Recent Advancements in Quality Assurance for Radiation Therapy: Advances for Autonomous Linac QA

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Disclosure

I have no conflicts of interest to disclose.

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Modern digital Linacs

- FFF beams, Dynamic/Virtual wedges…
- 6D Couch
- MLC
- Imaging Systems: *kV, MV, CBCT…*
- Respiratory gating
- Special techniques: *IMRT/VMAT, SRS/SBRT…*

Varian TrueBeam STx with Brainlab ExacTrac

TG-142: A comprehensive Linac QA Guideline

Task Group 142 report: Quality assurance of medical accelerators[a)]

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- Dosimetry
- Mechanical
- Safety
- MLC
- Imaging: kV, MV, CBCT
- Respiratory gating
- Special procedures: IMRT/VMAT, SRS/SBRT, TBI,…

Frequency:

- Daily
- Monthly
- Annually

Need for Autonomous QA

- QA for a modern Linac has been extremely extended with new components/functions added
- QA has become a complicated and very time consuming task

Table 3. Time (hours) spent undertaking linear accelerator QC testing

Time category	Minimum value	First quartile	Mean	Third quartile	Maximum value
Total machine time (hours per linear accelerator per month)	3.0	10.0	15.0	20.0	35.0
Total time including offline analysis (hours per linear accelerator per month)	5.0	13.1	19.5	26.2	56.0
Total time for patient-specific IMRT QC per patient	0.0	1.0	1.5	2.1	10.0

Autonomous QA: ***More Efficient, stable and accurate***

Palmer A et al, *Br. J. Radiol.* 2012(**85**) e1067–73

An Ideal Autonomous QA Process

Automatic Delivery & Data Acquisition

↓

Automatic Data Process

↓

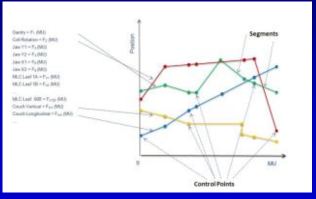
Automatic Analysis & Reporting

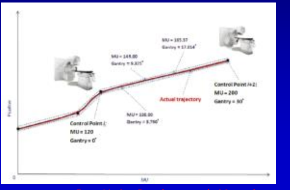
Hardware + Software

- One button QA
- Self-calibration
- Phantom pose invariant
- Reduce/Remove operator dependence
- Analyze results and generate QA report

Programmable Automatic Delivery/Operation

Control points and delivery trajectory

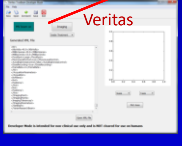




From Varian Developer mode Manual

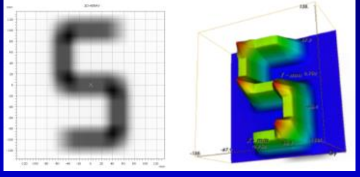
Varian TrueBeam Developer Mode

Control all motion axes, beam delivery and imaging through programmable XML Beam scripts

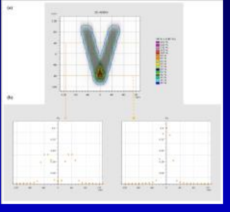


From Varian Developer mode Manual

Simple Examples



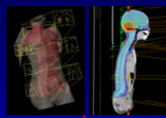
Produced by couch motion



(a) Resulting radiation pattern for Varian 'V' produced solely by couch motion (b) The left-right symmetry indicates high geometrical accuracy and stability of the automated couch motion

Courtesy of Ben Fahimian

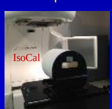
Complicated Examples



Courtesy of Ben Fahimian

TrueBeam Machine Performance Check (MPC)

+



Geometry Check

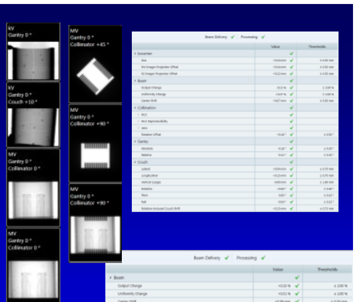
- Isocenter size and location
- Coincidence of radiation isocenter with kV&MV imager isocenters
- Gantry/Collimator rotation accuracy
- Jaw positioning accuracy
- MLC positioning accuracy
- 6D couch positioning accuracy

Beam Constancy check

- Beam output change
- Beam uniformity
- Beam center change

TrueBeam MPC

- Data is automatically acquired for pre-set gantry, collimator, MLC, and couch positions with/without IsoCal phantom
- Data(Images) automatically is processed
- Results are automatically analyzed and reported for evaluation
- Reports and data are automatically generated and saved for further offline analyzed



Barnes et al. Appl Clin Med Phys 2017; 18:3   Clivio et al. Radiation Oncology (2015) 10:97

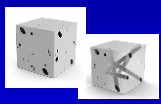
Autonomous Imaging QA

Daily Imaging QA

- *Imaging and treatment coordinate coincidence*
- Couch positioning/repositioning
- Winston-Lutz test

1. An XML script loaded in TrueBeam developer mode to automatically take MV images and CBCT images
2. Check the embedded BBs positions to verify coordinate coincidence

Winston-Lutz test kit from BrainLAB



MIMI Phantom from Standard Imaging Inc.

Gilmer Valdes et al, *JACMP, Vol. 16, No. 4, 2015*

Daily Imaging QA

Couch positioning/repositioning

Couch shift a random number (0~2cm) in three directions → Take CBCT → Registration and repositioning → Take verification CBCT

An XML script

Winston-Lutz test

1. An XML Script is used to automatically acquire eight MV images with different Gantry and Couch positions.
2. An in-house developed software to process data and report the results

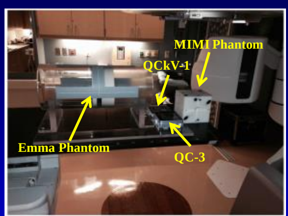
https://www.youtube.com/watch?v=JwOvALjRgqE

Gilmer Valdes et al, *JACMP, Vol. 16, No. 4, 2015*

Monthly imaging QA

- Image quality
- kV, MV and CBCT and treatment coordinate coincidence

1. An XML Script is used to automatically acquire images with different Couch positions.
2. An in-house developed software to process data and report the results



In-house phantom mount for monthly QA

Table 1. Imaging QA time (mins), physcist vs. full automation.

QA	*Physicists*	*Full Automation*
Daily QA	14.3±2.4	4.2±0.7
Winston-Lutz Test	29.1±6.2	3.1±0.9
Imaging monthly QA without geometry calibration and EPID position and reproducibility	58.7±6.6	19.3±1.0
Imaging monthly QA	70.7±8.0	21.8±0.6

Results: Physicists vs. Auto QA

Gilmer Valdes et al, *JACMP, Vol. 16, No. 4, 2015*

Autonomous QA at Stanford

Direct visualization of Radiation

When radiation irradiates a radio-luminescent sheet fabricated from a mixture of GOS:Tb and PDMS, the irradiated area become visible.

Is this possible to use this to improve our QA processes?

Jenkins C H *et al* 2015 *Med. Phys.* **42** 5–13

Courtesy of Cesare H Jenkins

Autonomous Mechanical QA

- Light Field/Radiation field coincidence
- Jaw position indicators
- Cross-hair centering
- Couch position indicators
- Laser localization

Mechanical		
Light/radiation field coincidence[b]		2 mm or 1% on a side
Light/radiation field coincidence[b] (asymmetric)		1 mm or 1% on a side
Distance check device for lasers compared with front pointer		1mm
Gantry/collimator angle indicators (@ cardinal angles) (digital only)		1.0°
Accessory trays (i.e., port film graticle tray)		2 mm
Jaw position indicators (symmetric)[c]		2 mm
Jaw position indicators (asymmetric)[d]		1 mm
Cross-hair centering (walkout)		1 mm
Treatment couch position indicators[e]	2 mm/1°	2 mm/1°
Wedge placement accuracy		2 mm
Compensator placement accuracy[f]		1 mm
Latching of wedges, blocking tray[g]		Functional
Localizing lasers	±2 mm	±1 mm

Components for Autonomous QA

Hardware + **XML Script** + **Software**

Hardware:
- Phantom
- Camera
- Laptop

XML Script: Automatic image acquisition, machine operations in Truebeam Developer mode

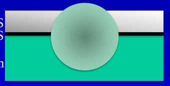
Software:
- Image process
- Data analysis
- Result report

Phantom

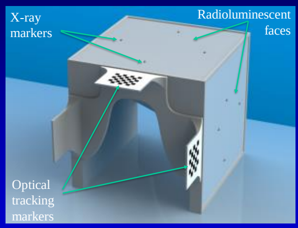
- Structure fabricated on a MakerBot Z18 3D printer
- 2.38 mm stainless steel balls
- PDMS
- $Gd_2O_2S:Tb$

Steel ball

PDMS
GOS
Phantom



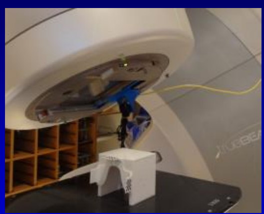
2.5 mm



Jenkins C H et al Phys. Med. Biol. 61 (2016) L29

Camera

- Power over Ethernet (POE) machine vision camera
  - Single cable connection
  - 5mm f/2.5 S-mount lens
- 3D printed holder that connects to LINAC tray



Automatic Delivery/Operations

XML Script to implement:

- Turn on/off field light
- Set jaw positions
- Beam on
- Rotate gantry
- Turn on/off laser
- Treatment couch motions
- kV imaging
- Set MLC

Courtesy of Cesare H Jenkins

Image Processing

- Image identification and capture
- Transformation
- Analysis

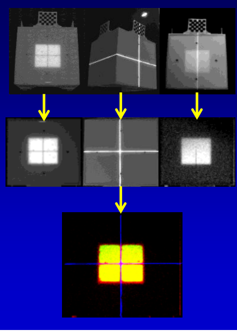
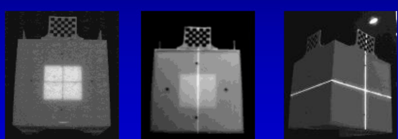


Image identification and capture

Key images were identified based on:

- Known delivery sequence
- Motion detection algorithm

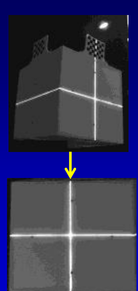


Light Field · Radiation Field · Left Laser

Transformation

1. Transform the pixels corresponding to the phantom face into a calibrated image space
2. The transformation was determined as the linear transform that transforms the locations of the four fiducials to their aligned locations within the calibrated image space
3. The calibrated images were analyzed to identify the locations of salient features such as field edges, cross-hairs and lasers.

- *Self-calibration*
- *Correct for variations in setup*



Analysis

- Field Edges
  -Fit logistic function to find location of half value
- Crosshairs and lasers
  -Gaussian curve fitting
- kV and MV images
  -Image center is projected into the calibrated coordinate space

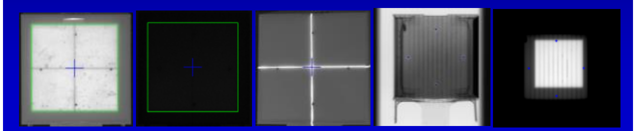
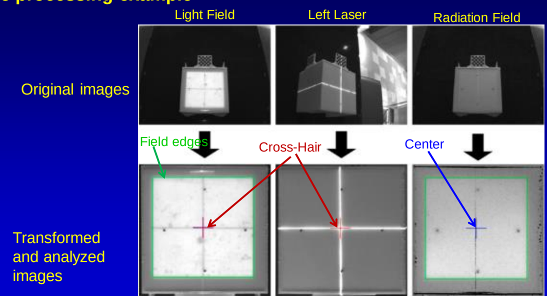


Image processing example



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Self-calibration Assessment

Table 1. Self-calibration assessment. *Six measurements*

Ten measurements → Single phantom setup; *Six measurements* → Varied phantom setup

Measurement	Single phantom setup: Light field cross-hair coincidence (mm)	Single phantom setup: Light/radiation field coincidence (mm)	Varied phantom setup: Light field cross hair coincidence (mm)	Varied phantom setup: Light/radiation field coincidence (mm)
Center shift X	-0.16 ± 0.03	0.21 ± 0.03	-0.10 ± 0.05	0.17 ± 0.06
Center shift Y	-0.80 ± 0.03	0.61 ± 0.06	-0.86 ± 0.09	0.60 ± 0.16
$X1$ difference		-0.19 ± 0.06		-0.19 ± 0.12
$X2$ difference		0.60 ± 0.05		0.53 ± 0.06
$Y1$ difference		0.99 ± 0.05		0.87 ± 0.11
$Y2$ difference		0.24 ± 0.11		0.32 ± 0.25

Note: Mean and standard deviations for light field to cross-hair and light/radiation field coincidence measurements made with a single setup versus a unique phantom setup for each measurement.

Variations in setup has no significant influence in the measurement results

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Auto QA vs. Manual QA

- Robust automated performance
- Accurate
  - *Be able to achieve 0.1mm~0.2mm accuracy, Better/Equivalent to current clinical practice*
- Repeatable
  - *Invariant to setup*
- More Efficient: ~10 min vs. manual 1~2 hours
  - *Set up: 7:00 min*
  - *Plan delivery: 1:21 min*
  - *Export DICOM: 1:00 min*
  - *Clean up: 2:00 min*

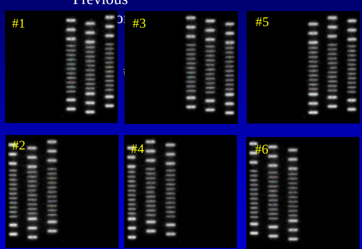
Table 2. System results compared to existing methods.

Light field/ radiation alignment	Symmetric beams	Center shift X (mm)	Center shift Y (mm)	Width difference (mm)	Height difference (mm)
Auto	5 × 5 cm	−0.02 ± 0.05	0.68 ± 0.11	−0.58 ± 0.05	−0.59 ± 0.09
Auto	10 × 10 cm	−0.21 ± 0.07	0.96 ± 0.12	−0.63 ± 0.15	−0.94 ± 0.31
FC-2	*15 × 15 cm*	*−0.19*	*0.40*	*−0.30*	*0.00*
	Asymmetric beams		Difference in position (mm)		
	(X1, X2, Y1, Y2)	X1	X2	Y1	Y2
Auto	(−3, 4, −3, 4) (cm)	0.23 ± 0.03	−0.39 ± 0.05	−0.26 ± 0.06	−0.95 ± 0.07
Jaw position indicators	Symmetric beams	Width Difference (mm)	Height Difference (mm)		
Auto	5 × 5 cm	−0.76 ± 0.02	−1.73 ± 0.06		
Auto	10 × 10 cm	−0.46 ± 0.16	−1.71 ± 0.19		
Iso-align	*5 × 5 cm*	*0.0*	*−2.0*		
Iso-align	*10 × 10 cm*	*0.0*	*−2.0*		
	Asymmetric beams		Difference in position (mm)		
	(X1, X2, Y1, Y2)	X1	X2	Y1	Y2
Auto	(−3, 4, −3, 4) (cm)	0.06 ± 0.06	0.80 ± 0.03	1.40 ± 0.16	0.63 ± 0.21
Iso-align	*(−5, 2.5, −5, −2.5) (cm)*	*0.0*	*1.0*	*1.0*	*1.0*
Cross-hair centering	Center shift X (mm)	Center shift Y (mm)	Walkout (mm)		
Auto	−0.35 ± 0.03	0.77 ± 0.01	0.87 ± 0.12		
FC-2/Iso-align	*−0.25*	*0.67*	*0.5*		
Couch position	Shifts (lat., long.) (mm)	Lat. (mm)	Long. (mm)		
Auto	(30, 30)	30.17 ± 0.25	30.22 ± 0.15		
Ruler	*(200, 300)*	*200.5*	*300.4*		
Laser localization (relative to cross hairs)	Center shift X (mm)	Center shift Y (mm)			
Auto	0.19 ± .30	−0.26 ± 0.13			
Iso-align	*0.25*	*−0.25*			

Note: Summary of tests performed by the autonomous system (mean ± standard deviation) and comparison to current QA techniques (shown in italics).

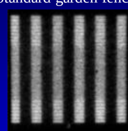
Linac MLC QA

Previous



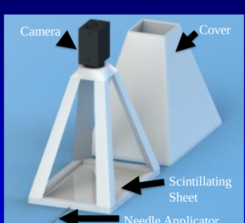
Sum

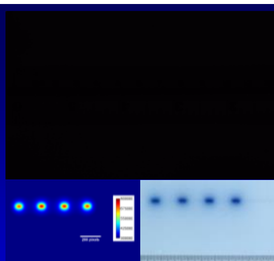
Standard garden fence



1. Automatic recognize leaves without extra device.
2. Avoid cross-talk in between; analysis will be based on separate images

Autonomous HDR QA





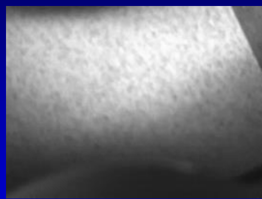
- Positioning: 1.99 ± .02 cm with the system while the result from autoradiography was 2.00 ± .03 cm
- Timing: 1 second were determined to be 1.01 ± .02 second

Courtesy of Cesare H Jenkins and Ben Fahimian

Cyberknife IRIS/MLC QA

Wireless camera

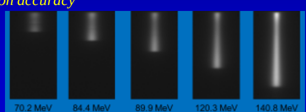
Real-time field of view



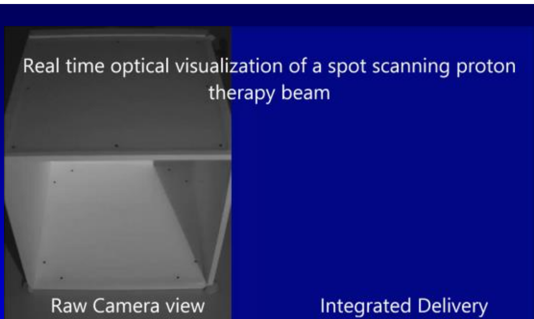
Discrete Spot Scanning Proton Beam Therapy

- MeV protons delivered in bursts to a single spot
- Spot can be steered in XY, modulating energy controls Bragg peak depth (Z)
  - Spot delivery and modulation occurs on millisecond time scale
- Hollow cubic phantom
- CMOS cameras

Spot location accuracy



Courtesy of Cesare H Jenkins



Courtesy of Cesare H Jenkins

Summary

- QA for a modern Linac has become a complicated and very time consuming task
- Programmable automatic delivery/operations are available for modern digital Linacs
- Autonomous QA has the potential to provide QA procedures with high efficiency and less operator/setup variation dependence
- Autonomous QA presents an attractive option for future Linac QA procedures

Thank You!