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

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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

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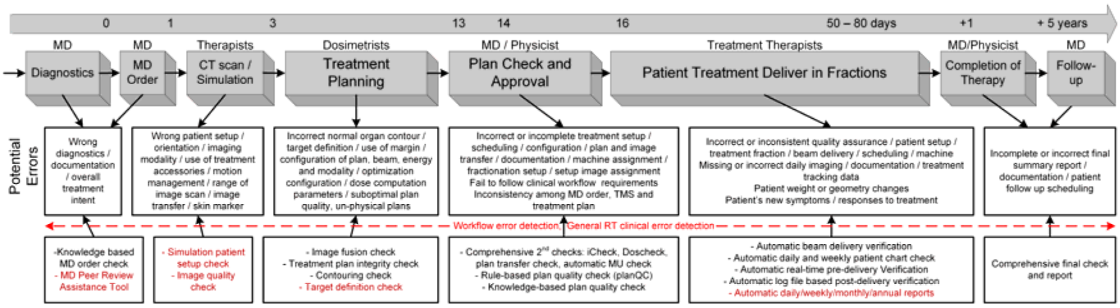
Goals – an automated HIT system



- 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

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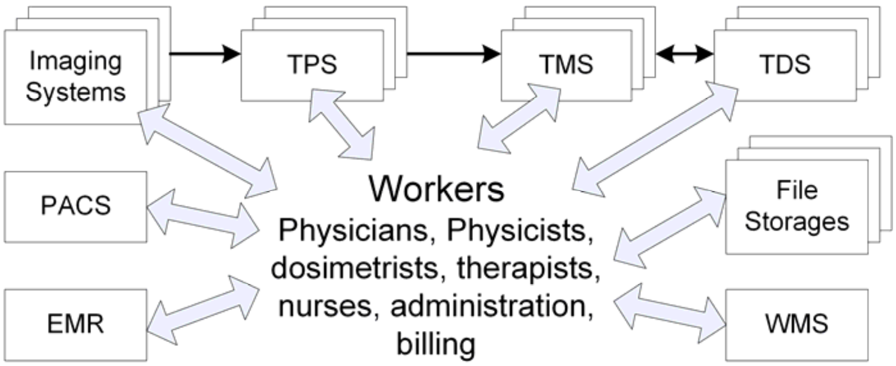
Computer systems in RO



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

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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

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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

7

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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

8

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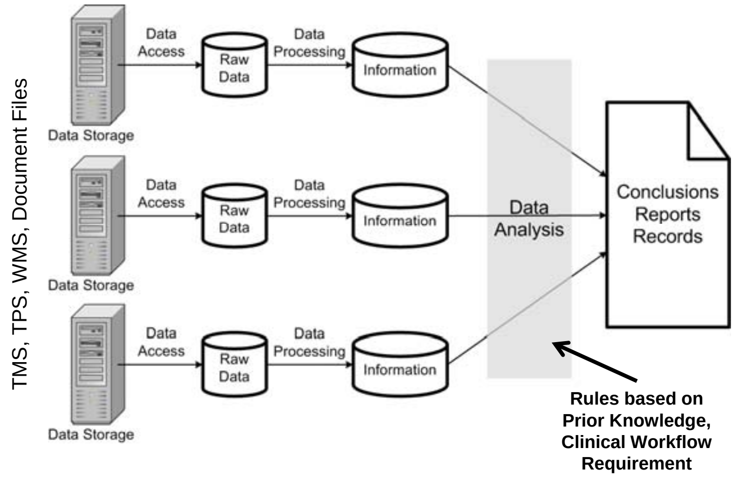
General HIT workflow



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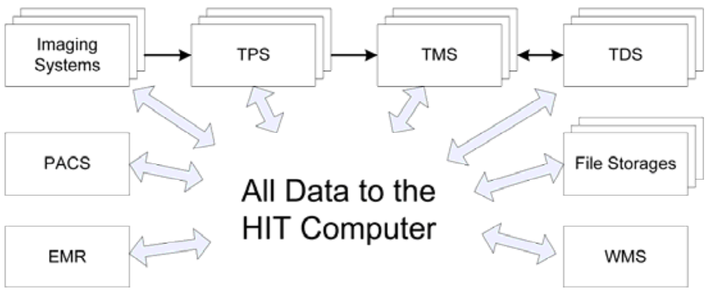
Data accessing

- 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



10

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Data accessing methods

System	Data accessing methods
TMS (Mosaiq, ARIA)	SQL query
TPS - Eclipse	SQL query, Eclipse API
TPS – Pinnacle	FTP
TDS (images, logs)	DICOM automatic forwarding, file sharing, SQL query
WMS	SQL query
EMR	SQL query
Stand-Alone Documents (Word, PDF, Excel files)	Specific file content parser programs

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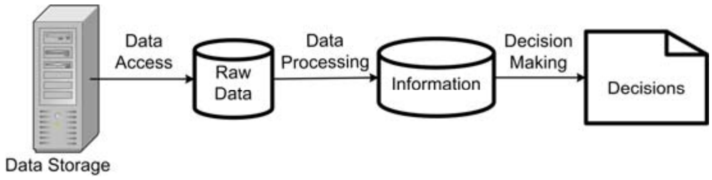
Data format and challenges

- 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



12

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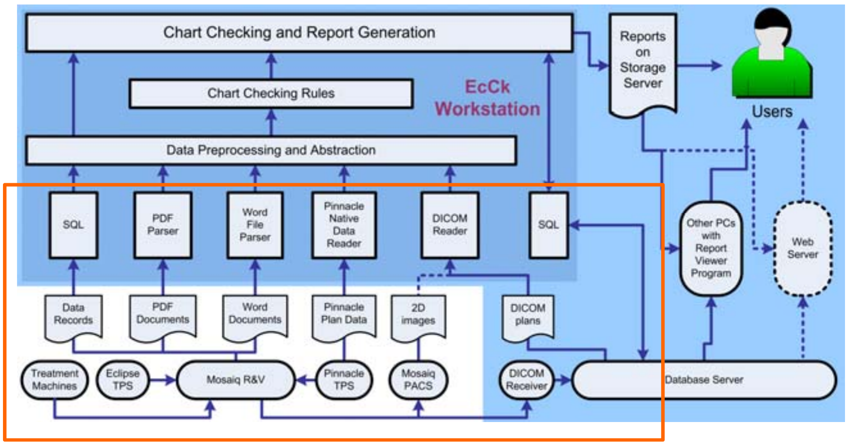
Example – WUSTL ECCK system



*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 source
    - 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

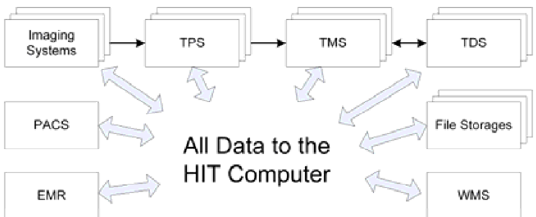
TDS – log files, treatment records

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



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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, …

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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

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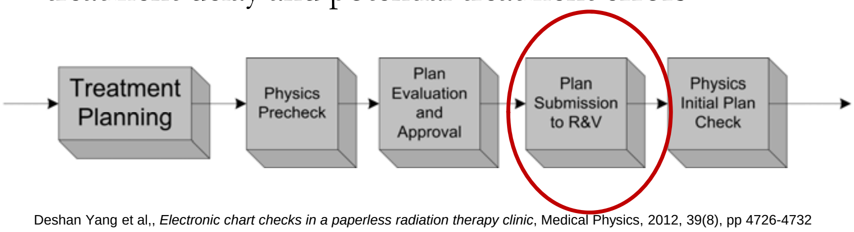
Example 3 – plan check for dosimetrist

- 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

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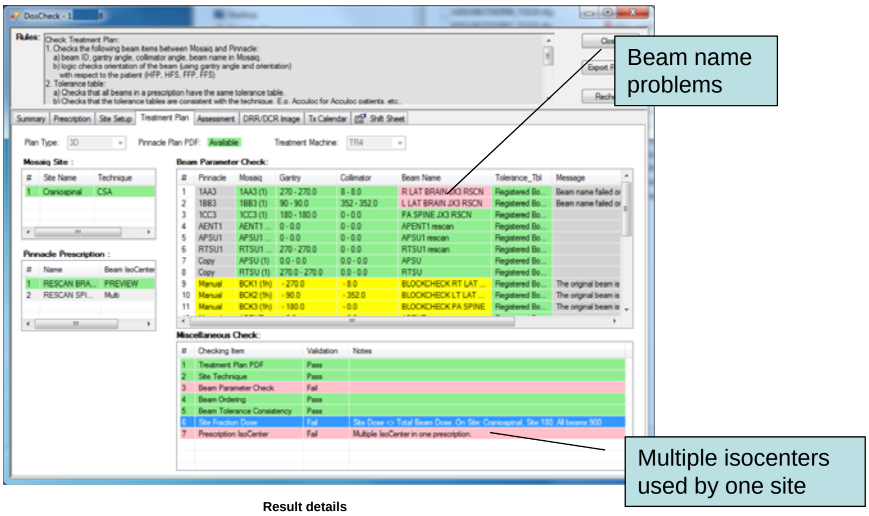

Result details

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

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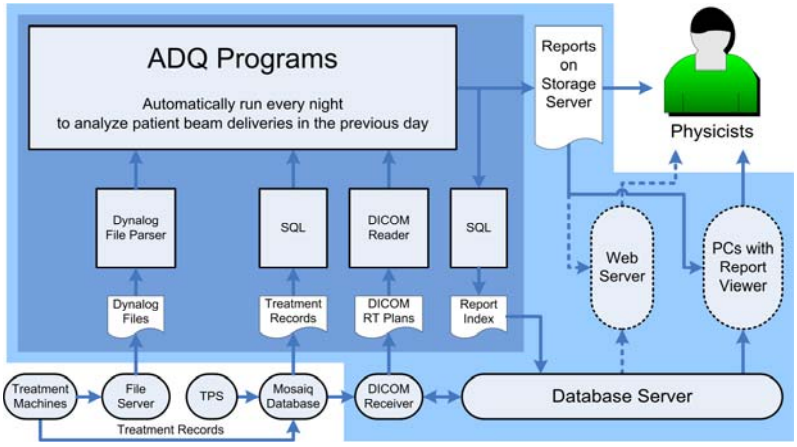
Automatic log QA for treatment deliveries



Y Wu, Deshan Yang, et al, *ADQ - a Software Tool That Automatically, Autonomously, Intelligently and Instantly Verify Patient Radiation Therapy Beam Deliveries, AAPM 2011*

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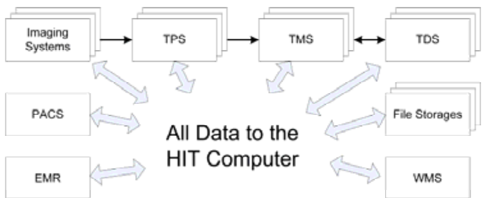
Methods to check data

- 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.

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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

21

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Data analysis – plan parameters

Techniques	
SMLC	TANGENTS
2D	TBI
AP/PA	ELECTRON BOOST
3D	WEDGED PAIR
SBRT	CSA
DMLC	EN FACE

Major techniques
2D
IMRT
3D

Treatment modalities
MVX
Electrons

Treatment sites	
Brain	Lung
Pelvis	Breast
Head & Neck	Extremity
Thorax	Pelvic
Prostate	Chest wall
Abdomen	TBI
CSA	Lymph nodal
Skin	Enface

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

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1D cluster analysis - MU/cGy ratio

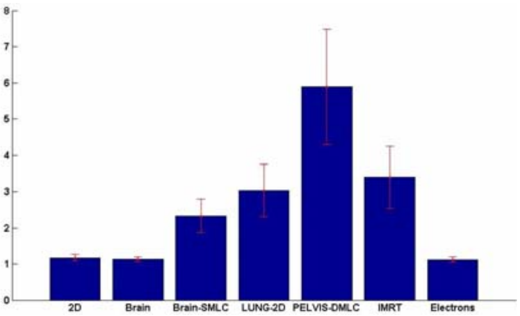

Figure 1, An error bar graph of selected MU/cGy ratio for various input parameters. Bar represents the mean values for corresponding parameters, and the red error line represents the corresponding standard deviations.

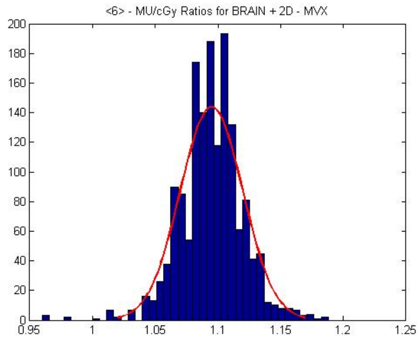

Figure 2. An example histogram of the MU/cGy radio for whole brain treatment (Brain + 2D). Mean value is 1.1, and the standard deviation is 0.02.

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

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2D cluster analysis

Plan data is more complicated. Cluster analysis not enough

MU/cGy ratio + averaged SSD:

- **Chi-Square distribution**: sum of squared Gaussian data points

$$\left(\frac{x}{a}\right)^2 + \left(\frac{y}{b}\right)^2 = s$$

- **For 95% confidence level:**

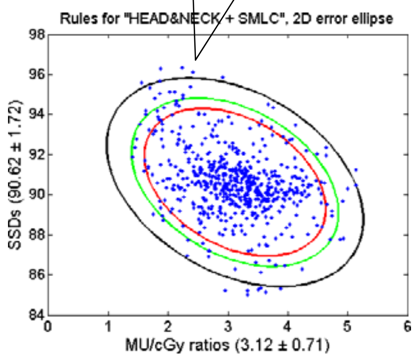
$$P(s < 5.991) = 1 - 0.05 = 0.95$$

$$\left(\frac{x}{\sigma_x}\right)^2 + \left(\frac{y}{\sigma_y}\right)^2 = 5.991$$

- **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

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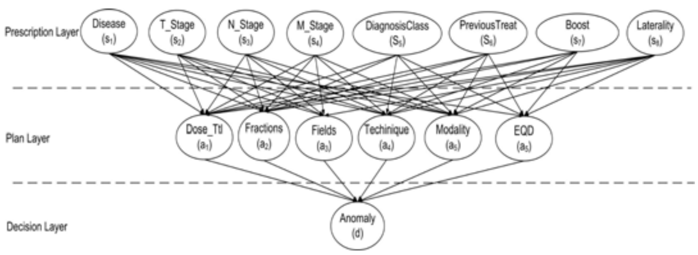
Bayesian network model



Error detection mode:

$$d^* = argmax_d p(d, a_1, \ldots, a_6 | s_1, \ldots, s_8)$$

Advantages of clustering

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

X Chang, A Kalet, S Liu, Deshan Yang*, A Unified Machine-Learning Based Probabilistic Model for Automated Anomaly Detection in the Treatment Plan Data, AAPM 2016

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Bayesian network model results

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

6 parameters: total dose, fractions, number of fields, modality, technique, EQD

X Chang, A Kalet, S Liu, Deshan Yang*, A Unified Machine-Learning Based Probabilistic Model for Automated Anomaly Detection in the Treatment Plan Data, AAPM 2016

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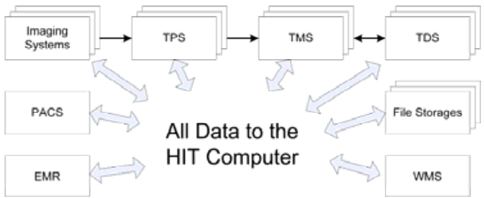
Methods to check data

- 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

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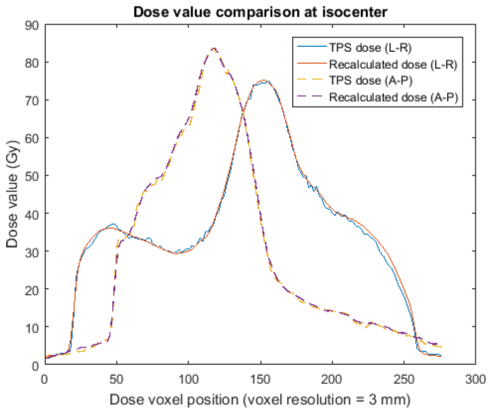
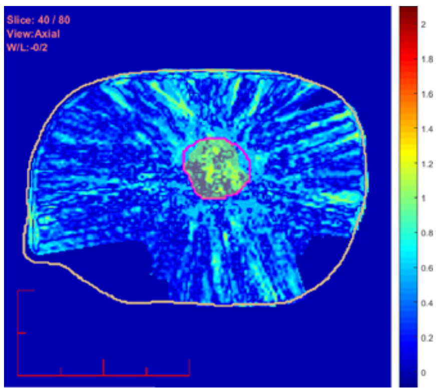
Online adaption dose check





3%/3mm Gamma Analysis

Automatic secondary Monto 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

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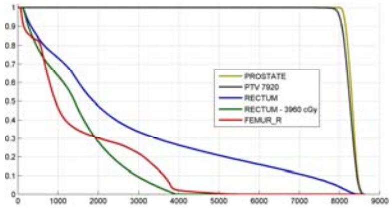
Automatic plan quality check

Plan Quality Check Results						
#	Rules	Goals	In the Plan	Pass/Fail	Priority	Comment
1	SPINALCORD, V[illegible] < 0.03 cc	V[illegible] < 0.0 cc	V[illegible] = 0.0 cc	Pass	1	Clinical guideline
2	CHIASM, V[illegible] < 1%	V[illegible] < 0.0 cc (1.0% of volume 1.9 cc)	V[illegible] = 0.0 cc	Pass	1	
3	OPTICNERVE_L, V[illegible] < 1%	V[illegible] < 0.0 cc (1.0% of volume 0.6 cc)	V[illegible] = 0.0 cc	Pass	1	
4	OPTICNERVE_R, V[illegible] < 1%	V[illegible] < 0.0 cc (1.0% of volume 0.7 cc)	V[illegible] = 0.0 cc	Pass	1	
5	BRAINSTEM, V[illegible] < 1%	V[illegible] < 0.3 cc (1.0% of volume 29.6 cc)	V[illegible] = 0.0 cc	Pass	1	
6	BRAIN, V[illegible] < 1%	V[illegible] < 15.5 cc (1.0% of volume 1549.3 cc)	V[illegible] = 0.0 cc	Pass	1	
7	SPINALCORD, D_{max} < 4500	D_{max} < 4500.0 cGy	D_{max} = 4082.0 cGy	Pass	2	
8	SPINALCORD_PRV, D_{max} < 4500	D_{max} < 4500.0 cGy	D_{max} = 5905.0 cGy	Fail	2	
9	SPINALCORD, D_{max} < 4000	D_{max} < 4000.0 cGy	D_{max} = 4082.0 cGy	Fail	3	
10	OPTICNERVE_L, D_{max} < 5400	D_{max} < 5400.0 cGy	D_{max} = 63.0 cGy	Pass	3	
11	OPTICNERVE_R, D_{max} < 5400	D_{max} < 5400.0 cGy	D_{max} = 68.0 cGy	Pass	3	
12	CHIASM, D_{max} < 5400	D_{max} < 5400.0 cGy	D_{max} = 67.0 cGy	Pass	3	
13	BRAINSTEM, D_{max} < 5400	D_{max} < 5400.0 cGy	D_{max} = 489.0 cGy	Pass	3	
14	BRAINSTEM, D_{mean} < 3600	D_{mean} < 3600.0 cGy	D_{mean} = 122.0 cGy	Pass	4	
15	PTV 7000 - jxl, D[illegible] > 95%	D[illegible] > 6650.0 cGy (95.0% of Rx=7000 cGy)	D[illegible] = 6163.0 cGy	Fail	4	
16	PTV 5600 - jxl, D[illegible] > 95%	D[illegible] > 5320.0 cGy (95.0% of Rx=5600 cGy)	D[illegible] = 4907.0 cGy	Fail	4	
17	PTV3, D[illegible] > 95%	Structure is not defined			4	
18	PTV 7000 - jxl, D_{max} < 110%	D_{max} < 7700.0 cGy (110.0% of Rx=7000 cGy)	D_{max} = 7646.0 cGy	Pass	4	
19	BRAIN, D_{max} < 6000	D_{max} < 6000.0 cGy	D_{max} = 514.0 cGy	Pass	5	



	ROI	Metric	Op	Threshold	Condition	Priority	Explanation
1	PROSTATE	Dmean	>	98%	1	1	Clinical guideline
2	PTV	D98%	>	100%	1	1	
3	PTV	V>110%	<	2%	1	1	
4	PTV	V>98%	>	99%	1	1	
5	RECTUM	V>6000...	<	17%	1	2	
6	RECTUM	V>4000...	<	35%	1	2	
7	BLADDER	V>6000...	<	25%	1	2	
8	BLADDER	V>4000...	<	50%	1	2	
9	LT FEMUR	V>5000...	<	10%	1	3	
10	RT FEMUR	V>5000...	<	10%	1	3	
11	SMALL BOWEL	V>5000...	<	150cc	1	3	
12	LARGE BOWEL	V>5000...	<	150cc	1	3	
13	BOWEL	V>5000...	<	150cc	1	3	
14	RECTUM - 50%	NOGAP			1	4	50% isodose line crossin
15	HOTSPOT - PTV	Volume	=	0	1	5	Hot spot must be inside F

Deshan Yang, et al, A Computer Software Program to Perform Comprehensive Plan Quality Evaluation, AAPM 2013

29

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Dose approximation to verify plan uncertainties

Uncertainty types	Magnitude	Geometrical Transformation
Setup error - translational in X, Y and Z directions	2 mm	Shift the composite dose volume by the same distance in left-right, anterior-posterior, and superior-inferior
Setup error - Couch rotational errors	2°	Rotate the composite dose volume by the same angle around the y-axis
Gantry rotation errors	1°	Rotate the per beam dose distribution by the same angle around the z-axis
Collimator errors	1°	Rotate the per beam dose distribution along the beam central axis by the same angle
MLC leaf bank position errors	2 mm	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°)

Combination of uncertainties: (a recent monthly machine QA)

$$D_G = D_o + \frac{\partial D}{\partial U_1}\Delta U_1 + \frac{\partial D}{\partial U_2}\Delta U_2 + \frac{\partial D}{\partial U_3}\Delta U_3 + \cdots$$

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

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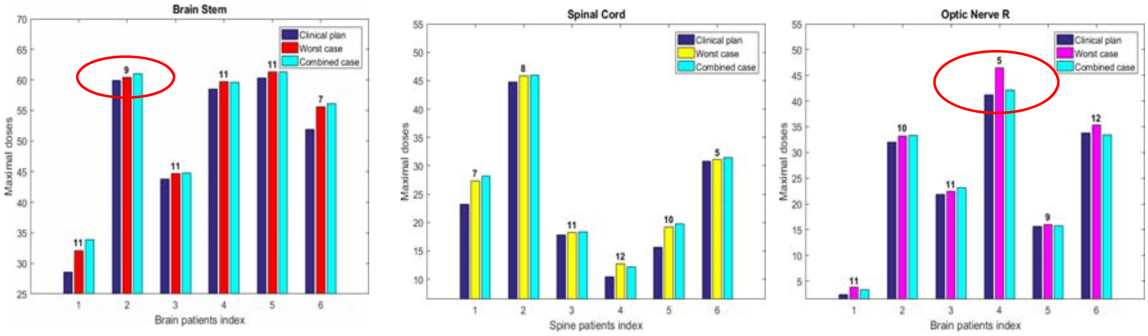
Dmax to OAR evaluation results



- ❑ **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

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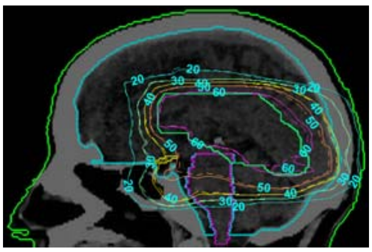
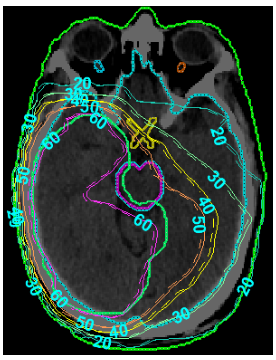
Dmax to OAR results (cont'd)





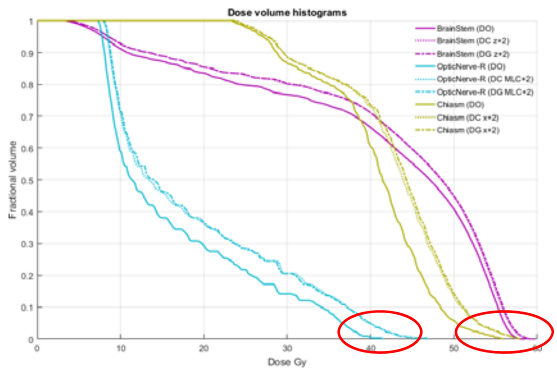


Figure. (a) Isodose lines of clinical dose D_O (solid lines) and geometrically approximate dose D_G (dashed lines) due to 2 mm superior ISO-shift (worst case) for one brain plan

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

(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)

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