Physics
Outline

- The XOFT System
- Dosimetry of X-Ray Source:
  - TG43
  - Balloon Applicators and APBI
  - Endo Rectal Applicators
  - Cervical Applicator
  - TG61
  - Surface Applicators
- Radioprotection:
  - Shielding
  - Room exposure
  - Regulatory
- Operations:
  - Calibration
  - Commissioning
  - QA
The Xoft System

IORT
- BREAST
- REST OF BODY

APBI

SKIN

GYN
- ENDOMETRIUM
- CERVIX

Source connected to source nest
Applicator hub attachment

Source high voltage cable attachment
Source Comparison I

Absolute Dose vs. Depth in Water for 50kV Xoft and Ir-192 Sources

Dose of 34 Gy to the Prescription point at 3.5 cm

Dickler A, et al. 2007. A dosimetric comparison of MammoSite HDR brachytherapy and Xoft Axxent EBS. Brachytherapy, 6, 64-168;

Source Comparison II

- Average energies: 26.7, 31.0, 32.6, 33.6 and 34.5 keV. “Beam Quality”, and Therefore RBE, is Similar To Iodine (28 keV average)*

- Leading radiobiology expert, Jack Fowler PhD, concluded that the RBE from the Axxent X-ray source is about 1.2 and a similar fractionation schedule to that commonly used in isotope APBI is appropriate.

DOSIMETRY OF XOFT X-RAY SOURCE
TG-43 Dosimetry

AAPM TG-43* Protocol For Brachytherapy Dose Calculation


- Source anode: less than 1mm effective length**
- Anisotropy due to attenuation from source envelope and catheter

Essentially a point source with 2D anisotropy
TG-43: General 2D Case (Line Source)

\[ \dot{D}(r, \theta) = S_k \cdot \Lambda \cdot \frac{G_L(r, \theta)}{G_L(r_o, \theta_o)} \cdot g_L(r) \cdot F(r, \theta) \]

\[ \dot{D}(r, \theta) \] Dose rate to water at P(r, \theta)

\[ S_k \] Source strength

\[ \Lambda \] Dose rate constant

\[ G_L(r, \theta) \] Geometry function

\[ g_L(r) \] Radial dose function

\[ F(r, \theta) \] Anisotropy function
TG-43: Simplified 1D Case (Point Source)

\[ \dot{D}(r) = S_k \cdot \Lambda \cdot \frac{1}{r^2} \cdot g_p(r) \cdot \phi_{an}(r) \]

- \( \dot{D}(r) \): Dose rate to water at P
- \( S_k \): Source strength
- \( \Lambda \): Dose rate constant
- \( g_p(r) \): Radial dose function
- \( \phi_{an}(r) \): Anisotropy factor
TG-43: Modified Case (Xoft Source)

\[ \dot{D}(r, \theta) = S_k \cdot \Lambda \cdot \frac{G_L(r, \theta)}{G_L(r_o, \theta_o)} \cdot g_L(r) \cdot F(r, \theta) \quad \text{(Line Source)} \]

\[ \frac{1}{r^2} \cdot g_p(r) \]

(Replace with Geometry and Radial Dose Function of a point source)

\[ \dot{D}(r, \theta) = S_k \cdot \Lambda \cdot \frac{1}{r^2} \cdot g_p(r) \cdot F(r, \theta) \quad \text{(Xoft Source)} \]

c.f. Rivard, et al: Medical Physics 33(11) 4020-4032 “Calculated and measured brachytherapy dosimetry parameters in water for the Xoft Axxent X-Ray Source”
Fig. 3. Spatial measurement apparatus in water tank, surrounding radiation shielding not shown. The structure at the top contains both rotary and linear stepper motors. Source catheters can enter from above for azimuthal, or through the front, for polar angle anisotropy function measurements. Radial dose function measurements can be made in either orientation. The ion chamber is encased in a sealed Solid Water™ box with a snorkel to allow equilibration with atmospheric pressure.
TG-43 Dosimetry

Delivered Dose Distribution On Film

Predicted Dose Distribution From TPS

TG43 formalism accurately represent the source characteristics

TG43 source data from Rivard, et al: Medical Physics 33(11) 4020-4032 “Calculated and measured brachytherapy dosimetry parameters in water for the Xoft Axxent X-Ray Source”
Balloon Applicators and APBI
### Xoft balloon applicators

<table>
<thead>
<tr>
<th>Balloon Configuration</th>
<th>Balloon Fill Volume</th>
</tr>
</thead>
<tbody>
<tr>
<td>3-4 cm Spherical</td>
<td>30-45 cc</td>
</tr>
<tr>
<td>4-5 cm Spherical</td>
<td>45-75 cc</td>
</tr>
<tr>
<td>5-6 cm Spherical</td>
<td>65-130 cc</td>
</tr>
<tr>
<td>5 x 7 cm Ellipsoidal</td>
<td>90-125 cc</td>
</tr>
</tbody>
</table>
Decreased Normal Tissue Dose

- Target $V_{100\%}$ - 96.5%
- Breast $V_{50\%}$ - 19.8%
- Lung $V_{30\%}$ - 3.7%
- Heart $V_{5\%}$ - 59.2%

- Target $V_{100\%}$ - 96.5%
- Breast $V_{50\%}$ - 13.0%
- Lung $V_{30\%}$ - 1.1%
- Heart $V_{5\%}$ - 9.4%

Slide courtesy of Dr. David Wazer

Endo-rectal Applicators
Advantages of Axxent Vaginal Cuff Applicator: Improved Dosimetry

- Axxent system source does not show anisotropy like Iridium - Xoft source can generate a continuous dome shaped dose distribution
- Less risk of underdosing target area without overdosing adjacent tissue
- Doses outside PTV (e.g. Bladder, Rectum) always less at 50kV than at 380 kV
Reduced Dose to Bladder and Rectum

Ir-192

- $V_{95\%} = 99.7\%$
- Bladder $V_{35\%} = 47.7\%$
- Rectal $V_{35\%} = 48.3\%$

Xoft Source

- $V_{95\%} = 99.6\%$ (p=ns)
- Bladder $V_{35\%} = 27.4\%$ (P<.05)
- Rectal $V_{35\%} = 28.3\%$ (P<.05)

Axxent Cervical Applicator

FDA clearance received 03/2013
AAPM TG-61* Protocol For Skin and Surface Applications

TG-61 Dosimetry

- In-air calibration for 40-100 kVp
- Parallel plate chamber required for 40-70 kVp
- Beam quality characterization (mm Al HVL) using “good geometry”
- “Effective point of measurement” is center of chamber volume
- \(N_K\) and \(P_{elec}\) from ADCL at specified energy (M50).
- Various corrections (\(P_{TP}, P_{ion}, P_{pol}, B_W, P_{stem,air}, \delta t,\) cone factors and cutout factors) are required
- Backscatter Factor (\(B_W\)) SHALL be determined via TG-61 tables
  - Monte Carlo preferred over less precise measurements
- Correction for Dose to Water vs. Dose to Tissue is needed
TG-61 Dosimetry

Xoft Surface Applicator In-air Calibration Fixture

- Used together with PTW 34013 chamber and surface applicator
- Provides stable, repeatable setup for in-air measurements
Applicator cone should be centered directly above chamber

Plastic end cap is used during in-air calibration and is flushed with chamber surface

Chamber is calibrated with a thin Kapton film over window
  – to reduce contamination and buildup effects specific to this chamber
  – to be left in place for all in-air measurements
TG-61 Dose Calibration Protocol

\[ D_{w,z=0} = M \cdot N_K \cdot B_W \cdot P_{stem,air} \cdot \left[ \frac{\mu_{en}}{\rho} \right]_{w,air} \cdot \left[ \frac{\mu_{en}}{\rho} \right]_{w,air}, \]

where

- \( M \) is the raw chamber reading corrected for
  - Temperature and Pressure, \( P_{TP} \)
  - Ion Recombination, \( P_{ion} \)
  - Polarity effect, \( P_{pol} \)
  - Electrometer accuracy from ADCL, \( P_{elec} \)
  - End Effect, \( \delta_t \)

- \( N_K \) is the ADCL air-kerma calibration factor (depends on HVL)

- \( B_W \) is the backscatter factor

- \( P_{stem,air} \) is the chamber stem correction factor

- \( \left[ \frac{\mu_{en}}{\rho} \right]_{w,air} \) is the ratio for water to air of the mean mass-energy absorption coefficients averaged over the incident photon spectrum
TG-61 HVL Determination

- TG-61 recommends the first two HVL (mm Al) be determined at 100 cm from source with narrow beam ("good geometry") collimated at 50 cm.
- This recommendation not suitable to measure Xoft energy:
  - Readings at this distance will be near background
  - Especially for small volume chambers (e.g. the PTW 34013)
TG-61 HVL Determination

- Modification to recommendation is required
  - Total distance is reduced to 30 cm
  - Use large enough parallel plate chamber to produce ionization current (e.g. 15 cc p-p chamber)

- The ADCL calibration energy most appropriate for this beam is the "M50"

TG-61 HVL Determination

- HVL characterizations conducted at Xoft for the 4 surface applicators ranged from
  - 1st HVL: 1.39 – 1.57 mm Al
  - 2nd HVL: 2.20 – 2.60 mm Al
  - Homogeneity Correction = 0.61 – 0.63
# TG-61 Mass Absorption Factors

Field size dependence of mass absorption is negligible at 50 kVp ( < 1/10% from 1 to 100 cm² )

<table>
<thead>
<tr>
<th>1st HVL (mm Al)</th>
<th>( [(\mu_{en} / \rho)^{w_{air}}]_{air} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.2</td>
<td>1.018</td>
</tr>
<tr>
<td>1.5</td>
<td>1.017</td>
</tr>
<tr>
<td>2.0</td>
<td>1.018</td>
</tr>
</tbody>
</table>
## TG-61 Backscatter Factors

<table>
<thead>
<tr>
<th>Surface Applicator:</th>
<th>10 mm</th>
<th>20 mm</th>
<th>35 mm</th>
<th>50 mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>1&lt;sup&gt;st&lt;/sup&gt; HVL (mm Al):</td>
<td>1.39</td>
<td>1.53</td>
<td>1.57</td>
<td>1.56</td>
</tr>
<tr>
<td>Nominal SSD (mm):</td>
<td>20.7</td>
<td>20.6</td>
<td>20.6</td>
<td>30.3</td>
</tr>
<tr>
<td>(B_w):</td>
<td>1.049</td>
<td>1.085</td>
<td>1.114</td>
<td>1.130</td>
</tr>
</tbody>
</table>

\(B_w\) for various diameters interpolated from Table V of TG-61

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**Note:** Reliable \(B_w\) measurements are non-trivial and should not be measured clinically for low energy beams. TG-61 recommends that these factors be obtained from Table V.
**TG-61 Stem Effect**

- $P_{stem,air}$ is the chamber stem correction factor
  - Accounts for change in photon scatter from chamber stem between the calibration in a standards laboratory and the in-air measurements in a user’s beam
- Factor varies with field size, energy and chamber
- Measured by inter-comparing a chamber with an unknown stem factor to a chamber with a known stem factor (c.f. TG-61)
  - A flat response chamber with known minimal stem effect is preferred (e.g. cylindrical farmer chamber)
TG-61 Stem Effect

- Xoft conducted measurements on the PTW 34013 chamber for various field sizes
  - Stem effects for various apertures ranging from 5 to 50 mm are within 0.3% of the measurements of full stem exposure
  - Indistinguishable from the systematic noise for a PTW 34013 system
- Xoft recommends that stem effect corrections not be made at this time for the PTW 34013 chamber
- $P_{stem,air} = 1.000$
TG-61 $P_{TP}$, $P_{ion}$, and $P_{pol}$

- $P_{TP} = 101.33 \text{kPa} / P(\text{kPa}) \times [273.2 + T(\text{C})]/295.2$
  
  101.33 kPa = 760 mmHg

- $P_{ion} = \left[1 - \left(\frac{V_H}{V_L}\right)^2\right] / \left[\left(\frac{M_{raw, H}}{M_{raw, L}}\right)^2 - \left(\frac{V_H}{V_L}\right)^2\right]$
  
  $V_H$ typically 300 V, $V_L$ typically 150 V

- $P_{pol} = \left|\frac{(M_{raw, +} - M_{raw, -})}{2 \ M_{raw}}\right|$
  
  Typically taken at +/- 300 V. The choice of the denominator $M_{raw}$ is determined by the voltage chosen for the final dose rate calculations.
Dose absorption in different tissues can vary widely at low energies.

TG-61 recommends a final conversion from dose to water to dose to tissue.

\[ D_{\text{med},w} = C_{\text{med},w} \times D_{w,z=0} \]
TG-61 End effect, $\delta t$

- End effect is additional dose which is delivered prior to timer start
  - Accrued during the ramp up
  - Should be subtracted from nominal dwell times
- Measurements of dose rate during calibration can be made without the end effect by using a timed exposure method or an electrometer
- Per TG-61, $\delta t$ can be measured by taking two exposures ($M_1$, $M_2$) for two different durations ($t_1$, $t_2$)
  $$\delta t = \frac{(M_2 \cdot t_1 - M_1 \cdot t_2)}{(M_1 - M_2)}$$
- Typical end effect will be between 1 and 2 seconds
TG-61 Output Factor Correction

- Any given cone set will have the **same relative output ratios regardless of the source used**
- Relative output ratios can be measured between cones by using the Surface QA phantom
- Absolute calibrations now required for only a single reference cone (e.g. 35 mm cone)
- \( \text{OF}_{\text{cone A}} = \frac{M_{\text{cone A}}}{M_{\text{cone ref}}} \)
TG-61 Cutout Factor Correction

- Surface QA phantom can be used to measure the decrease in relative dose by placing the cutout between the chamber and cone (with end cap)

\[ \text{OF}_{\text{cutout cone A}} = \frac{M_{\text{cone A (collimated)}}}{M_{\text{cone A (uncollimated)}}} \]

- Dose Rate should be adjusted by the cone and cutout corrections

\[ \tilde{D}_{\text{cutout}} = \tilde{D}_{\text{ref}} \times \text{OF}_{\text{cutout cone A}} \times \text{OF}_{\text{cone A}} \]
Skin - Surface Brachytherapy
Surface Applicators

- 10mm, 20mm, 35mm, 50 mm
- Covers target area up to 50 mm in diameter
- Stainless Steel:
  - Easily sterilizable
  - Applicator Cone and Source Channel
  - Flattening Filter integrated in Cone: Analogous to Valencia Applicator, not Leipzig
Xoft Surface Applicator Relative Depth Doses (normalized to the surface)
Xoft 3.5 cm Applicator

Percent Depth-Dose Comparison with Nucletron Ir-192 Leipzig & Standard Superficial Voltage

- 50 kVp – 3.5 cm diameter applicator; Xoft data taken in January 2009
- Ir-192 – 3.0 cm diameter Leipzig applicator; Nucletron Leipzig Applicator IFU
- 100 kVp – 3.0 cm cone, 1.5 mm Al filter, 15 cm FSD; Trout et al, Radiology 65, 703-744 (1955)
Beam Uniformity: 4 Applicator Sizes

Dose profile measurements for the 10 mm (upper left), 20 mm (upper right), 35 mm (lower left) and 50 mm (lower right) Surface Applicators at four depths (2, 5, 10 and 15 mm). The vertical black lines correspond to 80% of the field width.
Useful Treatment Area: 6 MeV vs. Xoft 50 kV

- 6 MeV: 3.0 cm cutout as typically treated (5 mm bolus, 90% isodose line)

- Xoft 35 mm applicator as typically treated (Prescribe 100% to surface, 80% isodose line is effective treatment area).
Physics: Shielding, Room Exposure, Regulatory
Radiation Safety

Standards for protection against radiation state that radiation exposure to hospital employees, visitors and patients should be kept “as low as reasonably achievable” – “ALARA”

- Average naturally occurring exposure in US for general population is 200-400 mR per year, from
  - Cosmic rays – high elevation, plane flights (40 mR)
  - Background radiation
  - Natural Isotopes (potassium, carbon)
  - Medically necessary exposure not included
  - Allowed to add 100 mR per year – ALARA

- For occupationally exposed personnel, allowed to add up to 5000 mR per year, or 100 mR/week
  - But, we often design to limit at 10% of that, or **10 mR per week**. Then we can absorb carelessness.
Room Exposure Measurements

Bare Source
Balloon in phantom with FlexiShield

1 mm Pb-equivalent rolling shield

3.4 mR/hr
0.04 mR/hr

6 R/hr
15 mR/hr

For most rooms in most facilities, including an OR or exam room,
2 layers of 1/2 inch gypsum wallboard will reduce external exposure to meet ALARA requirements.
Radiation Safety: Shielding Ir-192 vs. 50 kV for a 40 hours per week treatment facility

- Exposure rate for 10 Ci Ir-192 source ~7035 mR/hr at 1 meter
- Busy site treats 6.67 hours per week => 47,000 mR/week
- Move to 3 meters away reduces by 9-fold, down to 5200 mR/week
- Need to reduce this by factor of 520
- Add shielding of 15 inches concrete or 1.5 cm of lead (40 #/sq ft – 8x4 sheet weighs 1280 pounds).

- Exposure rate for bare Xoft s700 50 kVp tube is about 6000 mR at a distance of 1 meter in one hour
- 6.67 hours per week => 40,000 mR/week
- Move to 3 meters away reduces by 9-fold, down to 4444 mR/week
- Need to reduce this by factor of 444
- Add shielding of 0.45 mm lead (1 ¼ # per sq. foot), 4.5 cm concrete or 3 layers of 5/8” wallboard.
Operations: Calibration, Commissioning and QA
Initial and Daily Source Calibration

- Prior to first use verify:
  - Manufacturer’s AKS, Constancy
  - Dose distribution, Source offset
    - via film, chamber and depth gauges
- Per Treatment
  - A Source Dose Calibration is performed prior to EVERY fraction.
  - Source integrity, timing and dwell position accuracy
- During Treatment
  - kV, mA, time, position redundantly monitored
Typical Commissioning steps

- Controller functionality
- Beam Stability
- Output Stability
- Well chamber constancy
- Timer accuracy/End effect
- Source transit time
- Positional accuracy
- Safety characteristics
- Typical Physics Effort: 2 days

QA Tool Kit, Standard with every Axxent System

- QA Test Fixture
  - Shielded environment to test source parameters
  - Small ion chamber – source stability and strength, position reproducibility
  - Radiochromic film – dose distribution
  - Observe source operation

- Also included;
  - Applicator Depth Gauge
  - Source Length Gauge
  - Pullback Travel Indicator
  - Marker Catheters
    - CT-compatible
    - Fluoro-compatible
Surface Applicator Test Fixture and Jig

- Shielded test fixture and in-air jig included with applicator kit for AAPM TG-61 dosimetry
Thanks!