Normal tissue dose in pediatric VMAT

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Radiation induced effects in children

• Risk of inducing 2\textsuperscript{nd} cancers higher than for adults

• Low / intermediate doses increase risk of:
  - breast
  - leukemia
  - thyroid cancers

• Late effects include
  - bone growth
  - musculo-skeletal abnormalities
  - neurocognitive effects
  - endocrine deficiencies

Nitsch, Marcus et al (2009)
P Zygmanski: Normal tissue dose in pediatric VMAT (NEAAPM 2010)
Central nervous system toxicity

• Severity of radiation effects is greater than for adults

• Radiotherapy damages:
  - white matter
  - glial cells
  - microvasculature
  - neurons (demyelination)

• Executive function deficits
  - Processing speed
  - Working memory
  - Organizational skills

Nitsch, Marcus et al (2009)
Challenges of RT planning for pediatric patients

- Differences in adult / pediatric geometry
- Distances to normal organs much shorter for children
- Scatter / peripheral / penumbra / exit doses more important

Nitsch, Marcus et al (2009)

P Zygmanski: Normal tissue dose in pediatric VMAT (NEAAPM 2010)
Challenges of RT planning for pediatric patients

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- Greater impact of patient setup errors on dose errors
- Anesthesia required in small children

Nitsch, Marcus et al (2009)

P Zygmanski: Normal tissue dose in pediatric VMAT (NEAAPM 2010)
Challenges of RT planning for pediatric patients

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- Complex IMRT plans have relatively large amount of scatter
- Photon beams have problem with exit dose
- Proton therapy is not widely available

Nitsch, Marcus et al (2009)
What can we do with photon RT?

• Attempt to decrease dose to normal tissues
• Scatter dose (peripheral dose, leakage)

• Even small improvements → better quality of life

• Shorter treatment time (anesthesia, setup errors)

Nitsch, Marcus et al (2009)
Evaluation of VMAT vs IMRT

- Treatment planning
- Dose verification
  - methods
  - application

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P Zygmanski: Normal tissue dose in pediatric VMAT (NEAAPM 2010)
VMAT (RapidArc) vs IMRT (Eclipse)

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Rotation therapy
Stapleton 1953,
Smithers 1954
Kligerman et al 1954
Quimbly et al 1957

Mod-arc therapy
Wright et al 1970
Brahme et al 1982a, 1982b

Cormack et al 1987, 1998
Bratengeier 2001, 2005a, 2005b

SRS / SRT
Betti et al 1983
Colombo et al 1985
Hartman et al 1985
Lutz et al 1988
Podgorsak et al 1987a, 1987b

IMAT
Yu et al 1995a, 1995b, 2002
Cotruzel et al 2000
Wong et al 2002
Crooks et al 2003

IMRT
1990

Tomotherapy
Mackie 2003

DAO
Shepard et al 2002
Earl et al 2003
Beaulieu 2004
Schreibmann et al 2003

VMAT (RapidArc)
Otto 2008

Gradient search methods
Simulated annealing
Probabilistic methods
Iterative methods
Cost functions

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General criteria for VMAT vs IMRT

• Simpler, faster planning

• Simpler, more MU-efficient

• Faster treatment

• Better or equivalent dose distribution
  - Coverage
  - Dose homogeneity (PTV)
  - Critical structures
  - Medium-dose distribution

• Potential benefit for selected applications
  - prostate, SRS, SBRT, Pediatric etc

P Zygmanski: Normal tissue dose in pediatric VMAT (NEAAPM 2010)
Dose evaluation criteria

- Visual inspection: isodose lines slice by slice
- Final DVH vs original optimization goals

- Target coverage: $V_{100\%}$, $V_{98\%}$
- Homogeneity within target: $V_{105\%}$

- OAR: $V_{20cGy}$ $D_{\text{max}}$, $D_{\text{mean}}$

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6 patients:

- thorax sarcoma
- germ cell tumor of the ventricles
- T-spine
- nasal sinus
- rhabdomyosarcomas of the hip
- C-spine ependymoma

<table>
<thead>
<tr>
<th>OAR</th>
<th>Objective</th>
</tr>
</thead>
<tbody>
<tr>
<td>Globes</td>
<td>Maximum dose $&lt; 45$ Gy</td>
</tr>
<tr>
<td>Optic Nerves</td>
<td>Maximum dose $&lt; 54$ Gy</td>
</tr>
<tr>
<td>Chiasm</td>
<td>Maximum dose $&lt; 54$ Gy</td>
</tr>
<tr>
<td>Oral Cavity</td>
<td>Mean dose $&lt; 10$ Gy</td>
</tr>
<tr>
<td>Larynx</td>
<td>Mean dose $&lt; 20$ Gy</td>
</tr>
<tr>
<td>Parotids</td>
<td>Mean dose $&lt; 26$ Gy</td>
</tr>
<tr>
<td>Cord</td>
<td>Max dose $&lt; 45$ Gy</td>
</tr>
<tr>
<td>Lungs</td>
<td>Mean dose $&lt; 12$ Gy, $V_{20 Gy} &lt; 30%$, $V_{50 Gy} &lt; 50%$</td>
</tr>
<tr>
<td>Heart</td>
<td>Minimize</td>
</tr>
<tr>
<td>Liver</td>
<td>$V_{20 Gy} &lt; 20%$</td>
</tr>
<tr>
<td>Kidneys</td>
<td>$V_{20 Gy} &lt; 20%$</td>
</tr>
</tbody>
</table>

Nitsch, Marcus et al (2009)
General Results

- MU: VMAT < IMRT
- OARs: VMAT ≈ IMRT (directionality)
- Multiple / partial arcs needed
- Coplanar only tested

Nitsch, Marcus et al (2009)
General Results

• MU: VMAT < IMRT
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• Multiple / partial arcs needed
• Coplanar only tested

• Heterogeneity
  - bone growth problem
  - difficult to control & in evaluation
  - control points
  - mesh effects (45 collimator?)

Nitsch, Marcus et al (2009)

P Zygmanski: Normal tissue dose in pediatric VMAT (NEAAPM 2010)
Criteria for VMAT vs IMRT (RapidArc)

- Simpler, faster planning (opt = 1h & dose = 15min)
- Simpler, more MU-efficient
- Faster treatment
- Better or equivalent dose distribution
  - Coverage
  - Dose homogeneity (PTV) (opt & dose calc control points)
  - Critical structures
  - Medium-dose distribution
- Potential benefit for selected applications
  - prostate, SRS, SBRT, Pediatric etc

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Questions

• MU reduction $\rightarrow$ real dose reduction?

• TPS dose = measured dose (medium-low range)?

• Accurate low-dose measurement techniques?

• 2D?
Evaluation of VMAT vs IMRT

• Treatment planning
• Dose verification
  - methods (detector + MLC/gantry motion)
  - application

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Low-dose measurements

- TG-36 fetal dose
  - old open beam data / no MLC modulation

- Typical measurements done with an ion chamber
  - very cumbersome

- Monte Carlo simulations
  - are just “simulations” and require verification
Low-dose measurements

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- 2D ion chamber array (Matrixx)
Evaluation of Matrixx - setup

Han, et al (2010)

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Experimental MLC tests

- Static / rotating gantry
- "Open beam" / MLC gap tests
- IMRT / VMAT gap tests
- Simulated MLC effects

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Han, et al (2010)
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Evaluation of Matrixx - setup

- “Dark current” dose
- Angular dependence

Han, et al (2010)

P Zygmanski: Normal tissue dose in pediatric VMAT (NEAAPM 2010)
“Dark current” dose bias

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“Dark current” dose bias

\[ y = 0.00168x + 0.00310 \]

\[ R^2 = 0.99912 \]

Center
Hot
Cold
Linear (Center)

ROI dose (cGy)

Number of snaps

Han, et al (2010)

P Zygmanski: Normal tissue dose in pediatric VMAT (NEAAPM 2010)
“Dark current” dose bias

Han, et al (2010)

\[ y = 0.00168x + 0.00310 \]

\[ R^2 = 0.99912 \]

\[ R = \frac{D_{Mxx} - \delta - \beta \times D_{Mxx}}{D_{A12}} \]

Han, et al (2010)
"Dark current" dose bias

Han, et al (2010)

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Angular dependence of detector arrays

\[ \theta = \text{Wolfsberger, Wagar, et al (2009)} \]

\[ \text{P Zygmanski: Normal tissue dose in pediatric VMAT (NEAAPM 2010)} \]

\[ CF(\theta) = \frac{D(\theta)}{D_{\text{ref}}(\theta)} \]
Angular dependence of detector arrays

\[ \text{Peripheral Average} \]

\[ \text{Peripheral 10x10} \]

\[ \text{Peripheral fit} \]

\[ \text{Primary} \]

\[ CF(\theta) = \frac{D(\theta)}{D_{ref}(\theta)} \]

Han, et al (2010)
Total correction

\[ R = \frac{D_{Mxx} - \delta - \beta \times D_{Mxx}}{D_{A12}} \]

\[ CF(\theta) = \frac{D(\theta)}{D_{ref}(\theta)} \]

Han, et al (2010)
Uniform dose test: control points

Dose calc = 180 control points per 360°


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Uniform dose test: MLC position $x_{MLC}(t)$

Matrix-coronal = snap

$D(t)$ [%]

$x_{MLC}(t)$ [cm]


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**Uniform dose test: MLC position** $x_{MLC}(t)$

- **Matrix-coronal = snap**

- **Stable gantry**
- **Gantry fluctuations**

- **Film-axial**

- **$D(t)$ [%]**

- **$x_{MLC}(t)$ [cm]**


**P Zygmanski: Normal tissue dose in pediatric VMAT (NEAAPM 2010)**
Evaluation of VMAT vs IMRT

- Treatment planning
- Dose verification
  - methods
  - application (VMAT plans verification)
### TPS vs Measurement

**Han, et al (2010)**

**P Zygmanski: Normal tissue dose in pediatric VMAT (NEAAPM 2010)**

#### Graphs

<table>
<thead>
<tr>
<th>Gap10</th>
<th>Gap20</th>
<th>OB</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image1.png" alt="Graph 1" /></td>
<td><img src="image2.png" alt="Graph 2" /></td>
<td><img src="image3.png" alt="Graph 3" /></td>
</tr>
</tbody>
</table>

**VMAT tests / moving gantry**
TPS vs measurement

Pediatric VMAT plans

Han, et al (2010)
Pediatric VMAT plans

LD = low-dose = scatter
MD = medium dose = primary + scatter

Han, et al (2010)

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TPS vs measurement

Han, et al (2010)
Conclusions:
Low-dose verification with Matrixx

• LD (& to certain degree MD) measurements require custom corrections

• But good final dose agreement with reference ion chamber after correction can be achieved

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Conclusion: VMAT – dose verification (Eclipse)

• TPS - peripheral dose is underestimated 😞

• But less underestimated for VMAT than for IMRT 😊

• And not more than by 3cGy 😞

• Consequence: $V_{20\text{Gy}} \rightarrow V_{21\text{Gy}}$ 😞

• Medium dose range – sign / magnitude depend on the region (MLC motion, scatter, alignment) 😞

• But errors are smaller for VMAT than for IMRT 😊

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Conclusion: VMAT – dose verification

- Caution: LD/MD calc by other TPS may be quite different

- Experimental methods of TPS verification for LD/MD are recommended (at least for pediatric patients)
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