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 $X=R$
\[ R_{\text{ave}} = R_{\text{ave}}(D) \leftrightarrow D_R = D_R(R_{\text{ave}}) \]

 Color channels $X=\text{RGB}$
\[ D_X = D(X_{\text{ave}}) \]
correlates average response of film-scanner system

 Robust method
any $X$ value delivers dose $D_X(X)$
Single Channel Film Dosimetry

Problem:

Specific pixel does not behave like average

Disturbance $\Delta X$ generates $\Delta D_x$

$x + \Delta X \leftrightarrow D(x) + \Delta D_x$

- Film uniformity variations
- Scanner non-linearities
- Newton rings, noise, finger prints curling, ...

Any $X$ value delivers dose $D_x(x)$

- Each channel specific $\Delta D_x$
- No indication of ‘big’ $\Delta D_x$
- What dose $D_x$ is best?
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 $\Delta C$
- $C_{scan} = C(D) + \Delta C$

Solution: Optimize dose $D$ value, i.e. minimize $\Delta C$
- $|C_{scan} - C(D)| \rightarrow \min_D$
Triple Channel Film Dosimetry

Model:
Scanned optical density $d_{X,\text{scan}}$

- $d_{X,\text{scan}}(D) = d_{X,D}(D) * \Delta d$
- $d_X = -\log(X)$ for $X = \text{RGB}$
- $d_{X,D}$ is calibration function (average behavior)
- ! disturbance $\Delta d$ independent of dose + $X$ (wave length) !
  but $\Delta d = \Delta d(\text{thickness, scanner, noise, artifacts})$

Solution:
- Minimized function $\phi$ vs. disturbance $\Delta d$:
  $$\phi(\Delta d) = (D_R - D_B)^2 + (D_B - D_G)^2 + (D_G - D_R)^2 \rightarrow \min_{\Delta d}$$
Triple Channel Film Dosimetry Example

Signal split into dose dependent and dose independent part

- 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
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 \( \equiv 0 \)
**Multi Channel Calibration**

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

- **Multi-channel calibration**
  - \( X(D) = A + B x(a + bD) \)
    - \( X = \text{RGB} \)
    - 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**
- \[ X(D) = \frac{A + B}{C + D} \]
  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)
  \[ D_x = \frac{-C + B}{-A + X} \]
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
  \[ D_R(\, R_{\text{calib}} \, ) = D_G(\, G_{\text{calib}} \, ) = D_B(\, B_{\text{calib}} \, ) = D_{\text{calib}} \]
  for all calibration pixels \( X_{\text{calib}} \) (>10000 equations)

- Optimize calibration regions
- Select best model function

- Do Not
  \[ D_R(\, R_{\text{ave}} \, ) = D_G(\, G_{\text{ave}} \, ) = D_B(\, B_{\text{ave}} \, ) = D_{\text{calib}} \]
  for all calibration dose points (<10 equations)
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 \(a=0, b=1\)
  \[X(D) = A + Bx(D), X = \text{RGB}\]

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%
### 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>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>10.2 cGy</td>
<td>3.6 cGy</td>
<td>1.3 cGy</td>
<td>1.2 cGy</td>
</tr>
<tr>
<td></td>
<td>4.2%</td>
<td>1.5%</td>
<td>0.53%</td>
<td>0.49%</td>
</tr>
</tbody>
</table>

Consistency measured across frame $D_{max} = 243$ cGy, $D_{ave} = 139$ cGy
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 \((A=0, B=1, b=1)\)
  \[
  X(D) = x(a + D), \ X = \text{RGB}
  \]
- *Color* shift \((a=0, b=1, B=1)\)
  \[
  X(D) = A + x(D), \ X = \text{RGB}
  \]

**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
## Multi Channel Calibration

### Recalibration Comparison

<table>
<thead>
<tr>
<th>Recalibration points</th>
<th>0 points</th>
<th>1 point</th>
<th>2 points</th>
</tr>
</thead>
<tbody>
<tr>
<td>Passing rate 3%/3mm</td>
<td>99.6%</td>
<td>99.8%</td>
<td>99.9%</td>
</tr>
<tr>
<td>Passing rate 2%/2mm</td>
<td>95.6%</td>
<td>96.3%</td>
<td>97.1%</td>
</tr>
<tr>
<td>Passing rate 1%/1mm</td>
<td>44.5%</td>
<td>48.6%</td>
<td>49.6%</td>
</tr>
</tbody>
</table>

Example range: $D_{\text{max}} = 243$ cGy, $D_{\text{ave}} = 139$ cGy
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**

- **Gamma 2 mm**
- **Gamma 2 mm projected to plan**
- **Differential**

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

- **Gamma 2 %**
- **Gamma 2 % projected to plan**
- **Differential**

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

*Distance dependence chart suggest Resolution dependence*
Gamma Map Comparison
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 Differential Comparison

GafChromic
A. Micke, X. Yu, Europe, May 2014
www.FilmQAPro.com
Gamma Map Comparison
Passing Rate Dependencies

Passing Rate vs. Dose Map 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

A. Micke, X. Yu, Europe, May 2014
www.FilmQAPro.com
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!

<table>
<thead>
<tr>
<th>dose &lt;cGy&gt;</th>
<th>Consistency &lt;cGy&gt;</th>
<th>Consistency &lt;%&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td>None</td>
<td>Blank scan</td>
<td>None</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>
</tr>
<tr>
<td>101.0</td>
<td>5.9</td>
<td>8.4</td>
</tr>
<tr>
<td>50.5</td>
<td>5.9</td>
<td>7.9</td>
</tr>
<tr>
<td>0.0</td>
<td>4.8</td>
<td>0.4</td>
</tr>
</tbody>
</table>
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

<table>
<thead>
<tr>
<th>Gamma map Criterion</th>
<th>Calibration</th>
<th>Composite</th>
<th>Passing rate</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Single Channel</td>
<td>Triple Channel</td>
<td></td>
</tr>
<tr>
<td>2% / 2mm</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>≤ centered</td>
<td>90%</td>
<td>96%</td>
<td></td>
</tr>
<tr>
<td>≥ right edge</td>
<td>87%</td>
<td>96%</td>
<td></td>
</tr>
<tr>
<td>≤ centered</td>
<td>98%</td>
<td>98%</td>
<td></td>
</tr>
<tr>
<td>≥ right edge</td>
<td>94%</td>
<td>97%</td>
<td></td>
</tr>
</tbody>
</table>

- **Centered** = centered
- **Right Edge** = right edge
- Absolute dosimetry (no dose re-scaling), <5% (<12cG) lowest dose ignored,

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A. Micke, X. Yu, Europe, May 2014
www.FilmQAPro.com

[Graphs and images related to lateral scanner non-linearity]
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
Micke, Lewis, Yu - Multi-channel Film Dosimetry with Non-Uniformity Correction, Medical Physics, 38 (2011) 5, pp. 2523.