GafChromic Protocol
Multi-Channel Film Dosimetry + Gamma Map Analysis

Micke A.
Ashland Inc. – Advanced Materials
Ashland proprietary patented technology
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

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GafChromic Protocol
Exposure Procedure

GafChromic Quick Phantom

- Two Plastic Water® slabs
- Forced positioning on couch
- Automatic registration in FilmQA Pro
- Use with EBT3P

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

Asymmetric Film Registration Pins

Top Plate Locking Dowel Pins

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GafChromatic 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 EBT3 surface suppress Newton rings

No Color Correction, 72 dpi, 48 bpp

Same orientation of all Films
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
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
GafChromatic Protocol
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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GafChromic Protocol

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
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 \( X=\text{RGB} \) (optical density)

\[
D = D_X(X_{ave}) \leftrightarrow X_{ave} = X(D) \\
D = D_X(d_{X,ave}) \leftrightarrow d_{X,ave} = d_{X,D}(D) \quad (d_X = -\ln_{10}(X))
\]
Multi-Channel Calibration

Disturbance Factor

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

Example: Calibration Strip

- Calibration region all pixel have same (known) Dose
- Major contribution to \( \Delta d \) film non-uniformity
- \( \Delta d \) neutral with respect to \( X \)
Multi-Channel Dosimetry

Dose Calculation

\[ d_{X,\text{scan}}(D_X) = d_{X,\text{ave}}(D_X)\Delta d \]

- Disturbance factor connects \( D_X \) dose calculations, \( X=\text{RGB} \)

Consistency \( \kappa \)

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

- 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 \( \kappa \equiv 0 \)
  - At all pixels: 4 equations, 4 variables \( D_X \) and \( \Delta d \)
Multi-Channel Dosimetry

Signal split into \textit{dose dependent} and \textit{dose independent} part

Calculate Maps
- Dose - $D_X$
- Disturbance - $\Delta d$
- Consistency - $\kappa$
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** \( \Delta d \) removed error
- **Consistency** \( \kappa \) remaining error
  - \( \kappa \) absolute error
  - \( \kappa/D \) relative error

**Example:** Different sensors at different lateral position + lateral scanner effect cause (slightly) different average response.
Multi-Channel Dosimetry Disturbance Map

- Disturbance $\Delta d$ - removed error
- Presents relative film thickness when $\Delta d$ dominated by film non-uniformity → Uniformity Map
  Film uniformity: spec $\pm 1\%$, typical $\pm 0.5\%$
- $|\Delta d - 1| >> 1\%$ 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)
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** $\kappa \equiv 0$
- Calibration functions $\{ R(D), G(D), B(D) \}$ must match film dose spectrum

Optimize Consistency $\kappa$
shown relative consistency
Multi-Channel Calibration

- **Single channel calibration**
  average system response
  - $x = x(D)$
  - $x = \text{RGB}$
    each channel fitted separately

- **Multi-channel calibration**
  - $X(D) = A + B \times (a + bD)$
    $X = \text{RGB}$
    rescales calibration $x$
  - $a, b$ dose scaling, $A, B$ color scaling
  - Correlation $D_R(R_{\text{ref}}) = D_G(G_{\text{ref}}) = D_B(B_{\text{ref}})$
    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
  \[ x = \frac{1}{D} \]
  no parameters, ‘pure’ shape

**Recalibration**
- \[ X(D) = A + \frac{B}{(C + D)} \]
  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)
  \[ D_x = -C + \frac{B}{(-A + X)} \]
Multi-Channel Calibration

**Model functions**

- **Use Rational functions**
  Reciprocal \( X(D) = A + \frac{B}{C+D} \)
  Linear \( X(D) = \frac{(A+BD)}{(C+D)} \)
  Quadratic \( X(D) = \frac{(A+BD+CD^2)}{(E+D)} \)

**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

- 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)
  \[ X(D) = x(a + bD), \ X = \text{RGB} \]
- Color scaling (a=0, b=1)
  \[ X(D) = A + B \cdot x(D), \ X = \text{RGB} \]

Assumption
- Calibration functions keep shape
  \( \text{Shape}(x) = \text{Shape}(X), \ x, \ X = \text{RGB} \)

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
- $X(D) = A + B \times C D$ (3 point rescaling)
- $X(D) = A + B \times D^C$
- $X = RGB$

**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
  \[ \text{Shape}(x) = \text{Shape}(X), x, X = \text{RGB} \]
  disturbance caused by offset only

Single scan Evaluation

compensates for
- Offset generating disturbances
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

<table>
<thead>
<tr>
<th></th>
<th>Single Channel</th>
<th>Single Channel Recalibrated</th>
<th>Multi Channel</th>
<th>Multi Channel Recalibrated</th>
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<tbody>
<tr>
<td></td>
<td>10.2 cGy</td>
<td>3.6 cGy</td>
<td>1.3 cGy</td>
<td>1.2 cGy</td>
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<tr>
<td>%</td>
<td>4.2%</td>
<td>1.5%</td>
<td>0.53%</td>
<td>0.49%</td>
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</tbody>
</table>

Consistency measured across frame $D_{\text{max}} = 243$ cGy, $D_{\text{ave}} = 139$ 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
Gamma Map Comparison
Dose Map Projection

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

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

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www.FilmQAPro.com
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 !

<table>
<thead>
<tr>
<th>dose &lt;cGy&gt;</th>
<th>Consistency &lt;cGy&gt;</th>
<th>Consistency &lt;%&gt;</th>
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<tbody>
<tr>
<td></td>
<td>None</td>
<td>Blank scan</td>
</tr>
<tr>
<td>202.0</td>
<td>8.8</td>
<td>11.1</td>
</tr>
<tr>
<td>151.5</td>
<td>6.8</td>
<td>8.9</td>
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<td>4.8</td>
<td>0.4</td>
</tr>
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</table>

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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 $D_{\text{max}} > 20$ Gy
  - Wide fields use at $D_{\text{max}} > 5$ 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 2\textsuperscript{nd} Reference RGB 1.5/1.6/1.6%

Passing Rate vs Gamma Tolerance
Comparison Sensitivity

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 \sim 5\times5\text{cm}^2 \text{ 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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www.FilmQAPro.com
Mickey, Lewis, Yu - Multi-channel Film Dosimetry with Non-Uniformity Correction, Medical Physics, 38 (2011) 5, pp. 2523.