Improved safety, quality and efficiency in radiotherapy with automated health information technology

Deshan Yang, PhD

Learning objectives

• Understanding that automated physics software tool could be useful to detect errors, to improve patient safety and to improve workflow efficiency

• Understanding that machine learning based methods could be useful to extract physics knowledge from the clinical data and the extracted knowledge could be applied for safety and quality improvements
Goals – an automated HIT system

- Safety
- Efficiency
- Quality
- Consistency
- Responsiveness
- Cost reduction

- iCheck/ECCK/MU check
- Chart check assignment
- Auto new start list
- Auto report of Mosaiq data changes
- Auto dynalog QA (ADQ)
- Semi-auto weekly CC

- Tools are in clinical uses for 3+ years
- Are able to semi-automatically detect / catch 50% errors, mostly simple errors, based on simple value comparison and rules
- Additional errors are difficult to catch – our targets

Computer systems in RO

TPS = Treatment Planning System, TMS = Treatment Management System (Mosaiq, ARIA, etc.)
TDS = Treatment Delivery System (LINACs, HDRs), WMS = Workflow Management System (Whiteboard)
EMR = Electronic Medical Records, PACS = DICOM File Archive System
Physicist clinical workflow at WUSTL

- IMRT/VMAT/SBRT plan check
- New start chart check / physics 2nd check
  - Patient specific QA for IMRT, MU check for 2D/3D
- Weekly check
- Final check
- Check after 1st fraction for SBRT and other hypo-fractionated treatments

- Physicist daily coverage / machine QA / commissioning

Clinical computer systems

- Pinnacle TPS
- Eclipse TPS
  - Brachytherapy
  - External beam
  - Proton
- Gamma knife TPS
- MOSAIQ
- ARIA
- Viewray
- BrachyVision
- VelocityAI
- MimVista
- MU Check
Current situations in RO

- Charts are paperless
- A lot of computers
- Computers are used to do every work
- A lot of new and fantastic technologies: IMRT, IGRT, VMAT, SBRT, OBI, 4D motion management, ...
- We have not done our best job yet to assure patient safety and treatment quality
- New technologies require too much data and documents to work and check
- Charts in computer make my work slower instead of faster
- A lot of useful information in the patient data, but I never have time to go back to it to run an analysis or a study
- It does not make sense to use human to check data and documents in computers

Aims of HIT in RO

- To improve efficiency and clinical workflow
- To improve patient safety
- To improve the treatment quality
- To allow learning from previous results and mistakes
- Overall: to make use of computers and data in our computers to help us to do better job
General HIT workflow

- **TPS** – treatment plan parameters, images
- **TDS** – log files, treatment records
- **TMS** – treatment plan parameters, configuration, delivery records, documents
- **WMS** – treatment intent (MD order), QA results
- Files storages – documents, QA results
- **EMR** – patient medical records, lab results, diagnostic notes
## Data accessing methods

<table>
<thead>
<tr>
<th>System</th>
<th>Data accessing methods</th>
</tr>
</thead>
<tbody>
<tr>
<td>TMS (Mosaic, ARIA)</td>
<td>SQL query</td>
</tr>
<tr>
<td>TPS - Eclipse</td>
<td>SQL query, Eclipse API</td>
</tr>
<tr>
<td>TPS – Pinnacle</td>
<td>FTP</td>
</tr>
<tr>
<td>TDS (images, logs)</td>
<td>DICOM automatic forwarding, file sharing, SQL query</td>
</tr>
<tr>
<td>WMS</td>
<td>SQL query</td>
</tr>
<tr>
<td>EMR</td>
<td>SQL query</td>
</tr>
<tr>
<td>Stand-Alone Documents</td>
<td>Specific file content parser programs</td>
</tr>
<tr>
<td>(Word, PDF, Excel files)</td>
<td></td>
</tr>
</tbody>
</table>

## Data format and challenges

- Challenges – data accessibility and heterogeneity
- Common data formats
  - DICOM, database records via SQL query, C# objects (Eclipse API)
  - Plain text (with or without layouts)
  - Word, Excel and PDF files
- Native raw data formats
Example – WUSTL ECCK system

*ECCK = Electronic Chart Checking

Deshan Yang et al., Electronic chart checks in a paperless radiation therapy clinic, Medical Physics, 2012, 39(8), pp 4726-4732

Checking data

- Rule-based methods
  - Simple comparison
    - To data from different sources
    - To standard reference values
  - More complicated comparison
    - Data comparison with dependencies
    - Reference values are based on other conditions
- Knowledge-based methods
  - Mean, standard deviations
  - Machine learning methods

TPS – treatment plan parameters, images
TDS – log files, treatment records
TMS – treatment plan parameters, configuration, delivery records, documents
WMS – treatment intent (MD order), QA results
Files storages – documents, QA results
EMR – patient medical records, lab results, diagnostic notes
Example #1 - ECCK

- Initial plan check
  - Matching data from Pinnacle, DICOM and Mosaiq
  - Beam parameters
  - Patient site setup
  - Images and DRR attachments
  - Completeness of required documents
  - Prescriptions and treatment calendar
  - Notes

- Daily/weekly chart check
  - Beam delivery records versus planned beam parameters
  - Couch table position and trend
  - Documents
  - Rejections of beam portal images
  - Plots of different assessment data

Comparison between R&V, TPS, DICOM, PDF, treatment records, documents, …

ECCK examples

Physics Weekly Check

Physics New Start Plan Check

Deshan Yang et al., Electronic chart checks in a paperless radiation therapy clinic, Medical Physics, 2012, 39(8), pp 4726-4732
Example 3 – plan check for dosimetrist

• Problems with plan submission (to TMS/R&V)
  – Account for 30% - 50% of the reported clinical events
  – Including computer data transfer errors, human errors with documents and data entries in TMS/R&V
• Errors and inconsistencies cause redundant work, treatment delay and potential treatment errors

Deshan Yang et al., Electronic chart checks in a paperless radiation therapy clinic, Medical Physics, 2012, 39(8), pp 4726-4732

Beam name problems
Multiple isocenters used by one site

Deshan Yang et al., Electronic chart checks in a paperless radiation therapy clinic, Medical Physics, 2012, 39(8), pp 4726-4732
Automatic log QA for treatment deliveries

ADQ Programs
Automatically run every night to analyze patient beam deliveries in the previous day

Methods to check data

- Rule-based methods
  - Simple value comparison
  - More complicated data comparison with dependencies

- Knowledge-based methods
  - Mean, standard deviations
  - Machine learning methods

- Specialized error detection methods

To support dependencies and probabilities, and to detect advanced errors that cannot be quantitatively defined as rules.
Statistics and machine learning methods

- Regression and ANOVA
- Multivariate statistics
  - Principal component analysis (PCA)
- Probability distribution
  - Bayesian network (BNT)
- Machine learning
  - Classification
    - Support vector machine (SVM)
  - Cluster analysis

Data analysis – plan parameters

<table>
<thead>
<tr>
<th>Techniques</th>
<th>Major techniques</th>
<th>Treatment modalities</th>
<th>Treatment sites</th>
</tr>
</thead>
<tbody>
<tr>
<td>SMLC</td>
<td>2D</td>
<td>MVX</td>
<td>Brain</td>
</tr>
<tr>
<td>2D</td>
<td>IMRT</td>
<td>Electrons</td>
<td>Lung</td>
</tr>
<tr>
<td>AP/PA</td>
<td></td>
<td></td>
<td>Pelvis</td>
</tr>
<tr>
<td>ELECTRON BOOST</td>
<td></td>
<td></td>
<td>Head &amp; Neck</td>
</tr>
<tr>
<td>3D</td>
<td></td>
<td></td>
<td>Extremity</td>
</tr>
<tr>
<td>WEDGED PAIR</td>
<td>3D</td>
<td></td>
<td>Thorax</td>
</tr>
<tr>
<td>SBRT</td>
<td></td>
<td></td>
<td>Pelvic</td>
</tr>
<tr>
<td>CSA</td>
<td></td>
<td></td>
<td>Prostate</td>
</tr>
<tr>
<td>DMLC</td>
<td></td>
<td></td>
<td>Chest wall</td>
</tr>
<tr>
<td>EN FACE</td>
<td></td>
<td></td>
<td>Abdomen</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>TBI</td>
</tr>
</tbody>
</table>

S Liu, Y Wu, X Chang, H Li, Deshan Yang*, Automatic Pre-Delivery Verification Using Statistical Analysis of Consistencies in Treatment Plan Parameters by the Treatment Site and Modality, AAPM 2016
### 1D cluster analysis - MU/cGy ratio

![Error Bar Graph](image1.png)

Figure 1. An error bar graph of selected MU/cGy ratio for various input parameters. Bar represents the mean values for corresponding parameters, and the red error line represents the corresponding standard deviations.

![Histogram](image2.png)

Figure 2. An example histogram of the MU/cGy ratio for whole brain treatment (Brain + 2D). Mean value is 1.1, and the standard deviation is 0.02.

S Liu, Y Wu, X Chang, H Li, Deshan Yang*, Automatic Pre-Delivery Verification Using Statistical Analysis of Consistencies in Treatment Plan Parameters by the Treatment Site and Modality, AAPM 2016

### 2D cluster analysis

**MU/cGy ratio + averaged SSD:**

- **Chi-Square distribution**: sum of squared Gaussian data points
  \[
  \left( \frac{x}{\sigma_x} \right)^2 + \left( \frac{y}{\sigma_y} \right)^2 = s
  \]

- **For 95% confidence level:**
  \[
  P(s < 5.991) = 1 - 0.05 = 0.95
  \]
  \[
  \left( \frac{x}{\sigma_x} \right)^2 + \left( \frac{y}{\sigma_y} \right)^2 = 5.991
  \]

- **2D quadratic rules**: in the form of \([a, b, c, d, e, f]\)
  \[
  Error(x, y|95\%) = ax^2 + bxy + cy^2 + dx + ey + f = 0
  \]

- **90%, 95%, or 99% confidence levels**

S Liu, Y Wu, X Chang, H Li, Deshan Yang*, Automatic Pre-Delivery Verification Using Statistical Analysis of Consistencies in Treatment Plan Parameters by the Treatment Site and Modality, AAPM 2016

Plan data is more complicated. Cluster analysis not enough.
Bayesian network model

Advantages of clustering
- Answer probabilistic queries about single variables or variable combinations
- Handle numerical and/or categorical variables
- Learn probability distributions from data

Error detection mode:
\[ d^* = \arg \max_{d} p(d, a_1, \ldots, a_6 | s_1, \ldots, s_8) \]

Bayesian network model results

<table>
<thead>
<tr>
<th>Anomaly type</th>
<th># of anomaly type</th>
<th>True positive rate (%)</th>
<th>Positive predictive value (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 parameter</td>
<td>6</td>
<td>98.39</td>
<td>92.94</td>
</tr>
<tr>
<td>2 parameters</td>
<td>15</td>
<td>98.42</td>
<td>92.94</td>
</tr>
<tr>
<td>3 parameters</td>
<td>20</td>
<td>99.52</td>
<td>93.01</td>
</tr>
<tr>
<td>4 parameters</td>
<td>14</td>
<td>99.96</td>
<td>93.04</td>
</tr>
<tr>
<td>5 parameters</td>
<td>6</td>
<td>99.95</td>
<td>93.05</td>
</tr>
<tr>
<td>6 parameters</td>
<td>1</td>
<td>100</td>
<td>93.04</td>
</tr>
<tr>
<td>Avg.</td>
<td>99.37</td>
<td>93.00</td>
<td></td>
</tr>
</tbody>
</table>

6 parameters: total dose, fractions, number of fields, modality, technique, EQD
Methods to check data

- Rule-based methods
- Knowledge-based methods
- Specialized error detection methods
  - Plan quality evaluation, dose recalculation, dosimetry uncertainty evaluation, contour error detection

To support more advance physics QA tasks, e.g., knowledge-based plan quality evaluation, contour error detection

Online adaption dose check

Automatic secondary Monte Carlo dose re-calculation for Viewray plan adaptation cases

Deshan Yang, et al. A computer software tool to perform physics QA for MRI guided online radiation therapy treatment adaptation, under review at JACMP
Automatic plan quality check

Dose approximation to verify plan uncertainties

<table>
<thead>
<tr>
<th>Uncertainty types</th>
<th>Magnitude</th>
<th>Geometrical Transformation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Setup error - translational in X, Y, and Z directions</td>
<td>2 mm</td>
<td>Shift the composite dose volume by the same distance in left-right, anterior-posterior, and superior-inferior</td>
</tr>
<tr>
<td>Setup error - Couch rotational errors</td>
<td>$2^\circ$</td>
<td>Rotate the composite dose volume by the same angle around the y-axis</td>
</tr>
<tr>
<td>Gantry rotation errors</td>
<td>$1^\circ$</td>
<td>Rotate the per beam dose distribution by the same angle around the z-axis</td>
</tr>
<tr>
<td>Collimator errors</td>
<td>$1^\circ$</td>
<td>Rotate the per beam dose distribution along the beam central axis by the same angle</td>
</tr>
<tr>
<td>MLC leaf bank position errors</td>
<td>2 mm</td>
<td>Shift the per beam dose in the beam-eye view by the same magnitude, with the beam divergence considered (shift couch, gantry and collimator to $0^\circ$)</td>
</tr>
</tbody>
</table>

Combination of uncertainties: (a recent monthly machine QA)

$$D_c = D_0 + \frac{\partial D}{\partial U_1} \Delta U_1 + \frac{\partial D}{\partial U_2} \Delta U_2 + \frac{\partial D}{\partial U_3} \Delta U_3 + \ldots$$

Shi Liu, Deshan Yang, et al, A method to evaluate dosimetric effects on organs-at-risk for treatment delivery systematic uncertainties, Medical Physics, 44(4), April 2017
Dmax to OAR evaluation results

- **Worst case**: most significant change in Dmax to critical OARs
- Patient-specific and uncertainty-dependent
- Combination of multiple uncertainties (example from 08/2016 monthly QA report):
  1mm isocenter shift (P/R/I) + 0.5° gantry/collimator/couch + 1mm shift (R) MLC leaf bank

Shi Liu, Deshan Yang, et al. A method to evaluate dosimetric effects on organs-at-risk for treatment delivery systematic uncertainties, Medical Physics, 44(4), April 2017

Dmax to OAR results (cont’d)

**Figure.** (a) Isodose lines of clinical dose $D_2$ (solid lines) and geometrically approximate dose $D_2$ (dashed lines) due to 2 mm superior ISO-shift (worst case) for one brain plan

(b) DVHs with corresponding worst case of $D_{max}$ to
- brainstem (2mm superior isocenter shift, 58.5 - 59.7 Gy)
- chiasm (2mm left isocenter shift, 55.7 - 57.7 Gy)
- right optic nerve (2mm MLC bank leaf shift, 41.2 - 46.5 Gy)