New Performance Standard:
Multi-channel and One-scan Radiochromic Film Dosimetry

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Ashland Specialty Ingredients

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What is Radiochromic Film?

A film that instantly changes color upon exposure to ionizing radiation and needs no chemical or physical processing.
WHAT FOR DOSE MEASUREMENT?

- Primarily for radiotherapy (MV photons/electrons/protons)
  - EBT2/3 - 5 cGy to >10 Gy
  - MD-V3 – 1 Gy to 100 Gy
  - HD-V2 - 10 Gy to 1000 Gy
- Primarily for radiology (kV photons)
  - XR-RV3 - 5 cGy to 15 Gy
  - XRQA2 – 1 mGy to 20 cGy

With acknowledgements to Slobodan and Nada Devic, Samuel Trichter, Eduardo Villarreal, Jeffrey Guild, Gary Arbique and Scott Sample
WHAT FOR BEAM LOCATION?

- Primarily for radiotherapy (MV photons, electrons, protons)
  - RTQA2 - 2 cGy to 8 Gy
- Primarily for radiology (kV photons)
  - XRQA2 - 1 mGy to 20 cGy
  - XRCT2 - 1 mGy to 20 cGy
  - XRM2 - 1 mGy to 20 cGy

With acknowledgements to: Slobodan Devic, Theo van Soest, Andre Wopereis and Zheng Lu
<table>
<thead>
<tr>
<th>EBT2</th>
<th>EBT3</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Active layer 26-28 μm</td>
<td>Active layer 26-28 μm</td>
<td><strong>Active layer composition and response unchanged</strong></td>
</tr>
<tr>
<td>Asymmetric structure</td>
<td>Symmetric structure</td>
<td><strong>Scan EBT3 from either side</strong></td>
</tr>
<tr>
<td>Smooth polyester substrate</td>
<td>Matte polyester substrate</td>
<td><strong>Change prevents Newton’s Rings formation</strong></td>
</tr>
<tr>
<td>Density (unexposed)</td>
<td>Density (unexposed)</td>
<td><strong>Matte polyester slightly hazy</strong></td>
</tr>
<tr>
<td>~0.10 – 0.12</td>
<td>~0.12 – 0.14</td>
<td></td>
</tr>
<tr>
<td>Total thickness: ~ 0.28 mm</td>
<td>Total thickness: ~ 0.27 mm</td>
<td></td>
</tr>
</tbody>
</table>
## Configuration Change EBT2 to EBT3

<table>
<thead>
<tr>
<th>Layer Description</th>
<th>Thickness</th>
</tr>
</thead>
<tbody>
<tr>
<td>Polyester Laminate, 50 μm</td>
<td></td>
</tr>
<tr>
<td>Adhesive Layer, 25 μm</td>
<td></td>
</tr>
<tr>
<td>Active Layer, ~28 μm</td>
<td></td>
</tr>
<tr>
<td>Polyester, 175 μm</td>
<td></td>
</tr>
</tbody>
</table>

**EBT2**

<table>
<thead>
<tr>
<th>Layer Description</th>
<th>Thickness</th>
</tr>
</thead>
<tbody>
<tr>
<td>Matte Polyester, 120 μm</td>
<td></td>
</tr>
<tr>
<td>Active Layer, ~28 μm</td>
<td></td>
</tr>
<tr>
<td>Matte Polyester, 120 μm</td>
<td></td>
</tr>
</tbody>
</table>

**EBT3**
MATTE POLYESTER SURFACE

Gap $>> \lambda_{\text{light}}$

- Frustrates Newton’s Rings formation
EBT3 ELIMINATES NEWTON’S RINGS ARTIFACT

Newton’s Rings

EBT2

EBT3
RESPONSE OF EBT3 SIMILAR TO EBT2

EBT2 – Lot A011411

EBT3 – Lot A071111
COMPARISON EBT SERIES OF FILMS

- Gafchromic EBT film was well regarded in market
- Early EBT2 film had occasional problem
- Current EBT2 and EBT3 films are as good as if not better than original EBT
- Superior solution especially if combined with FilmQA Pro software
- New protocol will make dosimetry easier and faster
RADIOCHROMIC FILM DOSIMETRY
THE ADVANTAGES

- Handle in light
- Cut to size
- Bend to shape
- Immerse in water
- Wide dynamic range
- High spatial resolution

Specially valuable for new conformal therapies
Trends in conformal therapy
- Less fractions
- Higher doses per fraction
- Tighter conformity

Trending to a higher value on
- Spatial resolution, spatial resolution, spatial resolution
- Dynamic range
SMALL FIELD – HIGH SPATIAL RESOLUTION

With acknowledgements to: Steve Sorensen, Stefan van Hoof, Mark Oldham, Frank Verhagen, Guillaume Landry, Shane White and Sha Chang
PRESENT/FUTURE OF FILM DOSIMETRY

- Post-exposure waiting
- Film artifacts
- Scanner artifacts
- Environmental

How we turn film from a hassle to a snap?
NEW PERFORMANCE STANDARD

- Simplify calibration
  + Less films and all scanned together
  + Fitting functions that act like film

- Combine verification with calibration
  + Every patient film scanned with reference films
  + Eliminates environmental effects
  + Eliminates inter-scan variability

- Reduce post-exposure waiting to minutes

- Introduce multi-channel dosimetry
  + Eliminates or mitigates film and scanner artifacts
**ONE SCAN CALIBRATION**

- Expose three calibration films – doses approx. D(>maximum possible dose), 0.4D and 0.16D
- Scan the exposed films and an unexposed film all together
- Fit response data to a rational function like \( X(D) = a + \frac{b}{(D-c)} \) where a, b and c are constants
- Defines the shape of the calibration function
- Once per production lot

**Typical completion time <~20 minutes**
ONE SCAN CALIBRATION
FITTING CALIBRATION-BASES FOR FEWER POINTS

Polynomial Functions

\[ X(D) = A_1D^n + A_2D^{n-1} + \ldots + A_nD + C \]

\( D = \text{dose}, \ X(D) = \text{response} \)

Rational Functions

\[ X(D) = A + B/(D-C) \]

\( D = \text{dose}; \ X(D) = \text{response} \)

Not consistent with fundamental properties of film ✗
Function can oscillate between values ✗
Cannot be inverted ✗

Consistent with the behavior of film ✓
Easily inverted - \( D = C + B/(X(D)-A) \) ✓
COMPARISON OF 3 POINT CALIBRATION VS 7 POINT CALIBRATION
ONE SCAN DOSIMETRY-TWO POINT SCALING

- Set up patient film and expose treatment plan
- Expose a reference film (same lot as patient film) to dose similar to maximum dose on patient film
- Scan patient film, reference film and an unexposed film all together
- Convert to response to dose and analyze

Typical completion time ~20 minutes
ONE SCAN DOSIMETRY-TWO POINT SCALING
**BASIS FOR ‘ONE-SCAN’ DOSIMETRY**

- All dose response curves have similar shape
- Scan the patient and reference films together
- Two-point re-scaling – one exposed reference plus an unexposed film - applies to most situations
  - Post-exposure change
  - Inter-scan variation
  - Ambient temperature/moisture change
  - Photon energy
  - Type of scanner used
  - Film-scanner orientation
- Three-point re-scaling for lot-to-lot differences
Different Scanners of the Same Type

- Normalize responses to the response of unexposed film
- Scale normalized responses to the net response at a selected dose (480 cGy)
DIFERENT SCANNER TYPES

Absolute Response - Different Scanner Models
EBT3 A101711, red color channel

- 10000XL Scanner - 80 hrs
- V700 Scanner 1 - 80 hrs
- V700 Scanner 2 - 6 days
- V700 - Scanner 3 - 9 days

Relative/Scaled Response - Different Models
EBT3 A101711, red color channel

- 10000XL Scanner - 80 hrs
- V700 Scanner 1 - 80 hrs
- V700 Scanner 2 - 6 days
- V700 - Scanner 3 - 9 days
Effect of Scanning Temperature
EBT3 A121411, Epson V700 - Absolute Responses

Effect of Scanning Temperature
EBT3 A121411, Epson V700 - Responses Relative to Unexposed Film and Scaled
EBT3 Responses at 6MV and 160kVp

Relative/Scaled Responses at 6MV and 160kVp
Post-Exposure Changes, Absolute, red channel - EBT3 A101711

Post-Exposure Changes - Relative, scaled, red channel - EBT3 A101711
RECALIBRATION LOT-TO-LOT: CURVES HAVE DIFFERENT SHAPE
# Good Time Management: The Exposure Window for Patient and Reference Films

<table>
<thead>
<tr>
<th>Time after exposure, minutes</th>
<th>Exposure window, minutes</th>
<th>Dose error</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>5</td>
<td>1.0%</td>
</tr>
<tr>
<td>20</td>
<td>5</td>
<td>0.5%</td>
</tr>
<tr>
<td>40</td>
<td>5</td>
<td>0.25%</td>
</tr>
</tbody>
</table>
EXAMPLES - RESULTS VS. TIME

 Calibration films scanned 2 hours after exposure
 Patient/reference films scanned at different times

30 min. after  
4 hours after  
3 days after
## EXAMPLES - RESULTS VS. TIME

<table>
<thead>
<tr>
<th>Time after exposure</th>
<th>Gamma passing rate for 2%@2mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Calibration</td>
<td>Patient film and reference</td>
</tr>
<tr>
<td>2 hr</td>
<td>30 min.</td>
</tr>
<tr>
<td>2 hr</td>
<td>60 min.</td>
</tr>
<tr>
<td>2 hr</td>
<td>4 hr</td>
</tr>
<tr>
<td>2 hr</td>
<td>24 hr</td>
</tr>
<tr>
<td>2 hr</td>
<td>72 hr</td>
</tr>
</tbody>
</table>
Why One-scan dosimetry?

- Fast – results in minutes
- Less exposures and scanning
- Uncomplicated
- Easy use
- Economical
- Less film consumption
- Reliable and Accurate
- Multi-Channel Dosimetry
SINGLE CHANNEL 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 \( D_X(X) \)

Every measured response maps directly to a dose
Every response artifact maps to a dose artifact
1% response artifacts map to 3% dose artifacts
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 $C_{\text{scan}}$

is superposed with disturbance $\Delta C$

- $C_{\text{scan}} = C(D) + \Delta C$

Solution: Optimize dose $D$ value, *i.e.* minimize $\Delta C$

- $|C_{\text{scan}} - C(D)| \rightarrow \min_D$
Model:
Scanned optical density $d_{X,\text{scan}}$

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

Solution:

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

MULTI-CHANNEL FILM DOSIMETRY
WHY THE MARKER DYE?

- Red channel signal dominated by dose information
- Blue channel signal dominated by uniformity information
- Facilitates correction of film non-uniformities
  - U.S. Patent 6,285,031 September, 2001
  - U.S. Patent Application ????????
SPECTRA OF EBT2/EBT3 COMPONENTS

- Active component
  + Signal in red channel

- Marker dye
  + Signal in blue channel
DOSE MAP - SINGLE CHANNEL
DOSE MAP - MULTI CHANNEL
WHAT DO I NEED TO KNOW ABOUT SCANNING?
DISABLE ALL THE IMAGE ADJUSTMENT FEATURES

Check “No Color Correction”
Single (red) channel dosimetry

Triple channel dosimetry

DOSIMETRY METHOD AND LATERAL DISPLACEMENT
FILM PLACEMENT ON THE SCANNER

Central placement

Lateral placement

Scan direction
CLINIC EXAMPLES OF MULTI CHANNEL ONE SCAN DOSIMETRY

SYNERGY

Gafchromic Films and FilmQA Pro 3.0
CONVENTIONAL FILM DOSIMETRY

Typically >90% pixels passing gamma test of 3% at 3mm
SINGLE IMRT FIELD - MULTI-CHANNEL, ONE-SCAN

97.6% for 2%/2mm
COMPOSITE IMRT-MULTI-CHANNEL, ONE-SCAN

95.6% for 2%/2mm
RAPIDARC™, ONE ARC-MULTI-CHANNEL, ONE-SCAN

97.9% for 2%/2mm
RAPIDARC™, TWO ARCS-MULTI-CHANNEL, ONE-SCAN

97.1% for 2%/2mm
SRS ONE FIELD – MULTI-CHANNEL, ONE-SCAN

96.5% for 2%/2mm
New Film Dosimetry Standard

95% pixels passing 2% at 2mm

New Film Dosimetry Standard

Dosimetry we test accuracy 3% at 2mm

2% at 2mm

GafChromatic

With Conventional

Single-channel

One-scan

Multi-channel
NEW PHYSICS QA TOOLS
MULTI-CHANNEL AND ONE-SCAN DOSIMETRY IS THE NEW STANDARD

- Application and calibration films scanned simultaneously
  - Inter-scan variability is avoided
- Multi-channel dosimetry corrects/mitigates film and scanner artifacts
- Simplicity goes up and errors go down
- Gamma evaluation with 95% passing 2%/2mm
FILM DOSIMETRY SUMMARY OF ADVANTAGES

- Post-exposure timing rules are relaxed
- No concern whether a calibration is still valid
- Don’t need large number of calibration films
- Don’t need multiple scans
  - Entry costs - Film/Software/scanner
    - Much less than an array device
  - Running costs
    - Less film consumption
    - Less working time
EBT2/3 + FILMQAPRO 3.0-A COMPLETE SYSTEM

- Provides millions of measurements
  - Arrays only make 100 - 1000 measurements missing 99.9% of the picture
- Nothing is missed with film
- Shoot film from any angle
  - Shoot the whole plan on one film
  - Just like the patient gets it
DOSE MONITORING WITH GAFCHROMIC® XR-R

- Immediate visualization of patient exposure – magnitude and location
- Detailed dose distribution

L & R are patient’s orientation
### IAEA Study Results

<table>
<thead>
<tr>
<th></th>
<th>Coronary</th>
<th>Non-Coronary</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong># of patients</strong></td>
<td>400</td>
<td>250</td>
</tr>
<tr>
<td><strong>% &gt; 2Gy</strong></td>
<td>12</td>
<td>10</td>
</tr>
<tr>
<td><strong>Repeat</strong></td>
<td>40%</td>
<td>40%</td>
</tr>
</tbody>
</table>

- **Gafchromic® XR Film**
  - Easiest
  - Simple
    - Visual Reference
    - Feedback during procedure
  - Consistent and Reliable Results

- **DAP/KAP**
  - Difficult to correlate to peak skin dose

- **Importance of Dose Monitoring**
COMPARISON OF GAFCHROMIC XR-R WITH DIODES

*Data provide by Les Hopitaux Universitaires de Strasbourg, used with permission
260.522 R

average dose (2916 values, 0.000 m²)
34.138 R  69.525 R  429.379 R

calibration

scan image

Calibration (xyu) 2010-02-12 15-51 (EPSON Expression 166)
For more information
+ www.gafchromic.com
+ www.FilmQApro.com
+ www.FilmQAXR.com

Contact us directly
+ amicke@ashland.com
+ xiangyu@ashland.com
+ dlewis@ashland.com
Film is the **FUTURE**

With the New Protocol and Your Efforts