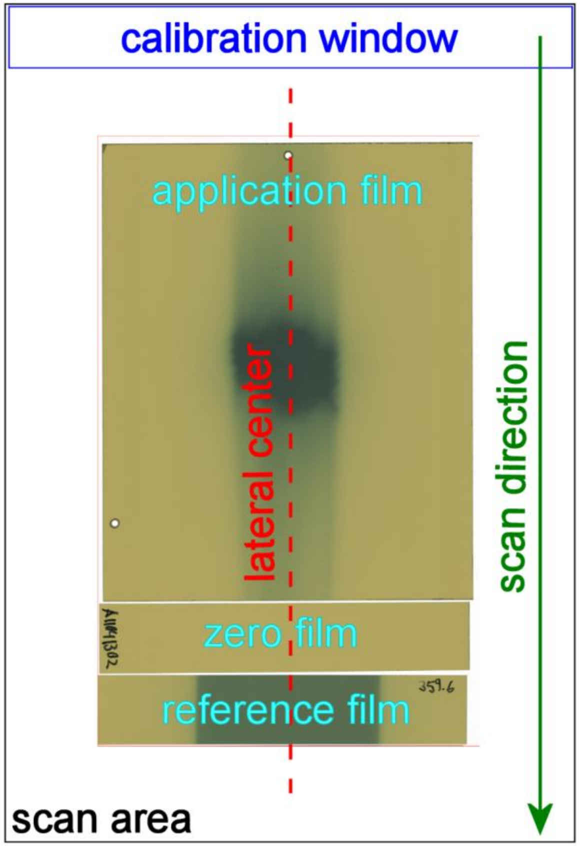
Asymmetric Film Registration Pins

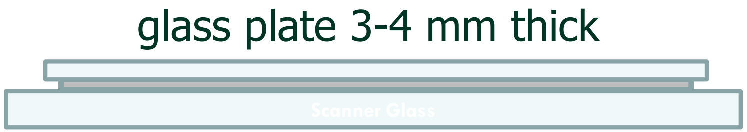
Top Plate Locking Dowel Pins

GafChromic Protocol

Scanning Procedure

- Film Positioning on Scanner
  - Highest dose at lateral center
  - Most of exposed areas at lateral center
- Flatten Film on Scanner
  - Use Glass Plate on top of all films
  - Cover scanner calibration window
  - No masks, No film overlap
  - Silica particles at EBT**3** surface suppress Newton rings
- No Color Correction, 72 dpi, 48 bpp
- Same orientation of all Films





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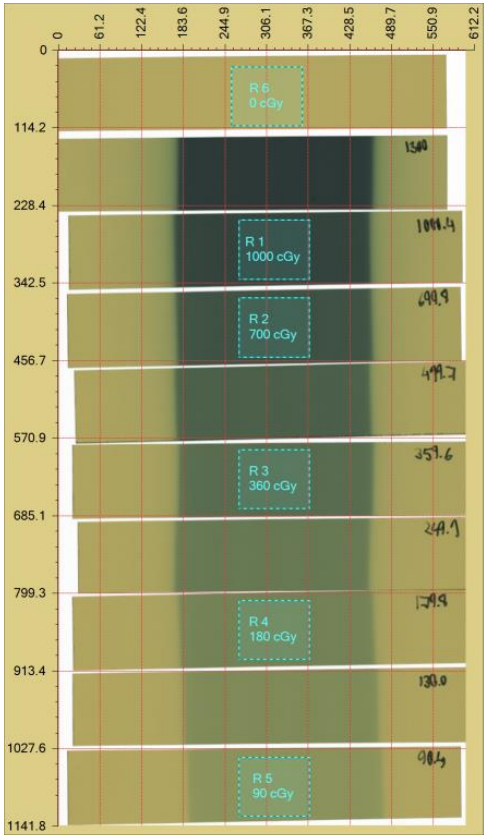
GafChromic Protocol
Primary Calibration

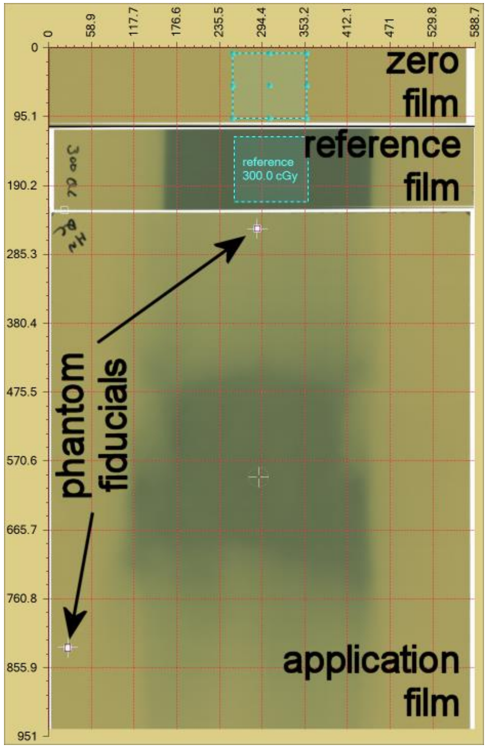
- Single calibration scan
  - 9 exposed strips with *geometric* dose sequence + unexposed strip
  - Single scan avoids scan to scan variations
- Optimize for specific measurement
  - Use only dose values relevant for measurement <(max dose + 10%)
  - Select 3-5 exposures + unexposed film
- Calibration criterion
  - Minimize dose error (best consistency)
  - Correlate only 'Shape' of functions



Active	Absorbed dose <cGy>	Red <%>	Green <%>	Blue <%>
☐	2200.0	13.2	15.1	17.7
☐	1700.2	15.3	18.7	20.1
☑	1300.0	17.8	22.7	22.0
☑	1000.4	20.7	26.6	24.1
☑	699.8	25.2	32.3	26.9
☑	499.7	30.0	37.5	29.2
☑	359.6	35.1	42.6	31.2
☐	249.9	40.7	47.5	32.9
☐	179.8	45.8	51.4	34.2
☑	0.0	70.4	65.3	38.3

GafChromic Protocol
Measurement Evaluation

- **Application Film**
  - Optimize calibration's dose range
- **Reference Film**
  - Reference dose at 'dose range of interest'
  - Recommended reference dose ~(max dose – 15%)
  - Multiple references possible to adjust best accuracy range
- **Zero Film**
  - Do Not use dedicated strip



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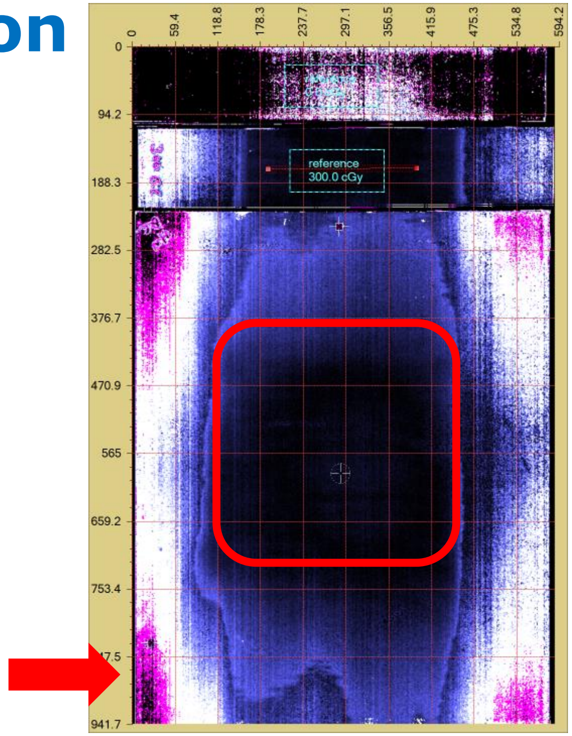
Measurement Evaluation

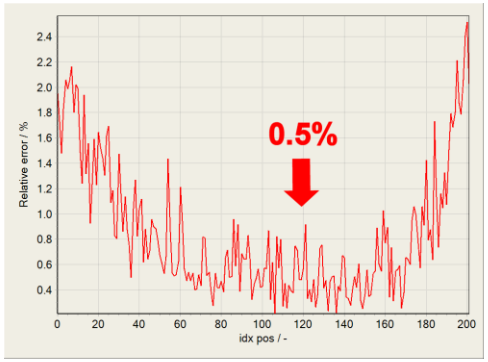


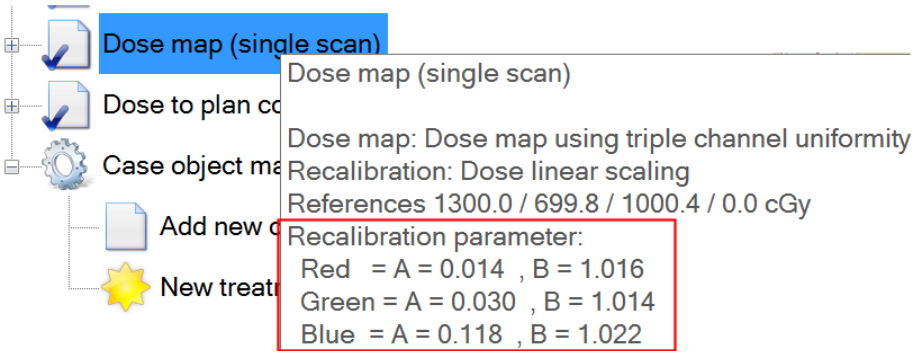
Verify Reference Film

- Reference patch has lowest dose error
- Rescaling correction <<5%
  otherwise reference inconsistent

Verify Dose Accuracy

- Screen 'dose area of interest'
  in consistency map (dose error)
- Watch for artefact pattern
  e.g. lifted film corners





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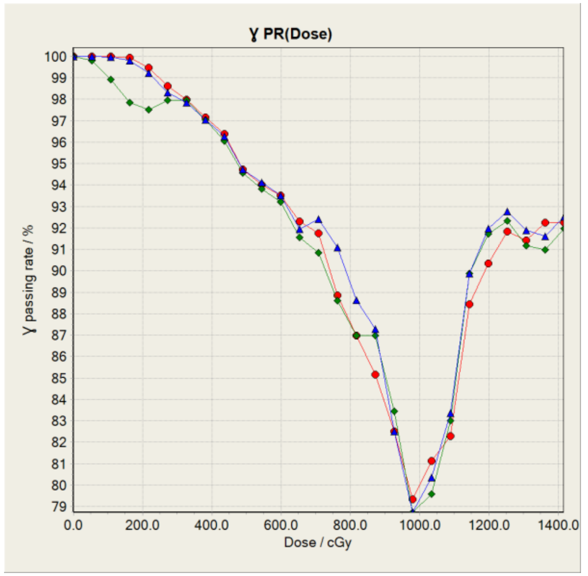
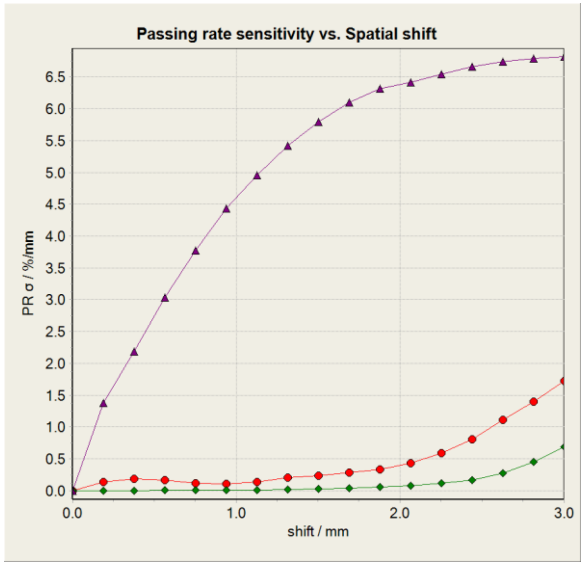
Dose Comparison



- **Advanced Comparison**
  - Chart Passing Rate vs parameters
  - RGB Passing Rates must be consistent
  - Chart Passing Rate vs Dose recognize calibration bias
  - Optimize calibration
- **Comparison Sensitivity**
  - Assure comparison is sensitive to targeted QA
    - e.g. spatial shift



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Multi-Channel Calibration

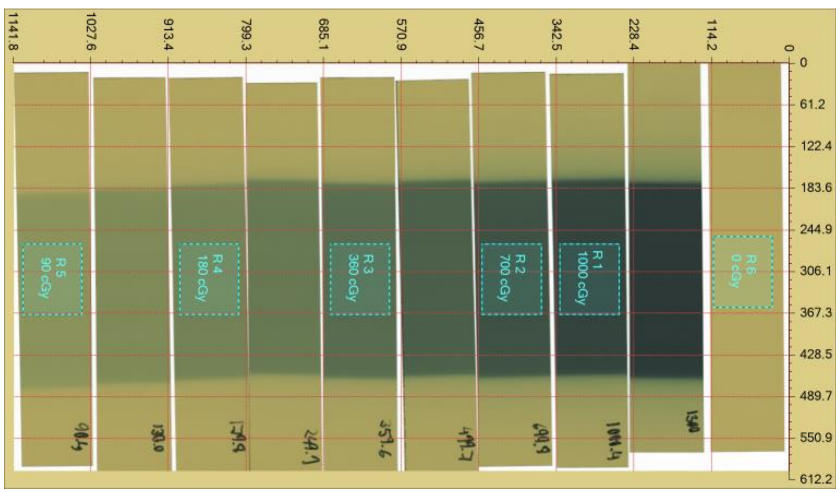
Correlates average response

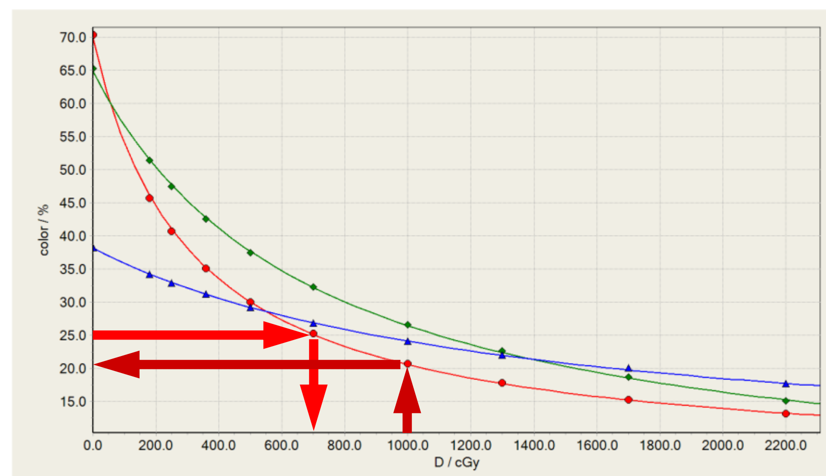
- System: **Radiation machine – Film - Scanner**
- Fixed protocol conditions: *dose range, ambient, scanner state*
- Mode of operation: *film orientation, scan glass plate*

Dose vs Color Channels X=RGB (optical density)

$$D = D_X(X_{ave}) \leftrightarrow X_{ave} = X(D)$$

$$D = D_X\left(d_{X,ave}\right) \leftrightarrow d_{X,ave} = d_{X,D}(D)\ \ (d_X = -ln_{10}(X))$$





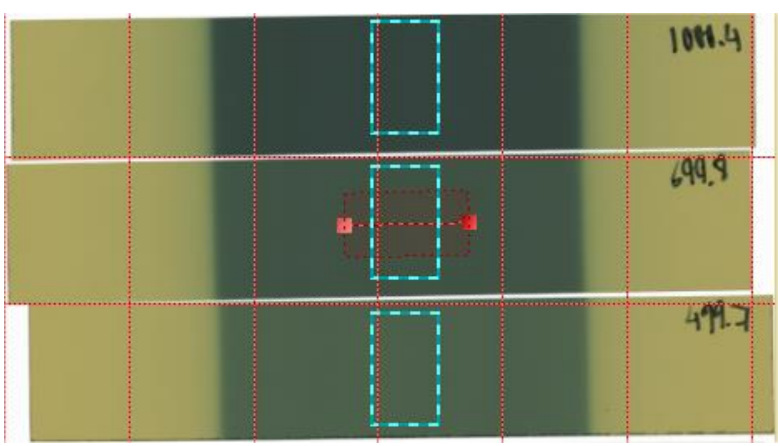
Multi-Channel Calibration

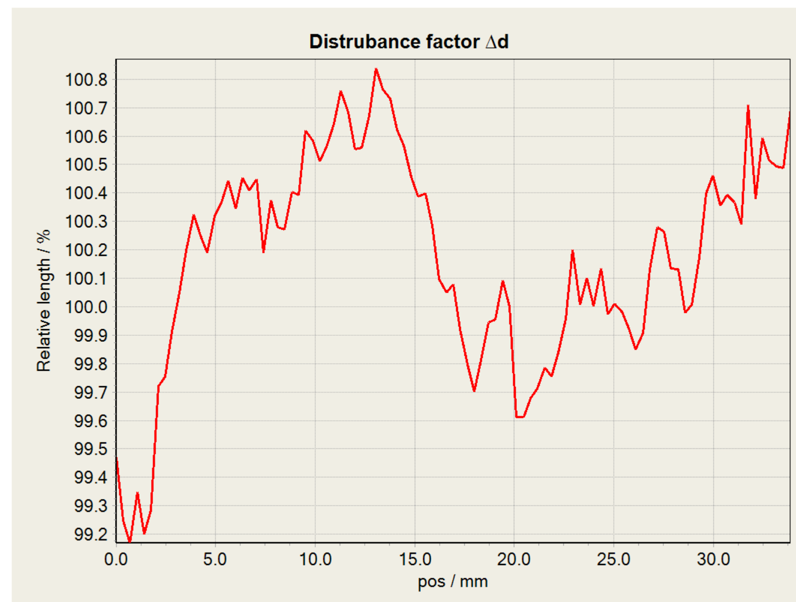
Disturbance Factor

$$\Delta d = \frac{d_{X,scan}(D)}{d_{X,ave}(D)} = \frac{\text{specific response}}{\text{average response}} \ @ \ \textit{same dose}$$

Example: Calibration Strip

- Calibration region all pixel have same (known) Dose
- Major contribution to Δd film non-uniformity
- Δd neutral with respect to X





Multi-Channel Dosimetry

Dose Calculation

$$d_{X,scan}(D_X) = d_{X,ave}(D_X)\Delta d$$

- Disturbance factor connects D_X dose calculations, X=RGB

Consistency κ

$$\kappa(\Delta d)^2 = \sum_{X \neq Y} (D_X - D_Y)^2$$

- Consistency is dose offset averaged at single location

Only 1 Dose at each location

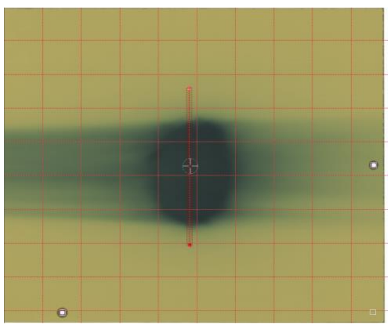
- Dose calculation must deliver same value, i.e.

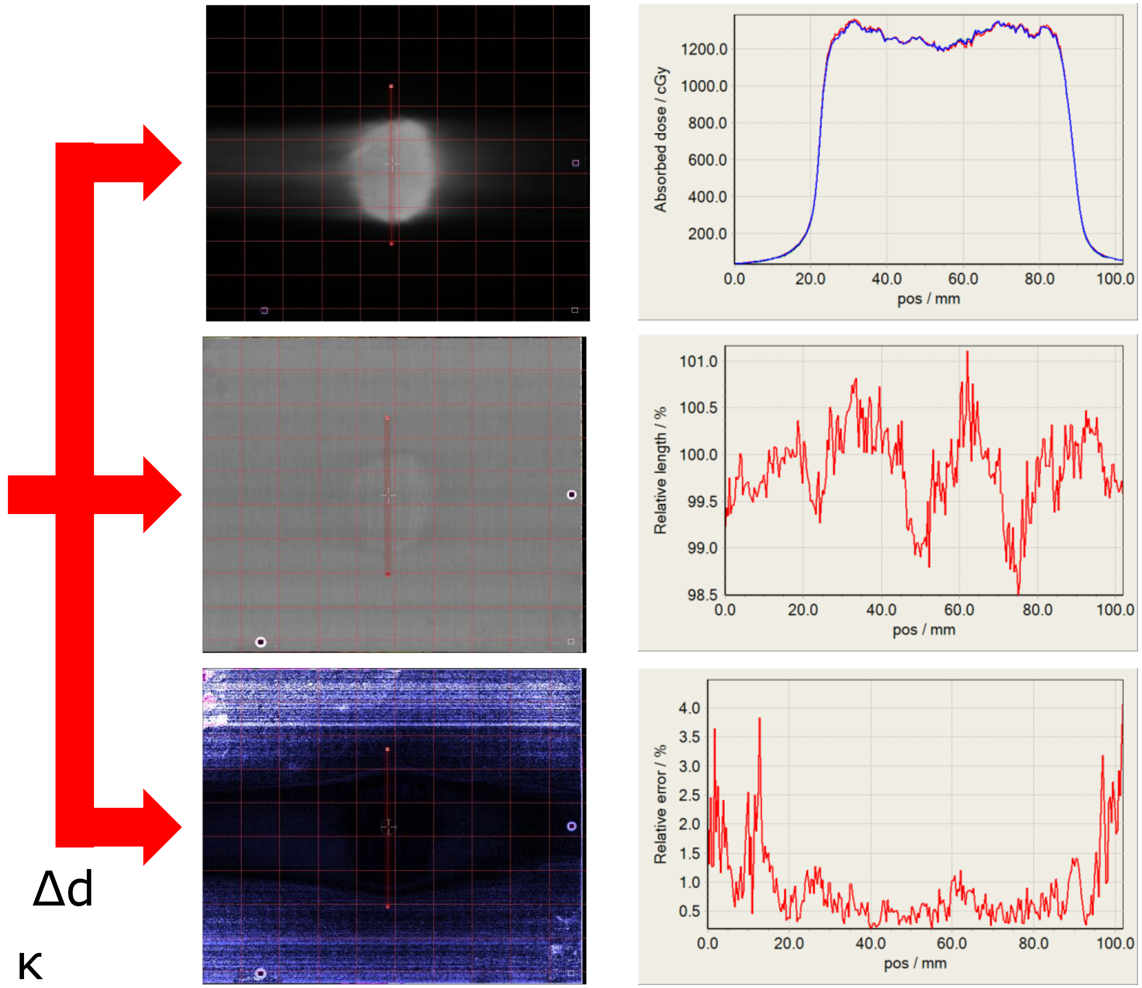
$$\kappa(\Delta d) \rightarrow \min_{\Delta d}$$

- Find Disturbance with best consistency, perfect **κ≡0**
- At all pixels: 4 equations, 4 variables D_X and Δd

Multi-Channel Dosimetry

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





Calculate Maps

- Dose - D_X
- Disturbance - Δd
- Consistency - κ

Multi-Channel Dosimetry Consistency

Film with Perfect Consistency

- Film's average dose response for X=RGB identical with Calibration

Imperfect Consistency

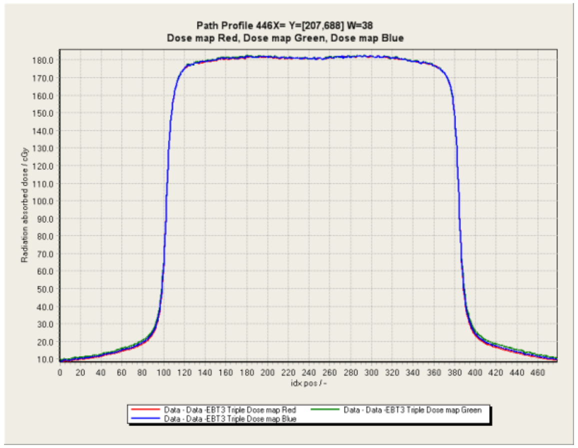
- Film's average dose response for X=RGB deviates from Calibration

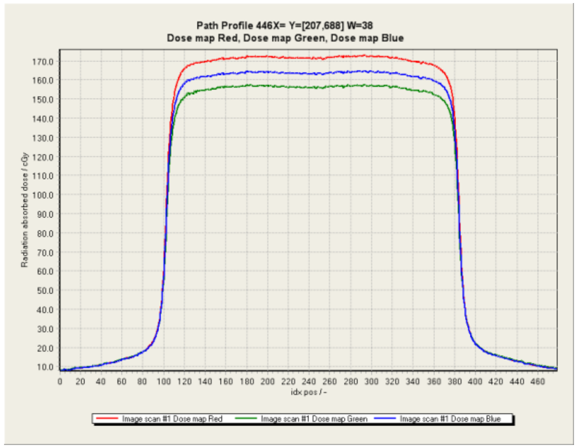
Assume Film has Same Response

- Imperfect Consistency is measure for Dose Error
- Offset between D_X estimates Dose Error

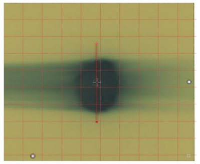
Example

- Profiles original calibration patch and 90° rotated scan

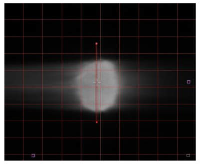




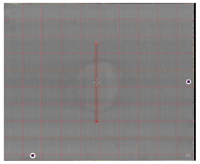
Multi-Channel Dosimetry
Consistency Map



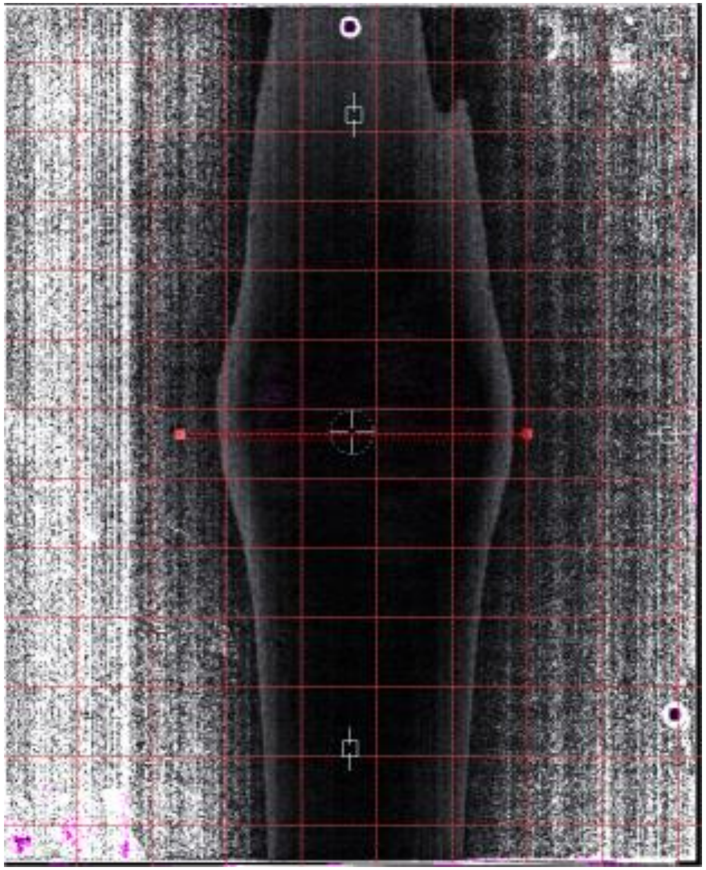
- Film scan
  measurement raw data



- Dose map – D_X
  measurement result



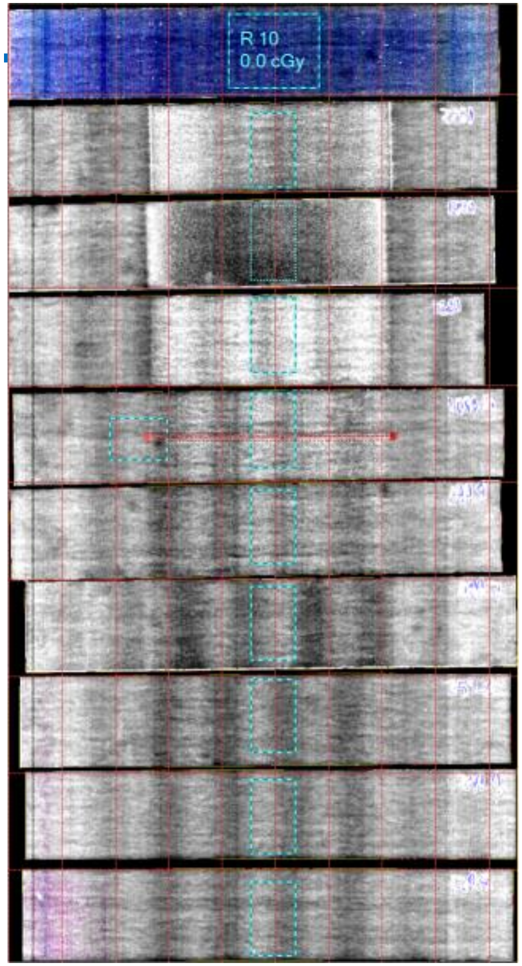
- Disturbance - Δd
  removed error
- Consistency – κ
  remaining error
  κ absolute error
  κ/D relative error



Example: Different sensors at different lateral position + lateral scanner effect cause (slightly) different average response.

Multi-Channel Dosimetry
Disturbance Map

- Disturbance Δd - **removed error**
- Presents **relative film thickness**
  when Δd dominated by film non-uniformity
  → Uniformity Map
  Film uniformity: spec ±1%, typical ±0.5%
- | Δd -1| >> 1%
  indication of other dominant disturbances
- Image pattern hints potential error sources
- Dose dependent disturbances mitigated
  e.g. lateral effect, curled film, calibration bias



Example: Calibration scan various dose levels (contrast advanced)

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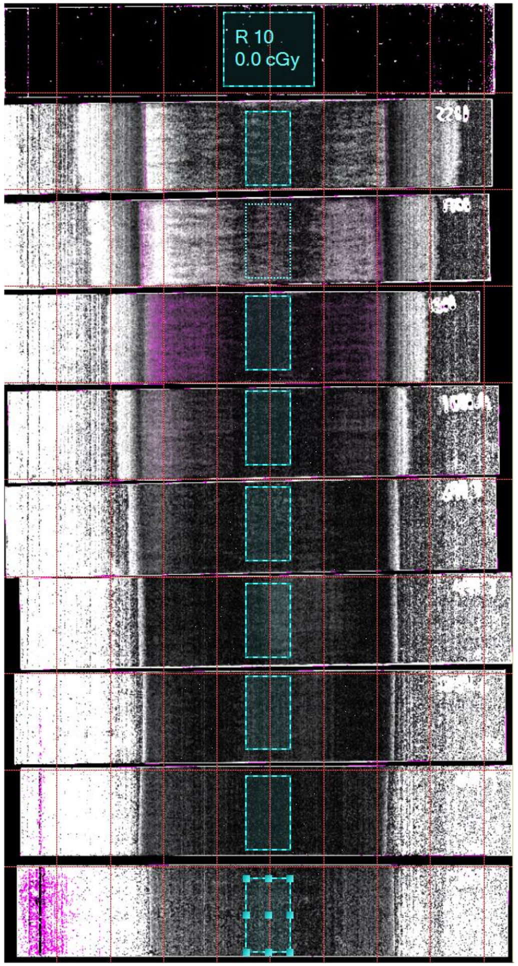
Multi-Channel Calibration

Optimize Calibration

- Lower consistency = better calibration
- Offset in calibration points is **not** a quality criterion
- Calibration strips must be consistent with calibration

Calibration goal

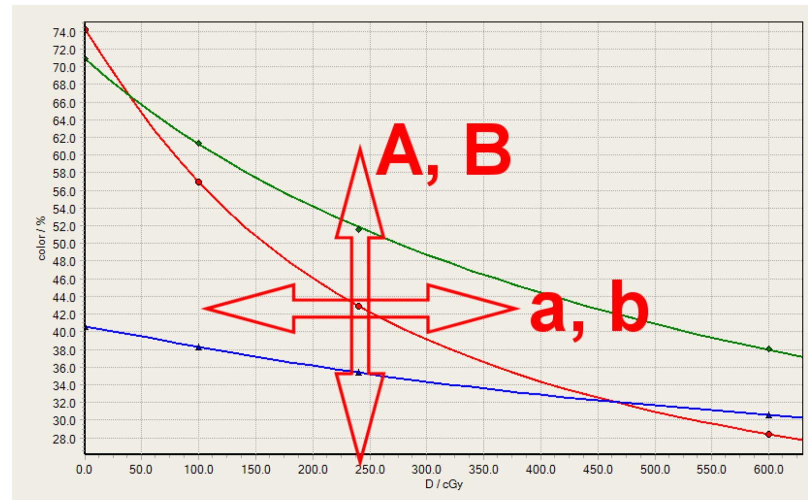
- Correlate calibration parameter for Perfect Consistency κ ≡ 0
- Calibration functions { R(D), G(D), B(D) } must match film dose spectrum

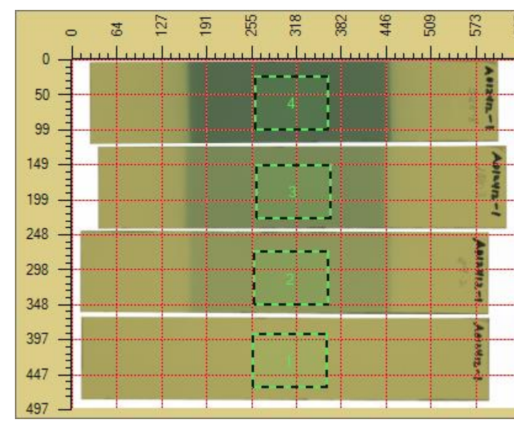


Optimize Consistency κ
shown relative consistency

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

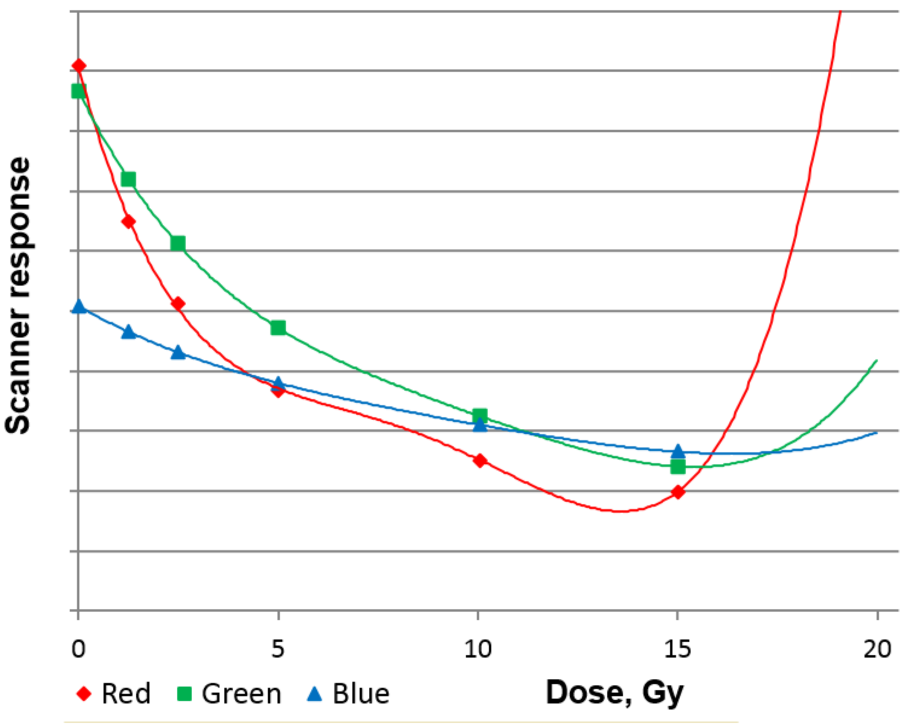




Polynomial Calibration

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

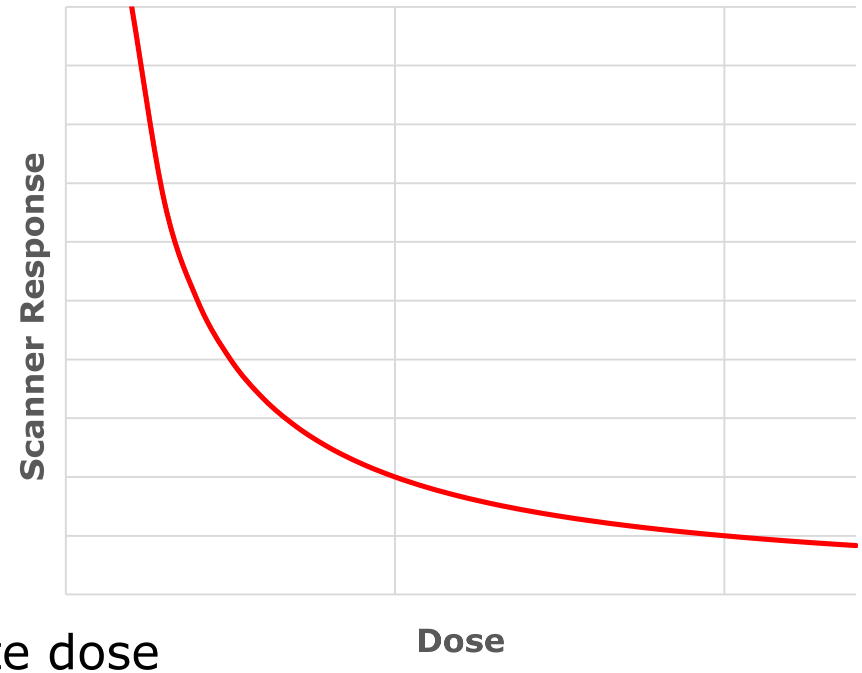


!Do Not Use!

- 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

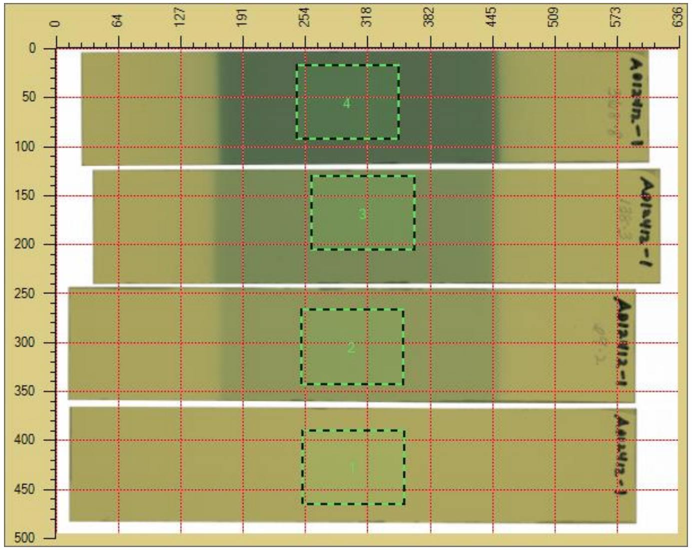
Model functions

- **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

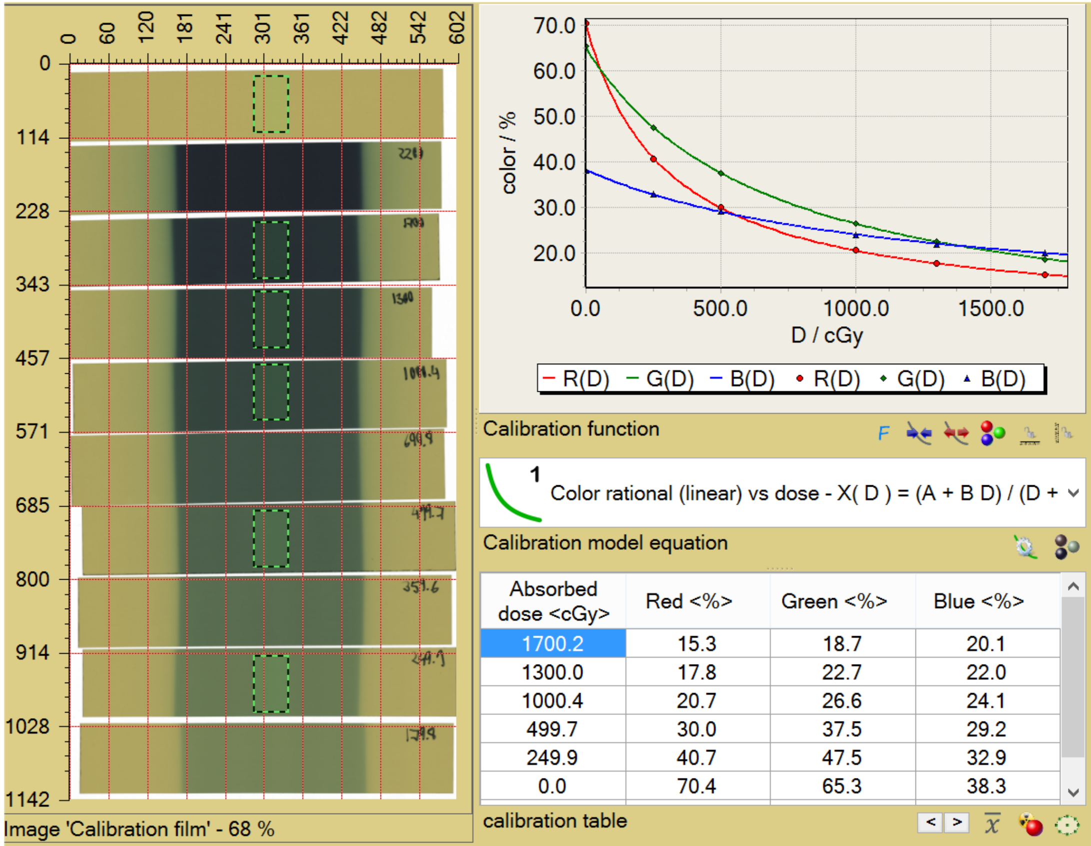
  $D_R(R_{calib}) = D_G(G_{calib}) = D_B(B_{calib}) = D_{calib}$

  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)

Multi-Channel Calibration



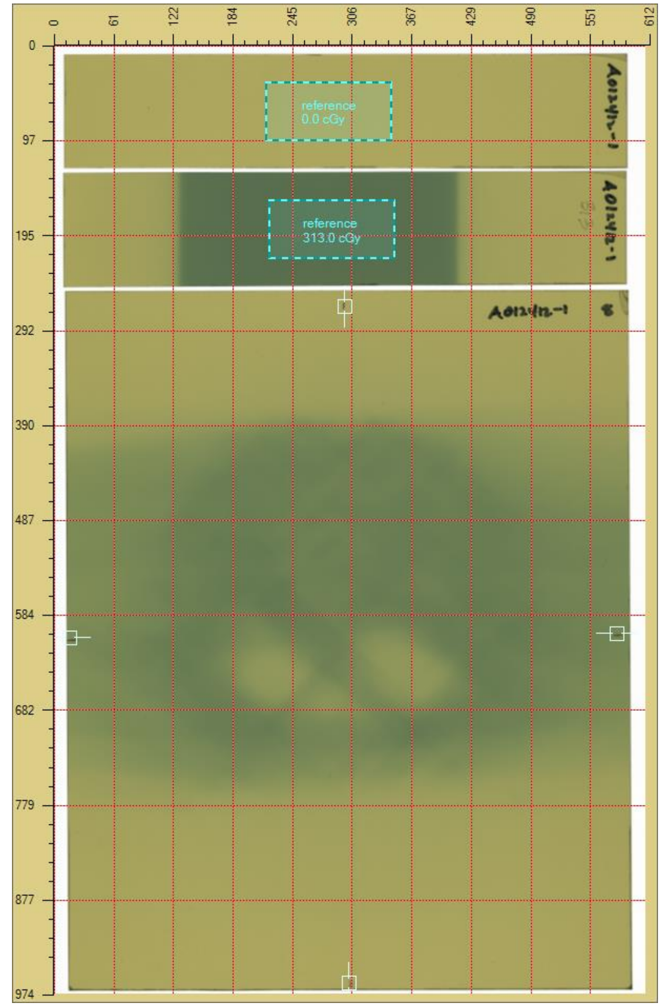
Absorbed dose <cGy>	Red <%>	Green <%>	Blue <%>
1700.2	15.3	18.7	20.1
1300.0	17.8	22.7	22.0
1000.4	20.7	26.6	24.1
499.7	30.0	37.5	29.2
249.9	40.7	47.5	32.9
0.0	70.4	65.3	38.3

- **Single Calibration Scan with 10 calibration strips**
  - **Use Geometric Sequence or Equal Color Steps**
- **Select only patches relevant for measurement**
  - **Optimize calibration to minimize dose error**

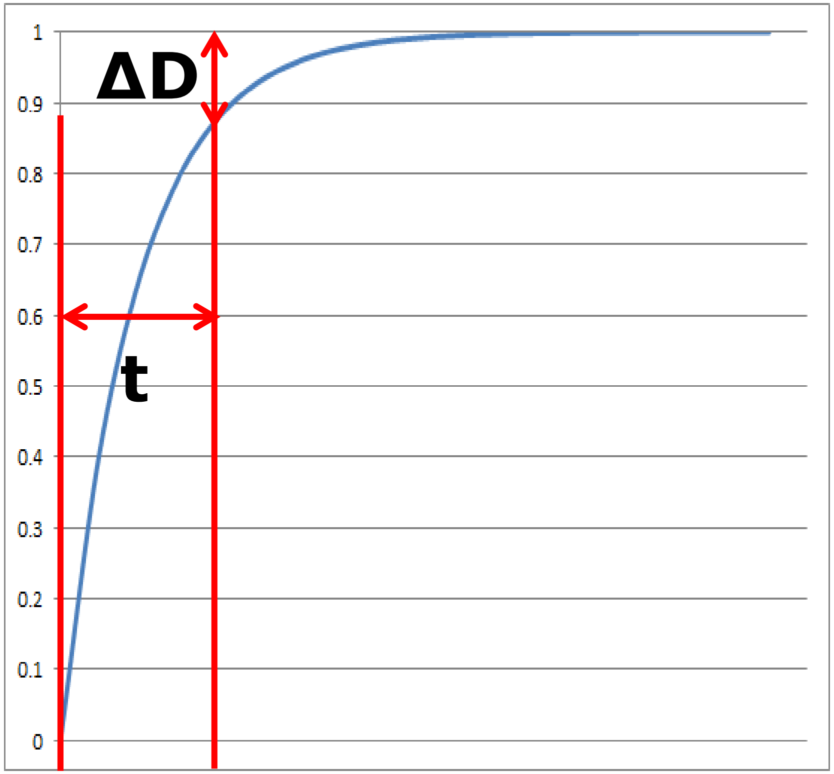
Multi-Channel Calibration

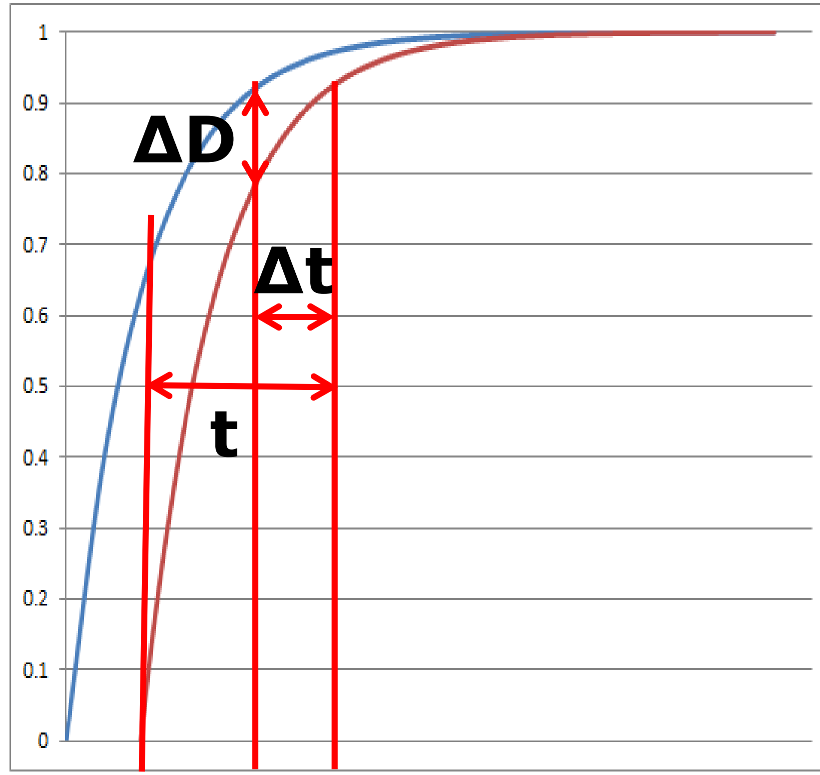
- **Two point recalibration**
  - 1 unexposed + 1 exposed film
    Minimum cost possible
  - *Dose* scaling (A=0, B=1)
    X(D) = x(a + b D) , X = RGB
  - *Color* scaling (a=0, b=1)
    X(D) = A + B x(D) , X = RGB
- **Assumption**
  - Calibration functions keep shape
    Shape(x) = Shape(X) , x, X=RGB
- **Single scan Evaluation**

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



Rescaling - Post Exposure Age



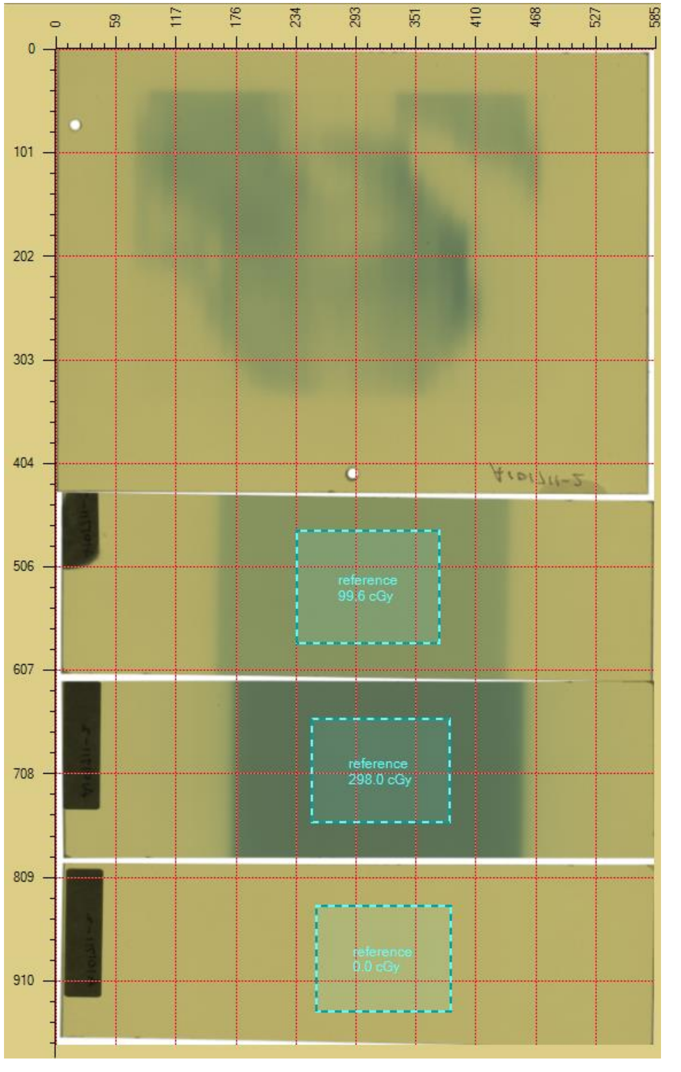


Absolute aging
wait t = 24 h
ΔD(t) < 0.5%

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

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



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

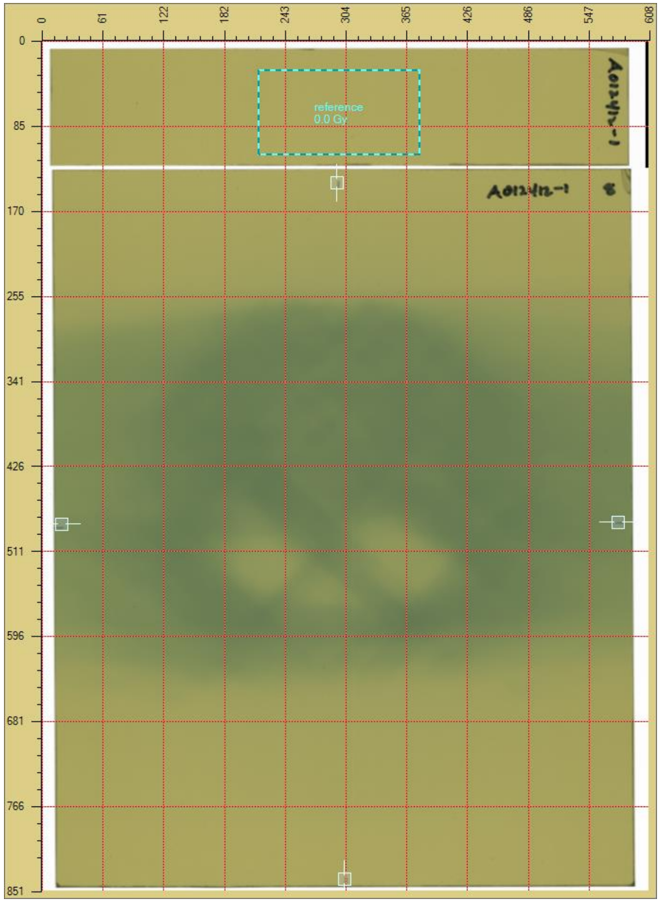
Assumption

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

Single scan Evaluation

compensates for

- Offset generating disturbances



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A. Micke, Europe, February 2015
www.FilmQAPro.com

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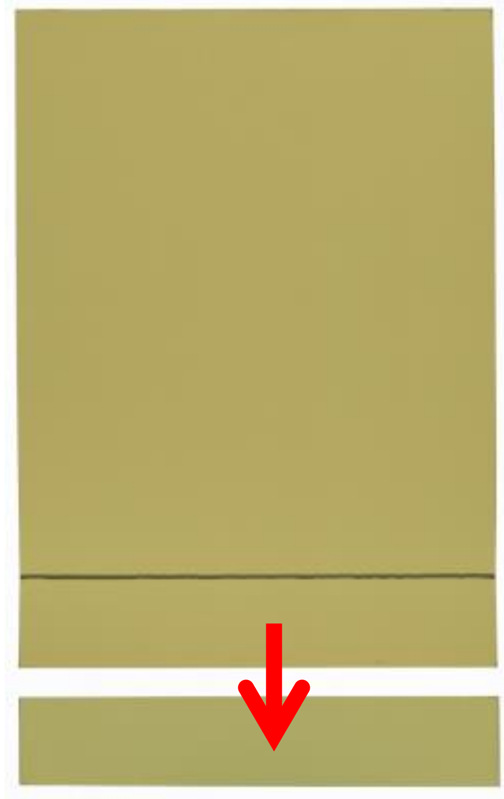
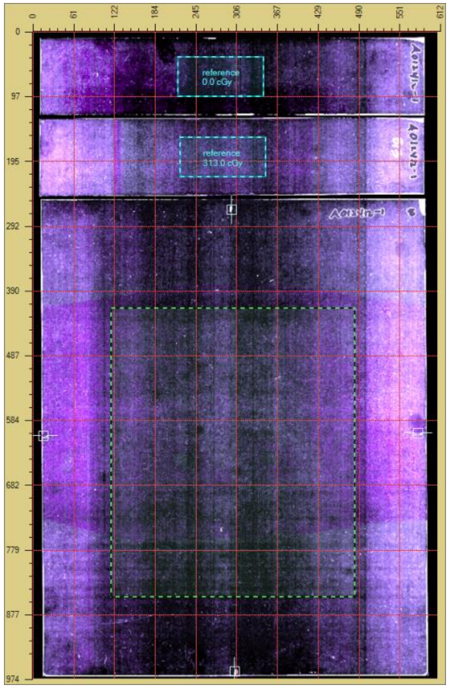
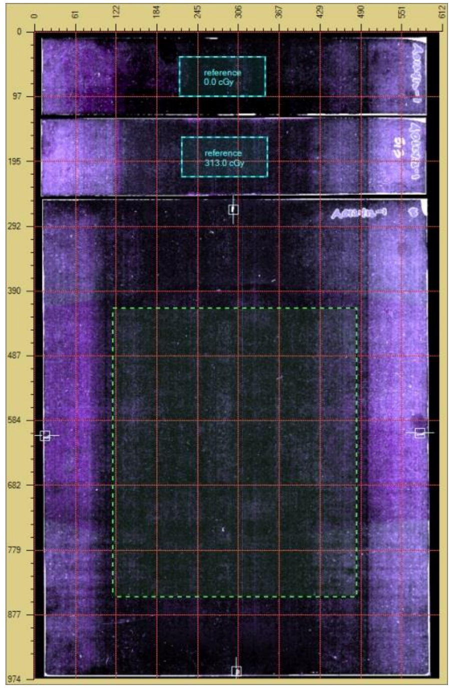
EBT3+ - Reference Recalibration

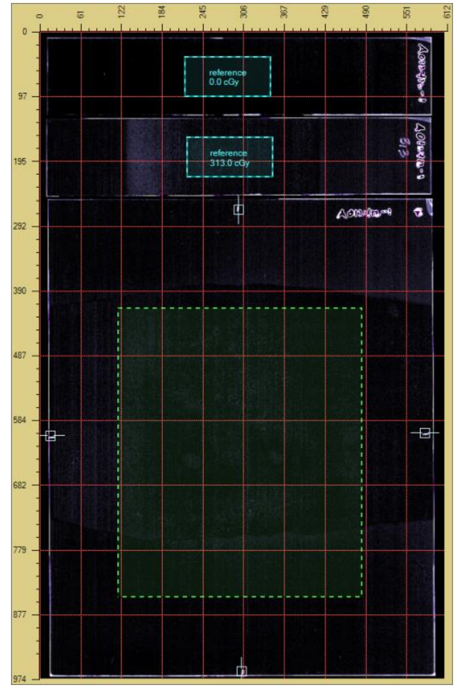
- Configuration same as EBT3
- Attached reference strip
  - Strip *properties as close as possible* to patient film
- Perforated Sheet
  easy to detach reference strip
  - Saves film cutting
  - Standardized strip size
- EBT3**+** available since 2012

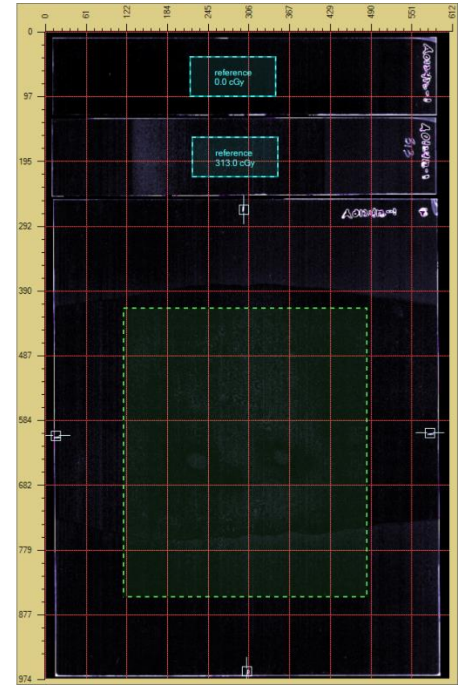


Consistency Comparison





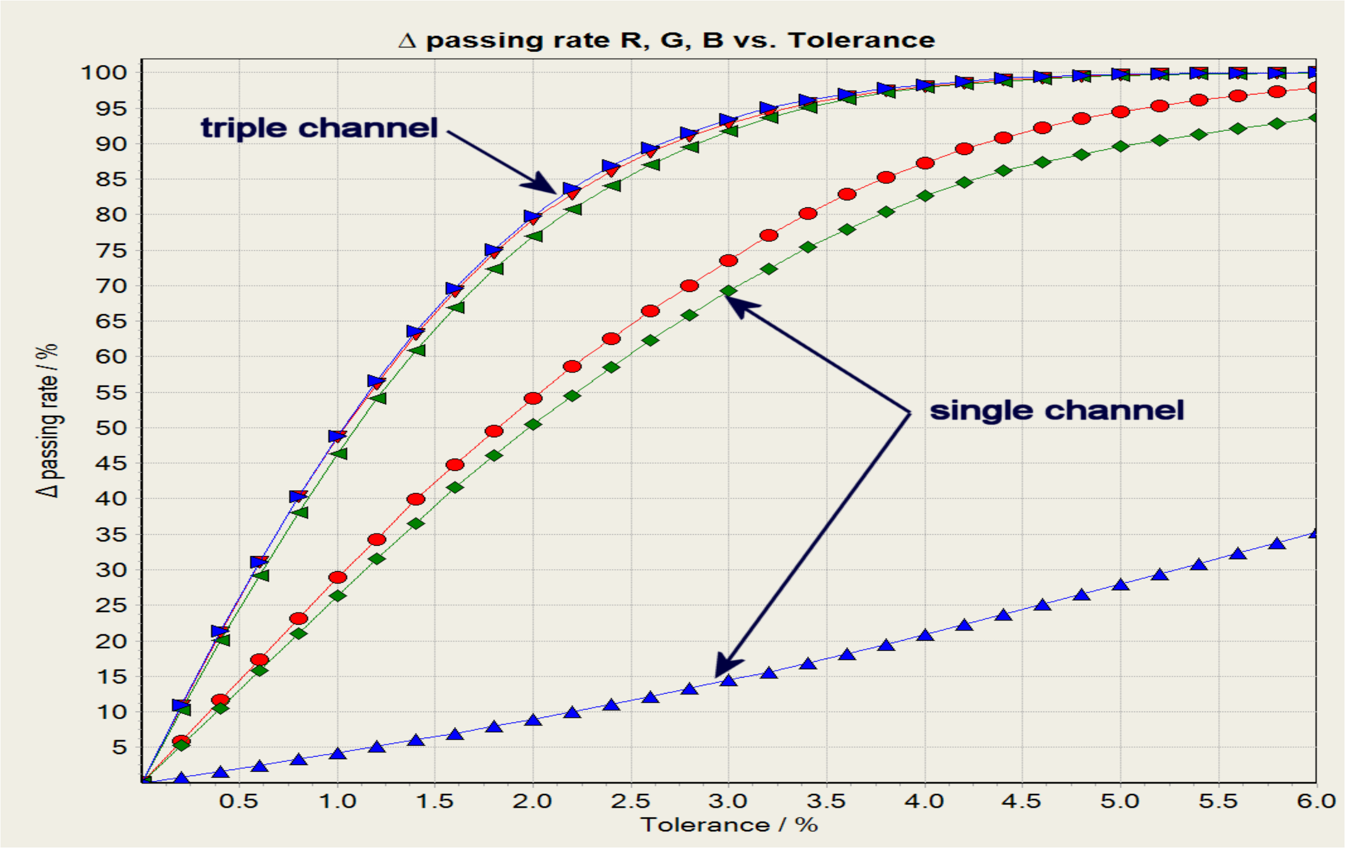




Single Channel	Single Channel Recalibrated	Multi Channel	Multi Channel Recalibrated
10.2 cGy	3.6 cGy	1.3 cGy	1.2 cGy
4.2%	1.5%	0.53%	0.49%

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

Single vs Multi-Channel Comparison

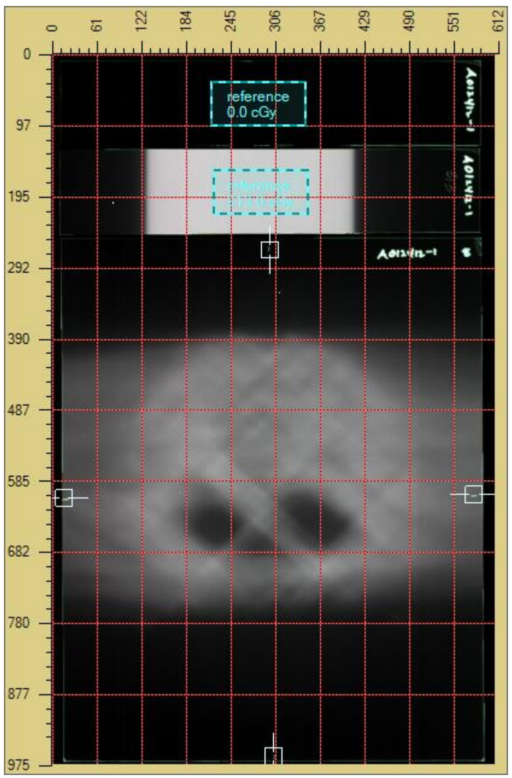


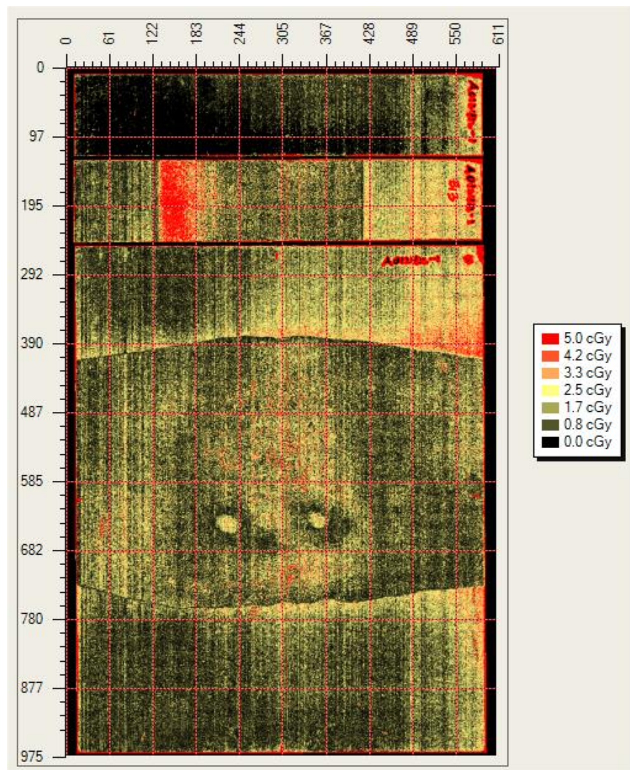
Differential pixel-wise direct comparison

- Multi channel: 90% passing rate at **2.7%** tolerance for All channels
- Single channel: 90% passing rate at **4.3%/5.1%/18.4%** RGB
- Multi channel method is consistent, single channel is Not

Multi-Channel Dosimetry
Dose Map Consistency

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

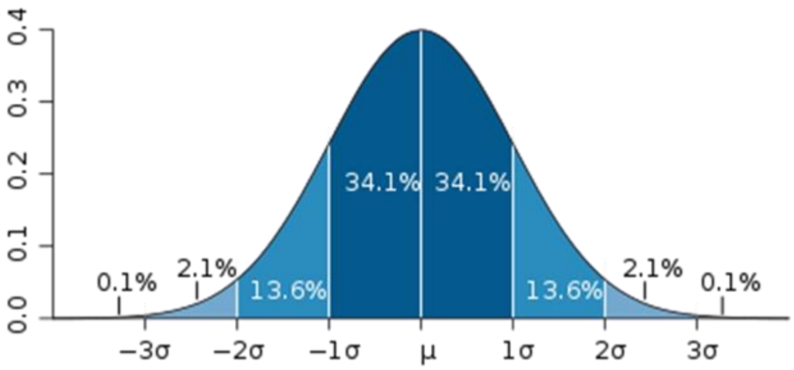




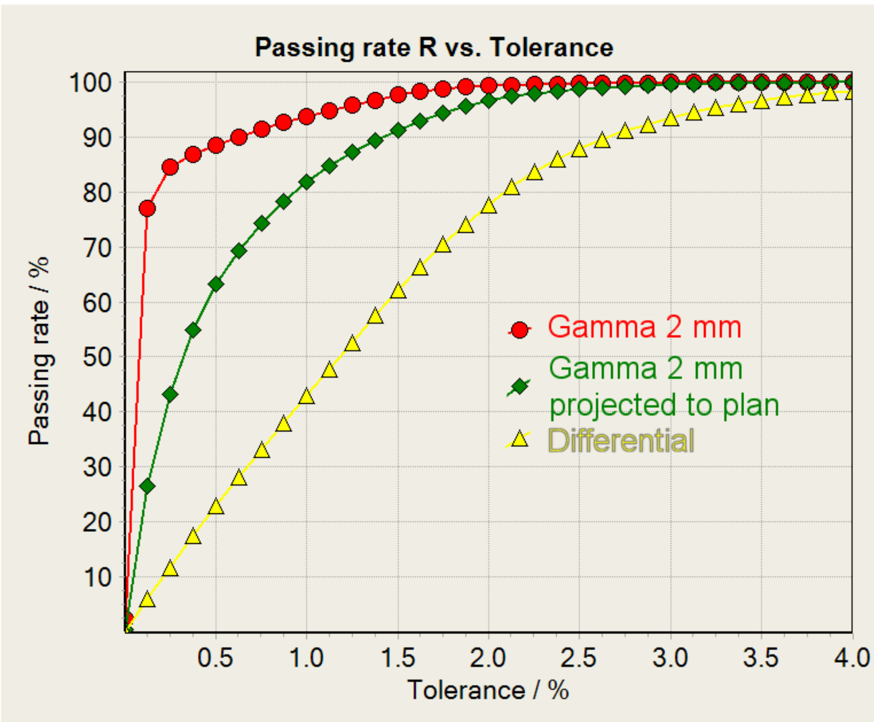
Example dose consistency map (iso-map) peak error ~2%

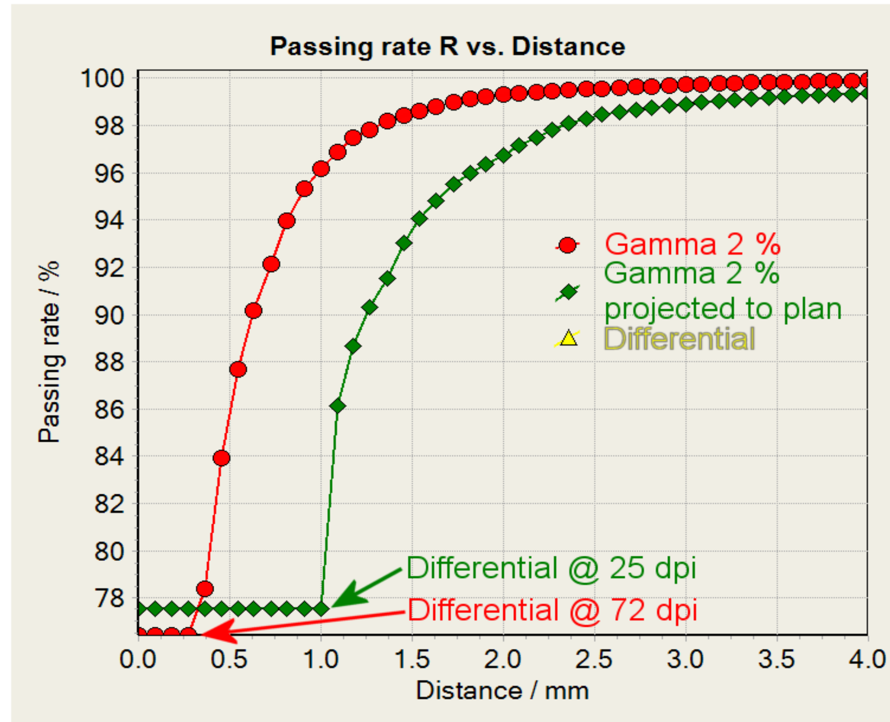
Multi-Channel Film Dosimetry Dose to Plan Comparison

- 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



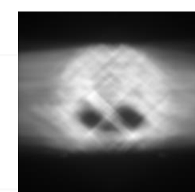
Gamma Map Comparison
Passing Rate Dependencies





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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A. Micke, Europe, February 2015
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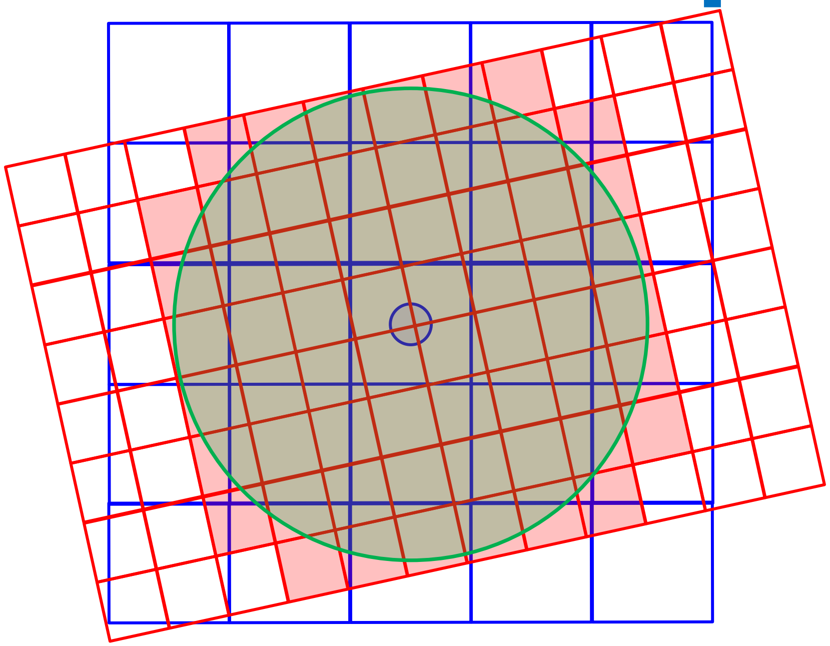
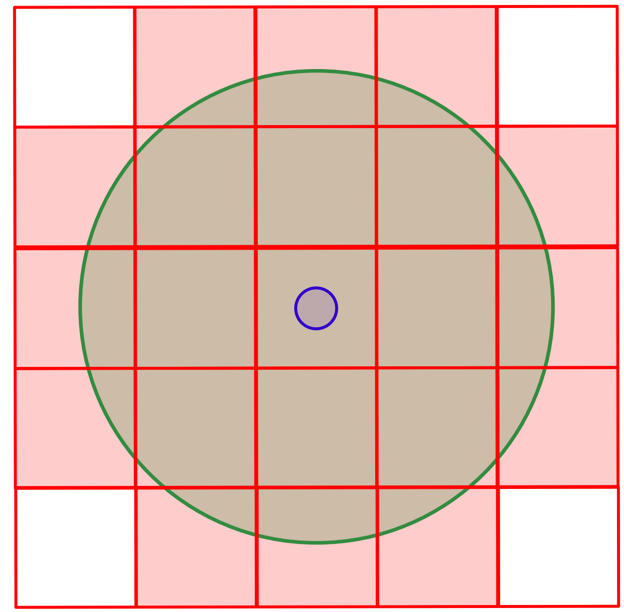
Gamma Map Comparison
Dose Map Projection





Dose Map Pixel

Dose Map Pixel Tested

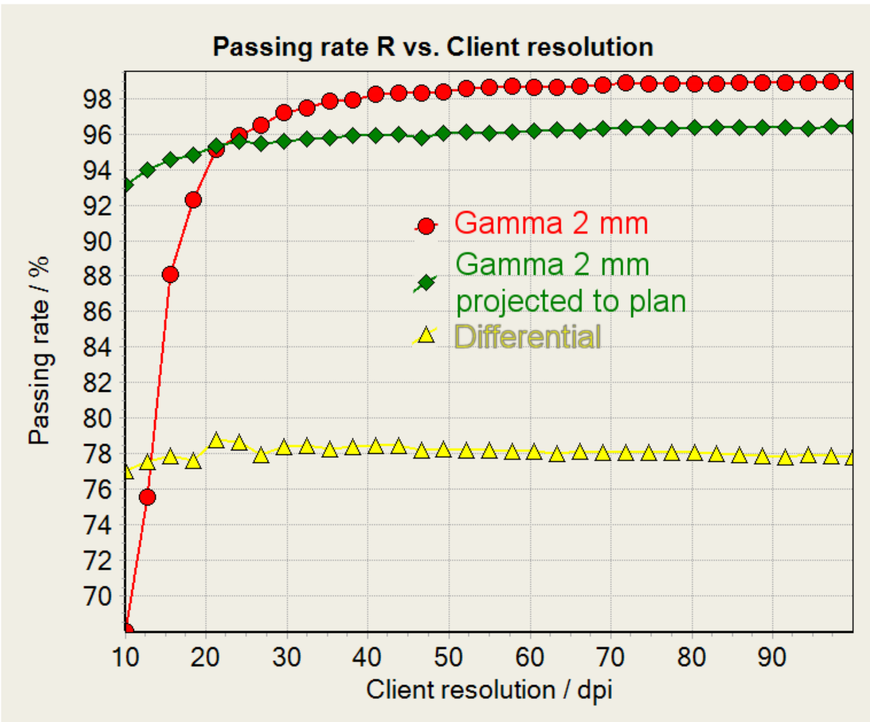
Plan Pixel Position

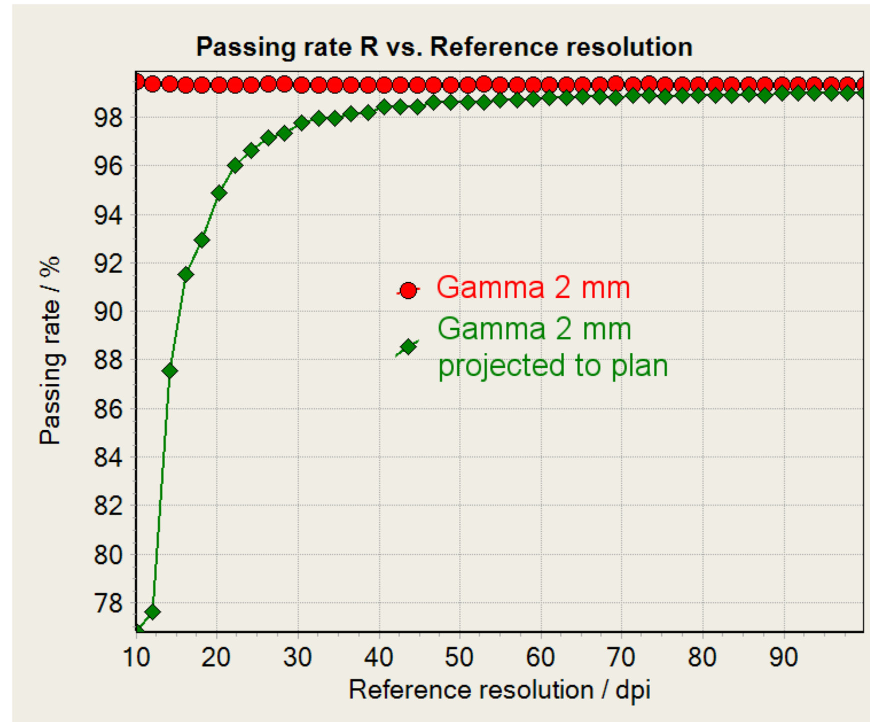
Search Circle

Treatment Plan Pixel

Gamma no projection   Gamma projected

Gamma Map Comparison
Passing Rate Dependencies



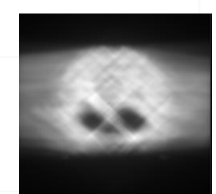


Passing Rate vs. Dose Map Resolution

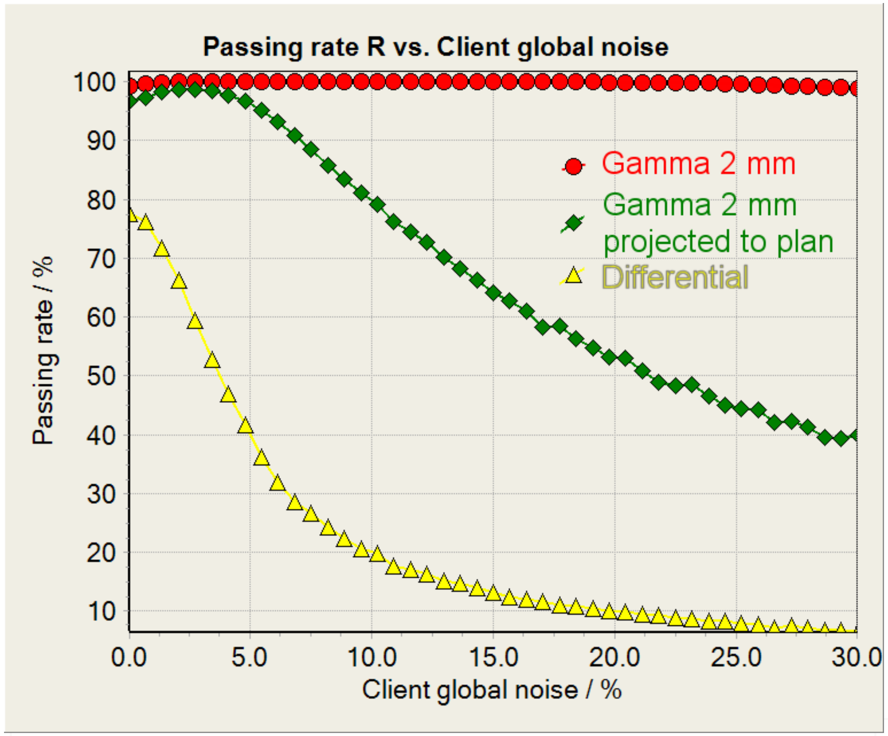
Passing Rate vs. Plan Resolution

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

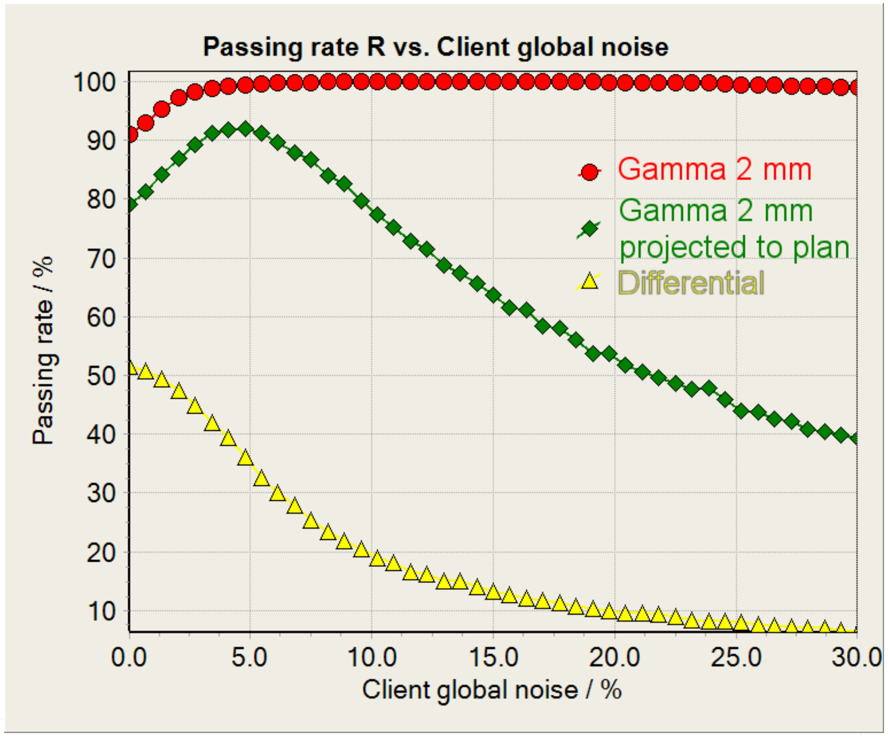
Passing rate R **99.3 %**



Gamma Map Comparison
Passing Rate Dependencies

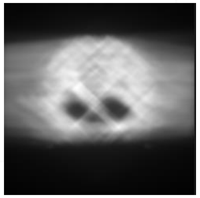


Passing Rate @ best location vs. Noise



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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A. Micke, Europe, February 2015
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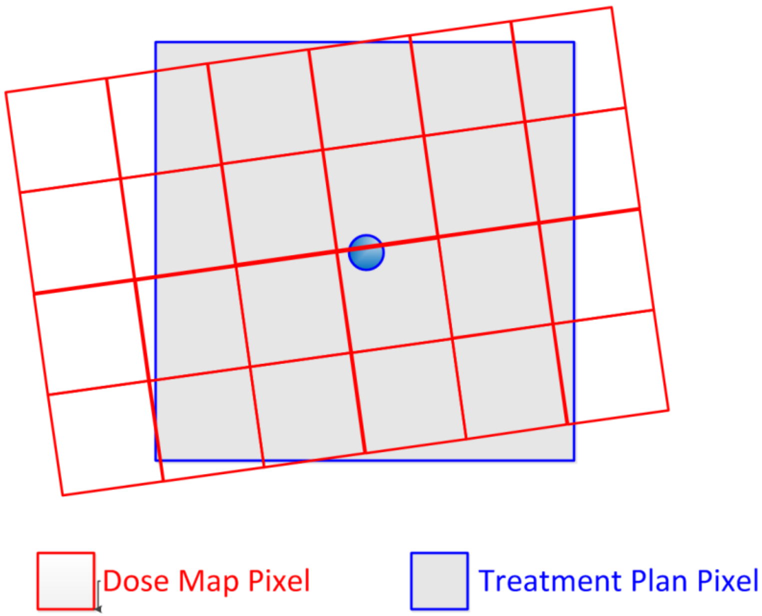
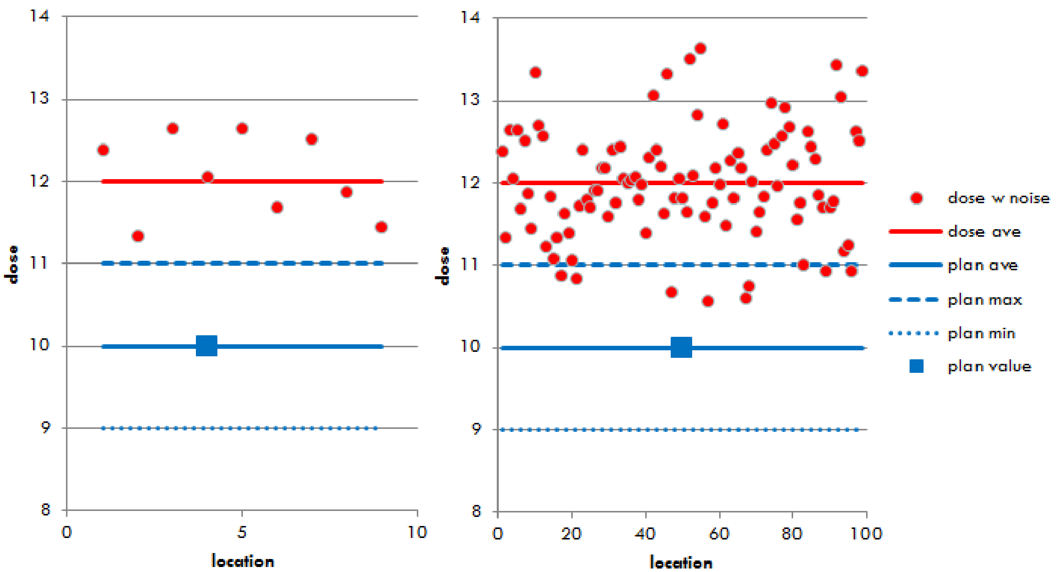
Gamma Map Comparison





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

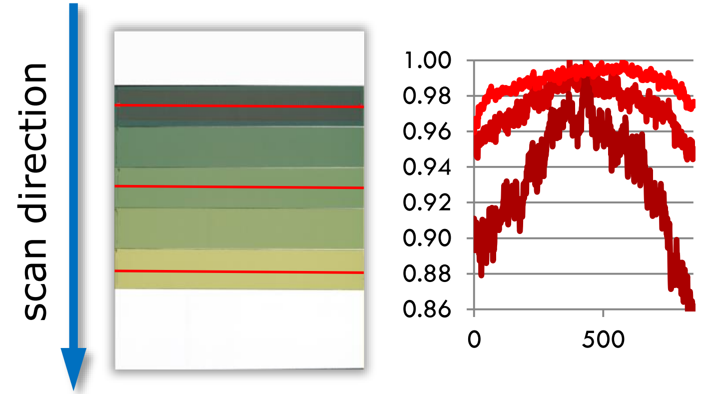
Filtering cannot fix this problem!

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

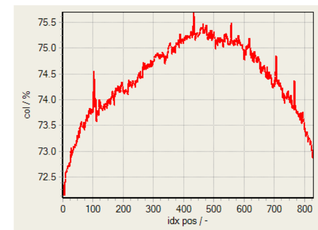
! DO NOT USE !

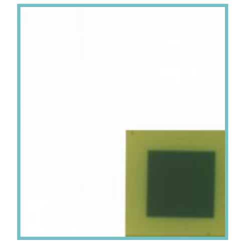


Calibration patch consistency comparison				
dose <cGy>	Consistency <cGy>		Consistency <%>	
	None	Blank scan	None	Blank scan
202.0	**8.8**	**11.1**	**4.3**	**5.5**
151.5	**6.8**	**8.9**	**4.5**	**5.9**
101.0	**5.9**	**8.4**	**5.9**	**8.3**
50.5	**5.9**	**7.9**	**11.6**	**15.6**
0.0	**4.8**	**0.4**	Infinity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

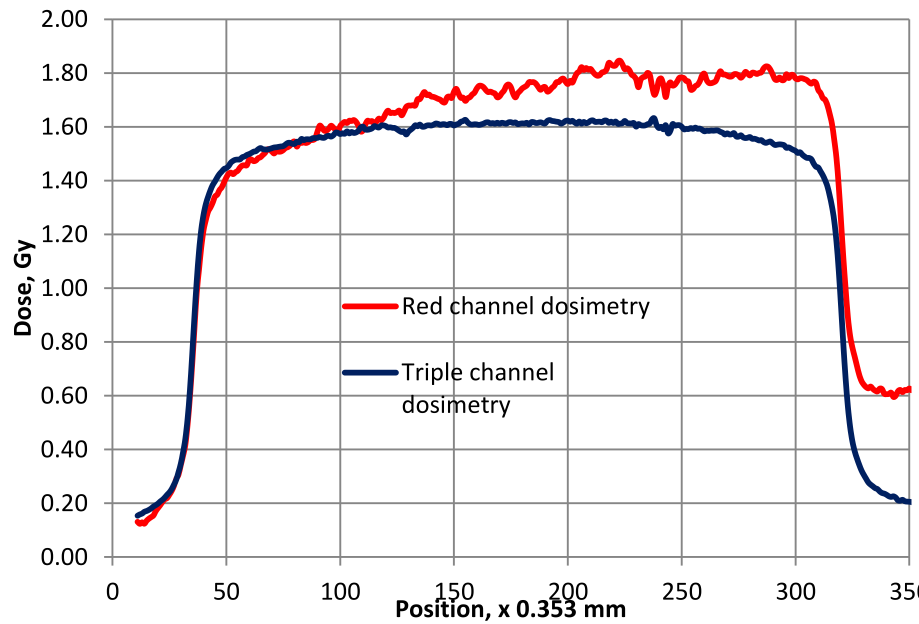
Triple Channel Dosimetry Lateral Scanner Non-Linearity

Scanner signal changes with lateral position (sensor direction)



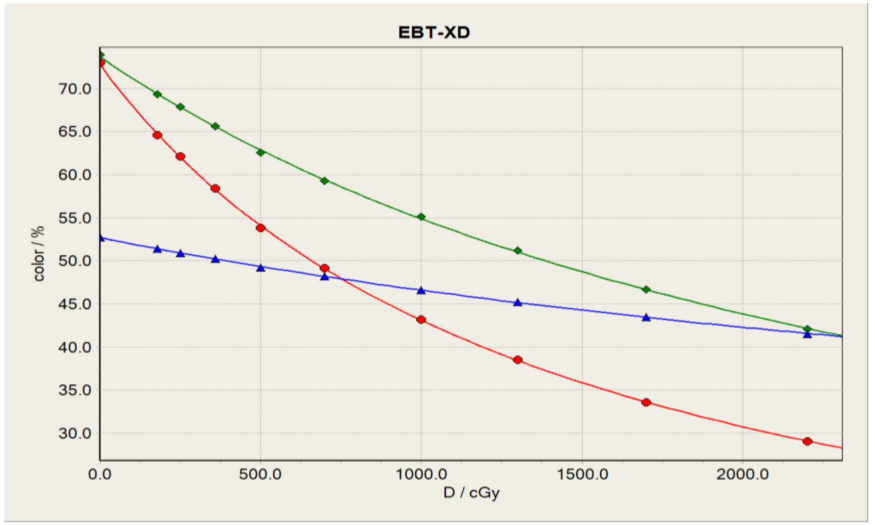


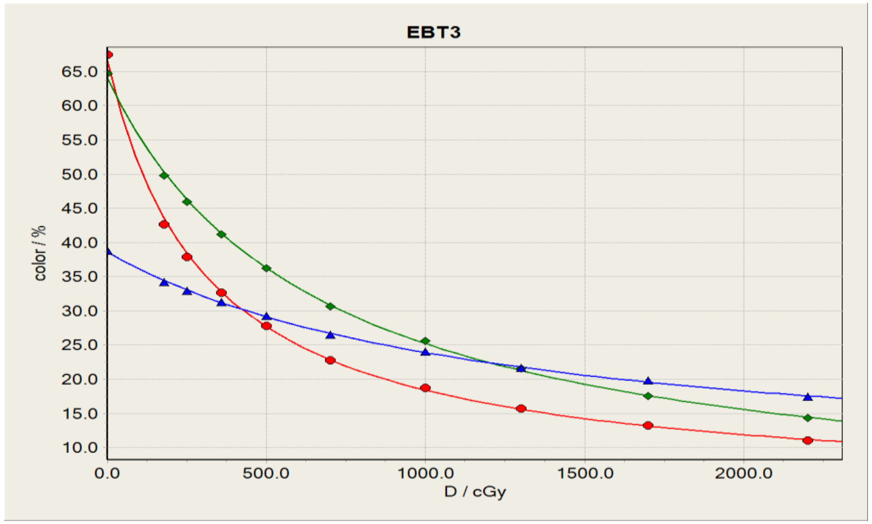
- EBT film polarization causes lateral effect
- Non-dose-dependent part of lateral effect is compensated
- Mitigation only (partial compensation)

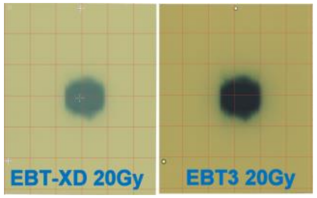


EBT-XD - Dose Range

- EBT-XD optical similar to EBT3 at 4x dose
  - Use at D_{max} > 20 Gy
  - Wide fields
    use at D_{max} > 5 Gy
  - High dose range better
    Low dose range worse
- Format same as EBT3
- EBT-XD available since 2015/1

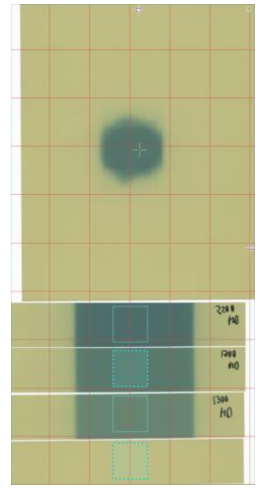


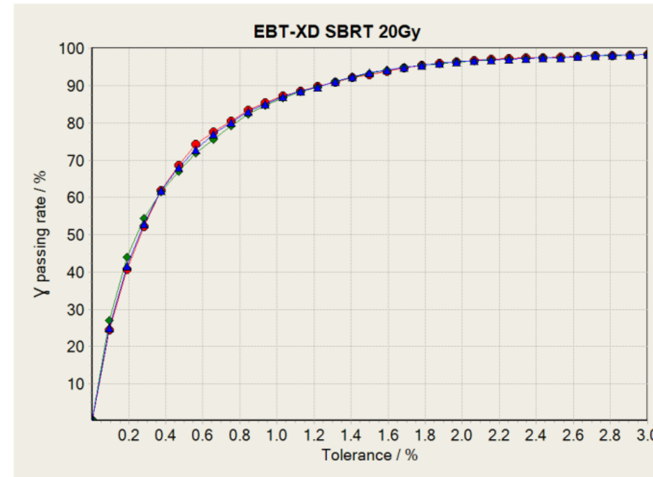


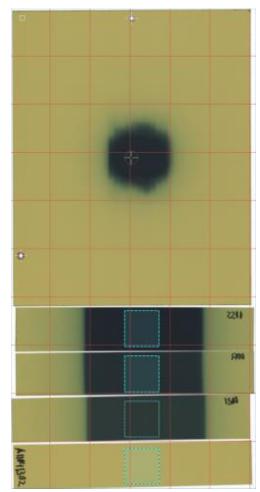


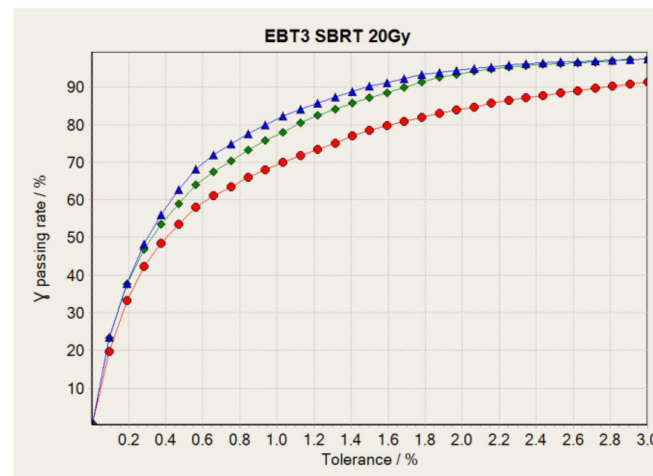
Multi-Channel - Dose Range
Example

- SBRT 20Gy case
  - Gamma 2 mm
  - Tolerance to reach 90% passing rate
- EBT-XD
  - Standard protocol RGB 1.2/1.2/1.2%
- EBT3
  - Standard protocol RGB 2.8/1.7/1.5%
  - With 2nd Reference RGB 1.5/1.6/1.6%









Passing Rate vs Gamma Tolerance

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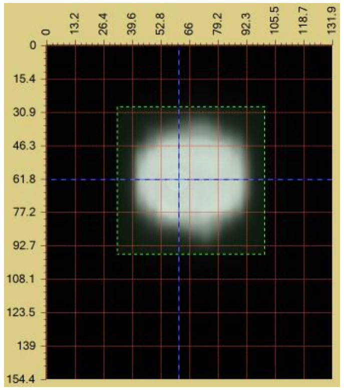
Comparison Sensitivity

$$\text{Sensitivity} = \frac{\text{Change of Passing Rate}}{\text{Change of Disturbance}}$$

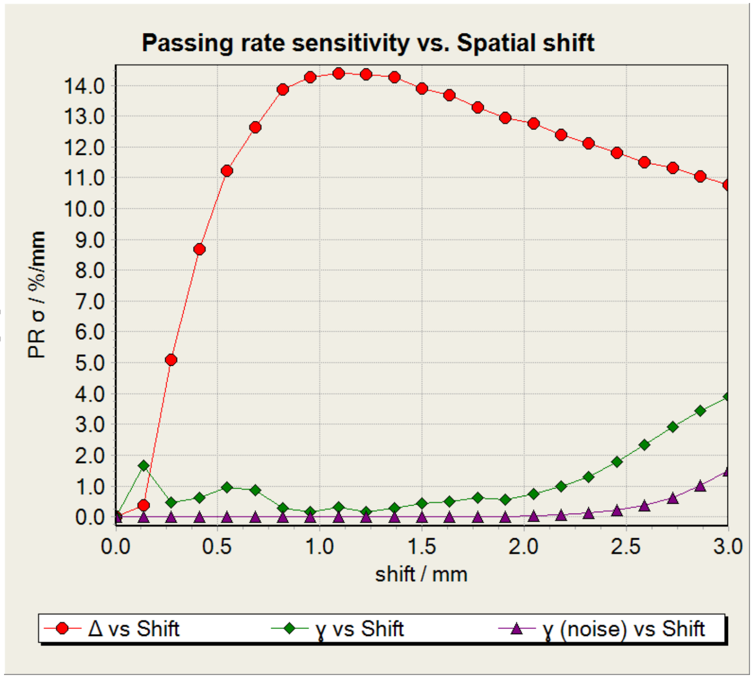


Ability of Comparison Map to QA specific Dose Disturbance

- Disturbance types
  - Spatial shift
  - Spatial rotation
  - Dose scaling
  - TPS calculated plan offset
- Random or Systematic

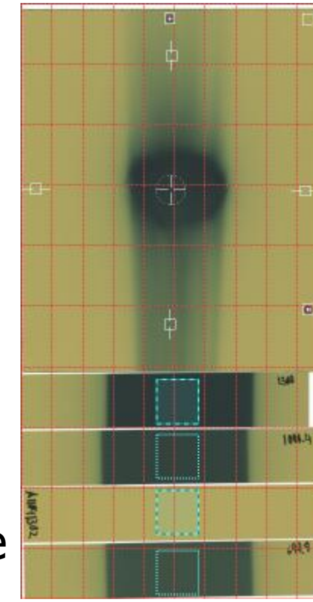
Example:

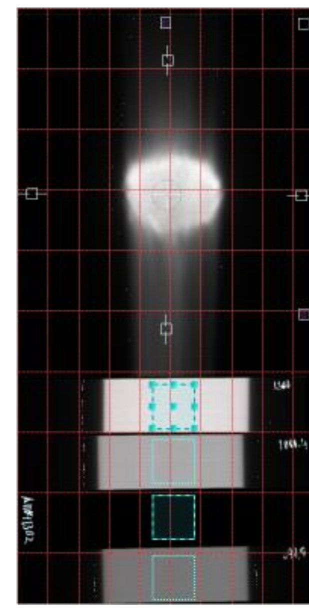
- SBRT ~5x5cm² field



GafChromic Protocol

- **Separate Dose and Dose-independent effects**
  - Compensates for film thickness variation
  - Mitigates scanner distortions
- **Enables entire film dose range**
  - Dynamic range ratio >1000
  - EBT2/EBT3 5 cGy - >20 Gy , EBT-XD 4x EBT3 range
- **Significant improvement of dose map accuracy**
  - ~0.5% routinely achievable
- **Consistency based estimation of dose error**
  - Active error improvement using reference exposures
- **Efficient workflow**
  - Package "Quick Phantom – EBT film – FilmQA Pro" enables best practice
  - Automatic registration using phantom fiducials
  - Evaluation 30 min after exposure possible





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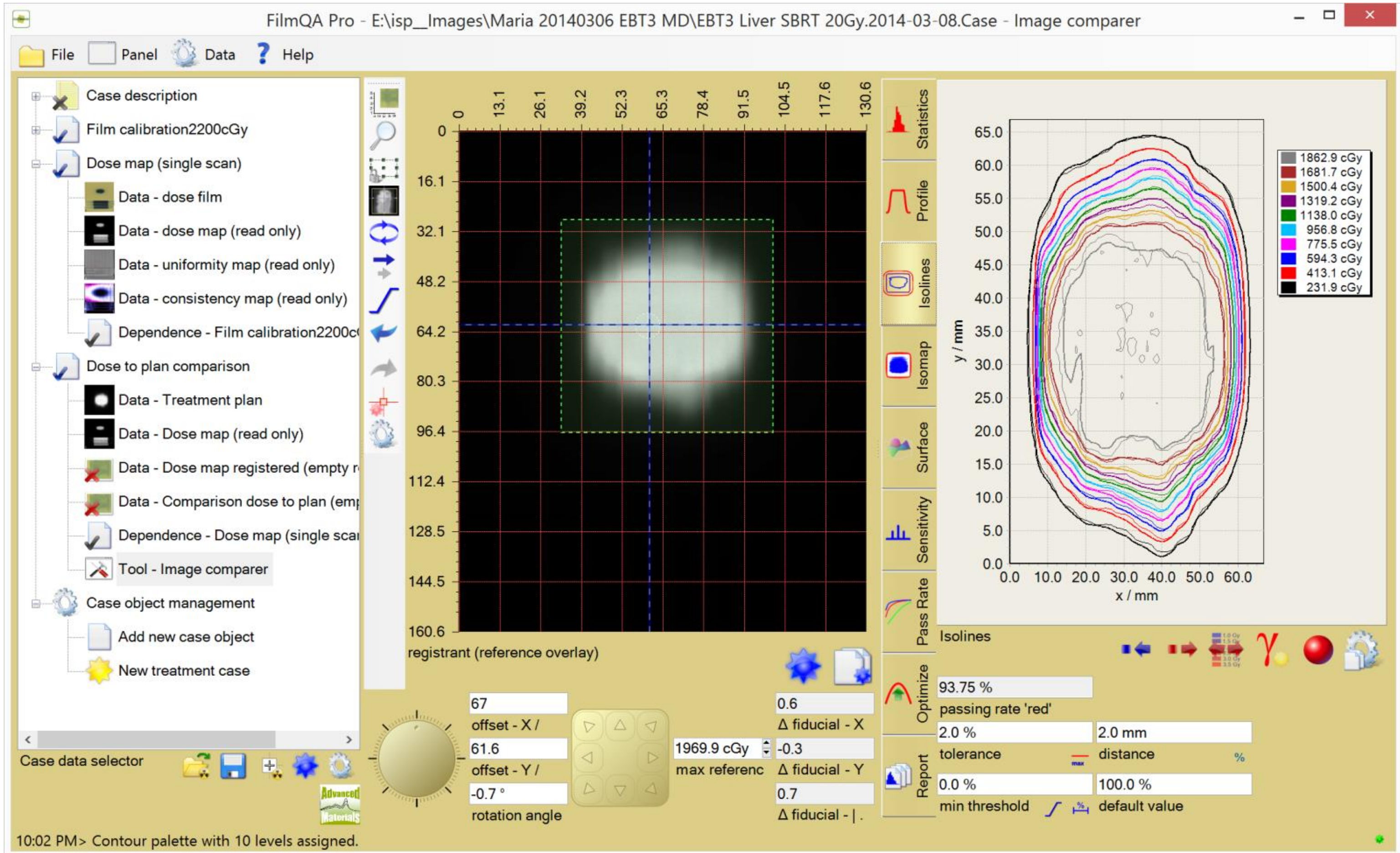

Micke, Lewis, Yu - Multi-channel Film Dosimetry with Non-Uniformity Correction, Medical Physics, 38 (2011) 5, pp. 2523.
Lewis, Micke, Yu, Chan - An Efficient Protocol for Radiochromic Film Dosimetry combining Calibration and Measurement in a Single Scan, Medical Physics, 39 (2012) 10, pp. 6339.

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