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

<table>
<thead>
<tr>
<th>Description</th>
<th>Thickness</th>
</tr>
</thead>
<tbody>
<tr>
<td>Polyester Laminate</td>
<td>50 µm</td>
</tr>
<tr>
<td>Adhesive Layer</td>
<td>25 µm</td>
</tr>
<tr>
<td>Active Layer</td>
<td>~28 µm</td>
</tr>
<tr>
<td>Polyester</td>
<td>175 µm</td>
</tr>
<tr>
<td>Matte Polyester</td>
<td>120 µm</td>
</tr>
<tr>
<td>Active Layer</td>
<td>~28 µm</td>
</tr>
<tr>
<td>Matte Polyester</td>
<td>120 µm</td>
</tr>
</tbody>
</table>
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 \sim 2 \text{ cGy} \text{ to } \gg 40 \text{ Gy}
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:

check “no color correction”
Measuring – Color Correction

Off

On
Measuring – Scan Orientation

Orientation Dependence
EBT3 A101711; 10000XL scanner

Response, red channel

Dose, cGy

Landscape
Portrait

Both deliver similar results – choose and be consistent!
Measuring – Scan Orientation

Angular Dependence of EBT2

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!
Single Channel – Lateral Effect

Dose map profile Red (single channel method)
Dose at lateral scanner edges overstated!
Measuring – Scanner Variation

Typical scan-to-scan variation

<0.2% color variation ➞ 0.2 – 1.0% dose variation
(dose range 0 - 500cGy)

Ashland Inc.
A. Micke, D. Lewis, Oregon, November 2012
www.FilmQAPro.com
Measuring – Scanner Variation

Accidental Scan-to-scan RGB Variation

>0.5% color variation ➔ 0.5 – 2.5% dose variation
(dose range 0 - 500cGy)
Measuring – Scanner Variation

Synchronic change with dose (Red channel)

Accidental Scan-to-scan Variation vs Dose

- 331 cGy, red channel
- 110 cGy, red channel
- Unexposed, red channel

Response relative to average

Scan #
Measuring – Film Flatness

Callier effect - Light change from collimated to diffused

Avoidable!
Measuring – Film Flatness

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

<table>
<thead>
<tr>
<th>Property</th>
<th>Transmission</th>
<th>Reflection</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low dose response</td>
<td></td>
<td>++</td>
</tr>
<tr>
<td>Dynamic range</td>
<td>++</td>
<td></td>
</tr>
<tr>
<td>Lateral response artifact</td>
<td>+</td>
<td></td>
</tr>
<tr>
<td>Scan-to-scan consistency</td>
<td>=</td>
<td>=</td>
</tr>
<tr>
<td>Film flatness</td>
<td></td>
<td>+</td>
</tr>
<tr>
<td>Humidity dependence</td>
<td></td>
<td>+</td>
</tr>
</tbody>
</table>
Measuring – Post Exposure Time

GAFCHROMIC EBT2: Post-Exposure Changes

Logarithmic growth approaching asymptotic value
Measuring – Post Exposure Time

Absolute aging
Compensate by waiting $t = 24$ h
$\Delta D(t) < 0.5\%$
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!
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 $t = 24 \ h$
$\Delta D(t) < 0.5\%$

Relative aging
wait $t = 4 \Delta t$
$\Delta D(t) < 0.5\%$
### One-Scan – Post Exposure Age

Expose application and reference films in a narrow time window

<table>
<thead>
<tr>
<th>Wait before scanning, min.</th>
<th>Exposure window, min.</th>
<th>Dose error</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>5</td>
<td>&lt;1%</td>
</tr>
<tr>
<td>20</td>
<td>5</td>
<td>&lt;0.5%</td>
</tr>
<tr>
<td>40</td>
<td>5</td>
<td>&lt;0.25%</td>
</tr>
</tbody>
</table>
Calibration – Post Exposure Age

Curves look similar – convertible?

Post-Exposure Changes, Absolute, red channel - EBT3 A101711

Response vs Dose (cGy) for different post-exposure times (65 min, 120 min, 255 min, 490 min, 1440 min, 4800 min)
Calibration – Post Exposure Age

All calibration curves have same Shape!
Can be converted by shifting + stretching

Color scaling
Color(0) = const
Color(D_{max}) = const

Scaled relative responses

Dose, cGy

Relative response

0  50  100  150  200  250  300  350  400  450  500

0  0.40  0.50  0.60  0.70  0.80  0.90  1.00  1.10
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 curves of different EBT lots are NOT Shape invariant!
One-scan Protocol

Procedure

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

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)
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
Film is a hassle!

Advantages, but

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

- Calibration Curve $X=R$
  \[ R_{\text{ave}} = R_{\text{ave}}(D) \iff D_R = D_R(R_{\text{ave}}) \]

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

- Unique mapping between $X$ value and dose $D_X(X)$
Single Channel Film Dosimetry

- **Rational function**
  \[ X(D) = A + \frac{B}{D - C} \]
  Use to fit calibration data

- Correct asymptotic
  \[ \lim_{D \to \infty} X(D) = A \]

- Easily invertible
  \[ D(X) = C + \frac{B}{X - A} \]

- Only 3 parameters
  reduces calibration to 2 exposures + blank film
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 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?
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 $\Delta C$
- $C_{scan} = C(D) + \Delta C$

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 \( d_{X,\text{scan}} \)

\[ d_{X,\text{scan}}( D ) = d_{X,D}( D ) \cdot \Delta d \]

\( d_X = -\log( X ) \) 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 (*dose dependent* part)
- Disturbance $\Delta d$ 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 \( \equiv 0 \)
Multi Channel Calibration

Single channel calibration
average system response

- \( x = x(D) \)
  \( x = RGB \)
  each channel fitted separately

Multi-channel calibration

- \( X(D) = A + B \cdot x(a + b \cdot D) \)
  \( X = RGB \)
  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
Multi Channel Calibration

- **Two point recalibration**
  - 1 unexposed + 1 exposed film
    Minim cost possible
  - *Dose* scaling \((A=0, B=1)\)
    \[ X(D) = x(a + bD) \text{, } X = RGB \]
  - *Color* scaling \((a=0, b=1)\)
    \[ X(D) = A + Bx(D) \text{, } X = RGB \]

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

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

---

*Ashland Inc.*
A. Micke, D. Lewis, Oregon, November 2012
www.FilmQAPro.com
## 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>
</tbody>
</table>

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

<table>
<thead>
<tr>
<th>Gamma map Criterion</th>
<th>Calibration</th>
<th>Composite</th>
<th>Passing rate</th>
<th>Single Channel</th>
<th>Triple Channel</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>⊙</td>
<td>⊙</td>
<td>90%</td>
<td>96%</td>
<td></td>
</tr>
<tr>
<td>2% / 2mm</td>
<td>→</td>
<td>→</td>
<td>87%</td>
<td>96%</td>
<td></td>
</tr>
<tr>
<td></td>
<td>⊙</td>
<td>→</td>
<td>98%</td>
<td>98%</td>
<td></td>
</tr>
<tr>
<td></td>
<td>→</td>
<td>⊙</td>
<td>94%</td>
<td>97%</td>
<td></td>
</tr>
<tr>
<td></td>
<td>→</td>
<td>→</td>
<td>64%</td>
<td>69%</td>
<td></td>
</tr>
<tr>
<td>1% / 1mm</td>
<td>⊙</td>
<td>⊙</td>
<td>58%</td>
<td>71%</td>
<td></td>
</tr>
<tr>
<td></td>
<td>→</td>
<td>→</td>
<td>64%</td>
<td>69%</td>
<td></td>
</tr>
<tr>
<td></td>
<td>⊙</td>
<td>→</td>
<td>81%</td>
<td>85%</td>
<td></td>
</tr>
<tr>
<td></td>
<td>→</td>
<td>⊙</td>
<td>73%</td>
<td>78%</td>
<td></td>
</tr>
</tbody>
</table>

- ⊙ = centered
- → = right edge

Absolute dosimetry (no dose re-scaling), <5% (<12cG) lowest dose ignored.
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

<table>
<thead>
<tr>
<th>dose (&lt;cGy&gt;)</th>
<th>Consistency &lt;cGy&gt;</th>
<th>Consistency &lt;cGy&gt;</th>
</tr>
</thead>
<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>
</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>
<tr>
<td></td>
<td>None</td>
<td>Blank scan</td>
</tr>
<tr>
<td>202.0</td>
<td>4.3</td>
<td>5.5</td>
</tr>
<tr>
<td>151.5</td>
<td>4.5</td>
<td>5.9</td>
</tr>
<tr>
<td>101.0</td>
<td>5.9</td>
<td>8.3</td>
</tr>
<tr>
<td>50.5</td>
<td>11.6</td>
<td>15.6</td>
</tr>
<tr>
<td>0.0</td>
<td>Infinity</td>
<td>Infinity</td>
</tr>
</tbody>
</table>
## Lateral Scanner Non-Linearity Normalized Blank Scan

<table>
<thead>
<tr>
<th>Dose cGy</th>
<th>Usable Scanner Width Triple Channel Dosimetry</th>
<th>Usable Scanner Width Green + Blue Channel Dosimetry</th>
</tr>
</thead>
<tbody>
<tr>
<td>250</td>
<td>full (26 cm)</td>
<td></td>
</tr>
<tr>
<td>500</td>
<td>24 cm</td>
<td></td>
</tr>
<tr>
<td>1000</td>
<td>18 cm</td>
<td></td>
</tr>
<tr>
<td>2000</td>
<td>14 cm</td>
<td>full (26 cm)</td>
</tr>
<tr>
<td>3000</td>
<td>6 cm</td>
<td>20 cm</td>
</tr>
<tr>
<td>4000</td>
<td>5 cm</td>
<td>20 cm</td>
</tr>
</tbody>
</table>

Dose error < 1%
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)
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

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!
## Single vs. Triple Channel Noise Dependence

<table>
<thead>
<tr>
<th>Triple Channel</th>
<th>Criterion</th>
<th>Passing rate</th>
<th>0% noise</th>
<th>0.5% noise</th>
<th>1% noise</th>
<th>2% noise</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>3% / 3mm</td>
<td></td>
<td>97%</td>
<td>96%</td>
<td>95%</td>
<td>95%</td>
</tr>
<tr>
<td></td>
<td>2% / 2mm</td>
<td></td>
<td>94%</td>
<td>96%</td>
<td>94%</td>
<td>87%</td>
</tr>
<tr>
<td></td>
<td>1% / 1mm</td>
<td></td>
<td>68%</td>
<td>70%</td>
<td>58%</td>
<td>41%</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Single Channel</th>
<th>Criterion</th>
<th>Passing rate</th>
<th>0% noise</th>
<th>0.5% noise</th>
<th>1% noise</th>
<th>2% noise</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>3% / 3mm</td>
<td></td>
<td>94%</td>
<td>95%</td>
<td>95%</td>
<td>94%</td>
</tr>
<tr>
<td></td>
<td>2% / 2mm</td>
<td></td>
<td>89%</td>
<td>92%</td>
<td>94%</td>
<td>91%</td>
</tr>
<tr>
<td></td>
<td>1% / 1mm</td>
<td></td>
<td>57%</td>
<td>65%</td>
<td>61%</td>
<td>48%</td>
</tr>
</tbody>
</table>

### 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
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
Film is a hassle!

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

Conclusion!
Micke, Lewis, Yu - Multi-channel Film Dosimetry with Non-Uniformity Correction, Medical Physics, 38 (2011) 5, pp. 2523.