QA for Modern Radiation Therapy: Autonomous QA Strategy for Digital Linacs

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Disclosure

I have no conflicts of interest to disclose.

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Objectives

- Understand the complex and time consuming nature of quality assurance (QA) for a modern Linac
- Understand the programmable features of digital Linacs
- Understand the advantages and general process of autonomous QA for digital Linacs

Outlines

- Quality assurance (QA) for a modern medical Linac
- An overview of the programmable features of digital Linacs
- Autonomous QA for digital Linacs
- Summary

QA for A Modern Medical Linac: TG-142

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

Daily QA

- Dosimetry
- Mechanical
- Safety
- Imaging

- EDW/Virtual/Universal wedge: functional
- MLC: Weekly Picket Fence

TABLE VI. Imaging.

Procedure	Application-type tolerance non-SRS/SBRT	SRS/SBRT
Daily[a]		
Planar kV and MV (EPID) imaging		
Collision interlocks	Functional	Functional
Positioning/repositioning	≤2 mm	≤1 mm
Imaging and treatment coordinate coincidence (single gantry angle)	≤2 mm	≤1 mm
Cone-beam CT (kV and MV)		
Collision interlocks	Functional	Functional
Imaging and treatment coordinate coincidence	≤2 mm	≤1 mm
Positioning/repositioning	≤1 mm	≤1 mm

TABLE I. Daily.

Procedure	Machine-type tolerance Non-IMRT	IMRT	SRS/SBRT
Dosimetry			
X-ray output constancy (all energies)			
Electron output constancy (weekly, except for machines with unique e-monitoring requiring daily)		3%	
Mechanical			
Laser localization	2 mm	1.5 mm	1 mm
Distance indicator (ODI) @ iso	2 mm	2 mm	2 mm
Collimator size indicator	2 mm	2 mm	1 mm
Safety			
Door interlock (beam off)		Functional	
Door closing safety		Functional	
Audiovisual monitor(s)		Functional	
Stereotactic interlocks (lockout)	NA	NA	Functional
Radiation area monitor (if used)		Functional	
Beam on indicator		Functional	

Monthly QA

- Dosimetry
- Mechanical
- Safety
- Gating
- Wedge factors
- MLC
- Imaging

Monthly	
Setting vs radiation field for two patterns (non-IMRT)	2 mm
Backup diaphragm settings (Elekta only)	2 mm
Travel speed (IMRT)	Loss of leaf speed >0.5 cm/s
Leaf position accuracy (IMRT)	1 mm for leaf positions of an IMRT field for four cardinal gantry angles. (*Picket fence* test may be used, test depends on clinical planning-segment size)

TABLE II. Monthly.

Procedure	Machine-type tolerance: Non-IMRT	IMRT	SRS/SBRT
Dosimetry			
X-ray output constancy			
Electron output constancy		2%	
Backup monitor chamber constancy			
Typical dose rate[a] output constancy	NA	2% (@ IMRT dose rate)	2% (@ stereo dose rate, MU)
Photon beam profile constancy		1%	
Electron beam profile constancy		1%	
Electron beam energy constancy		2%/2 mm	
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°	1 mm/0.5°
Wedge placement accuracy		2 mm	
Compensator placement accuracy[f]		1 mm	
Latching of wedges, blocking tray[g]		Functional	
Localizing lasers	±2 mm	±1 mm	<±1 mm
Safety			
Laser guard-interlock test		Functional	
Respiratory gating			
Beam output constancy		2%	
Phase, amplitude beam control		Functional	
In-room respiratory monitoring system		Functional	
Gating interlock		Functional	

Monthly QA---Imaging

EPID, kV imaging, CBCT

- Safety and functional
- Mechanical
- OBI isocenter accuracy
- Couch shift accuracy
- Image quality

Monthly

Planar MV imaging (EPID)		
Imaging and treatment coordinate coincidence (four cardinal angles)	≤2 mm	≤1 mm
Scaling[b]	≤2 mm	≤2 mm
Spatial resolution	Baseline[c]	Baseline
Contrast	Baseline	Baseline
Uniformity and noise	Baseline	Baseline
Planar kV imaging[d]		
Imaging and treatment coordinate coincidence (four cardinal angles)	≤2 mm	≤1 mm
Scaling	≤2 mm	≤1 mm
Spatial resolution	Baseline	Baseline
Contrast	Baseline	Baseline
Uniformity and noise	Baseline	Baseline
Cone-beam CT (kV and MV)		
Geometric distortion	≤2 mm	≤1 mm
Spatial resolution	Baseline	Baseline
Contrast	Baseline	Baseline
HU constancy	Baseline	Baseline
Uniformity and noise	Baseline	Baseline

Annual QA

- Dosimetry
- Mechanical
- Safety
- Gating
- Wedge angles
- MLC
- Imaging

Safety	
Follow manufacturer's test procedures	Functional
Respiratory gating	
Beam energy constancy	2%
Temporal accuracy of phase/amplitude gate on	100 ms of expected
Calibration of surrogate for respiratory phase/amplitude	100 ms of expected
Interlock testing	Functional

TABLE III. Annual.

Procedure	Machine-type tolerance		
	Non-IMRT	IMRT	SRS/SBRT
Dosimetry			
X-ray flatness change from baseline		1%	
X-ray symmetry change from baseline		±1%	
Electron flatness change from baseline		1%	
Electron symmetry change from baseline		±1%	
SRS arc rotation mode (range: 0.5–10 MU/deg)	NA	NA	Monitor units set vs delivered: 1.0 MU or 2% (whichever is greater) Gantry arc set vs delivered: 1.0° or 2% (whichever is greater)
X-ray/electron output calibration (TG-51)		±1% (absolute)	
Spot check of field size dependent output factors for x ray (two or more FSs)		2% for field size $<4\times4$ cm^2, 1% $\geq4\times4$ cm^2	
Output factors for electron applicators (spot check of one applicator/energy)		±2% from baseline	
X-ray beam quality (PDD_{10} or TMR_{10}^{20})		±1% from baseline	
Electron beam quality (R_{50})		±1 mm	
Physical wedge transmission factor constancy		±2%	
X-ray monitor unit linearity (output constancy)	±2% ≥5 MU	±5% (2–4 MU), ±2% ≥5 MU	±5% (2–4 MU), ±2% ≥5 MU
Electron monitor unit linearity (output constancy)		±2% ≥5 MU	
X-ray output constancy vs dose rate		±2% from baseline	
X-ray output constancy vs gantry angle		±1% from baseline	
Electron output constancy vs gantry angle		±1% from baseline	
Electron and x-ray off-axis factor constancy vs gantry angle		±1% from baseline	
Arc mode (expected MU, degrees)		±1% from baseline	
TBI/TSET mode		Functional	
PDD or TMR and OAF constancy		1% (TBI) or 1 mm PDD shift (TSET) from baseline	
TBI/TSET output calibration		2% from baseline	
TBI/TSET accessories		2% from baseline	
Mechanical			
Collimator rotation isocenter		±1 mm from baseline	
Gantry rotation isocenter		±1 mm from baseline	
Couch rotation isocenter		±1 mm from baseline	
Electron applicator interlocks		Functional	
Coincidence of radiation and mechanical isocenter	±2 mm from baseline	±2 mm from baseline	±1 mm from baseline

Annual QA

MLC

- MLC transmission
- MLC spoke shot
- Coincidence of light and x-ray field
- IMRT/VMAT checks

Imaging

- Imaging dose
- Beam quality/energy

Annually	
MLC transmission (average of leaf and interleaf transmission), all energies	±0.5% from baseline
Leaf position repeatability	±1.0 mm
MLC spoke shot	≤1.0 mm radius
Coincidence of light field and x-ray field (all energies)	±2.0 mm
Segmental IMRT (step and shoot) test	<0.35 cm max. error RMS, 95% of error counts <0.35 cm
Moving window IMRT (four cardinal gantry angles)	<0.35 cm max. error RMS, 95% of error counts <0.35 cm

Annual (A)		
Planar MV imaging (EPID)		
Full range of travel SDD	±5 mm	±5 mm
Imaging dose[e]	Baseline	Baseline
Planar kV imaging		
Beam quality/energy	Baseline	Baseline
Imaging dose	Baseline	Baseline
Cone-beam CT (kV and MV)		
Imaging dose	Baseline	Baseline

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

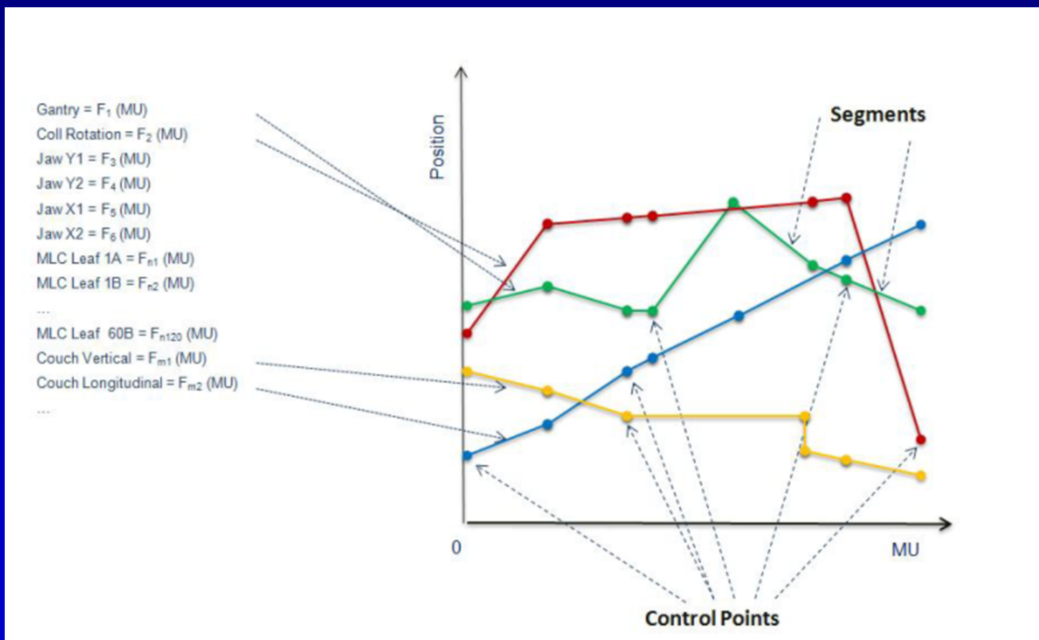
Autonomous QA: ***More Efficient, stable and accurate***

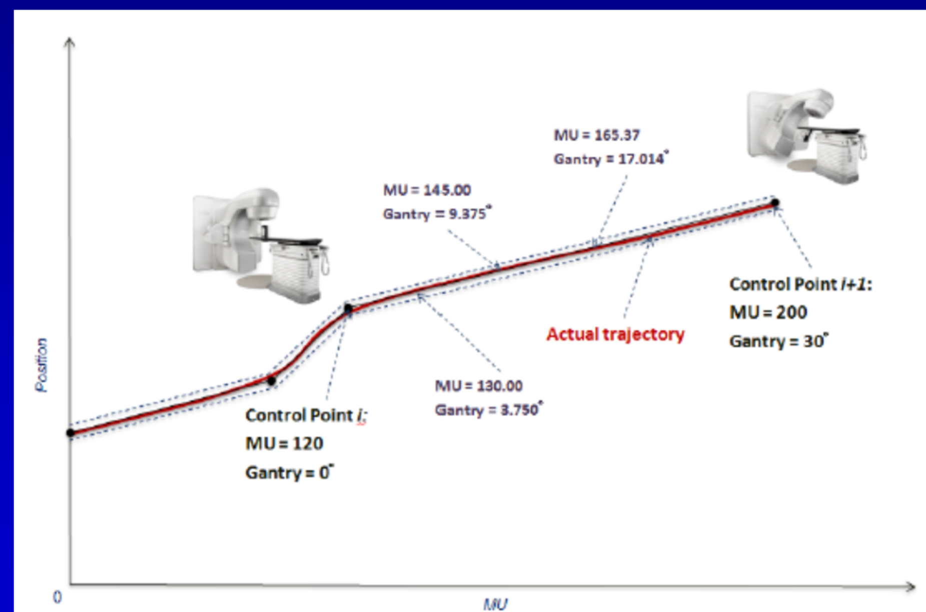
Palmer A et al, *Br. J. Radiol.* 2012(**85)** e1067–73

Programmable Automatic Delivery/Operation

Implementation of Automatic Delivery

Control points and delivery trajectory

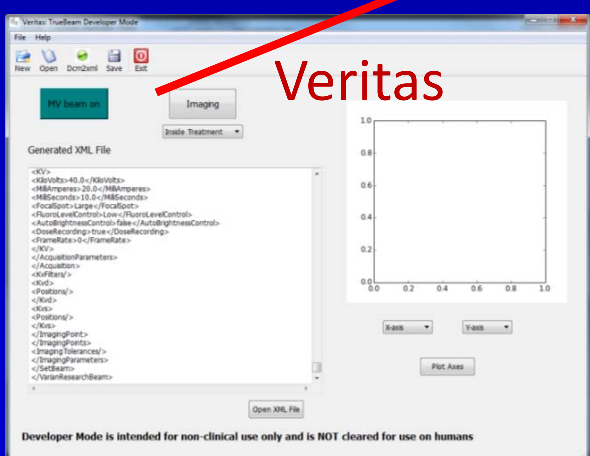


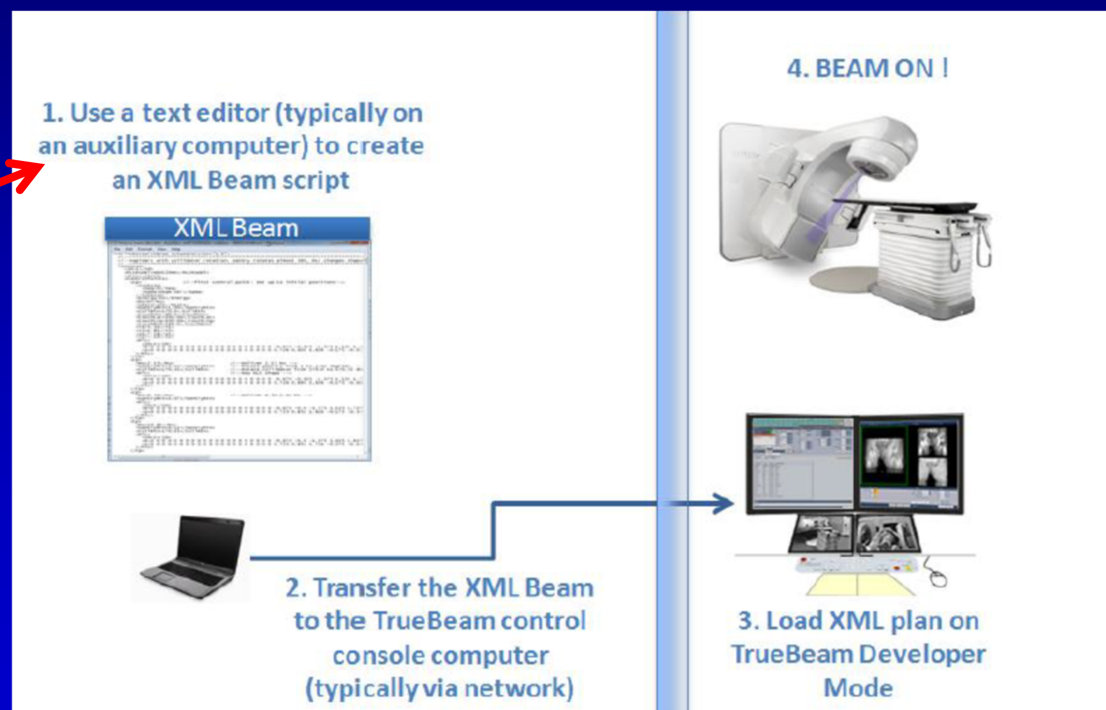


From Varian Developer mode Manual

Varian TrueBeam Developer Mode

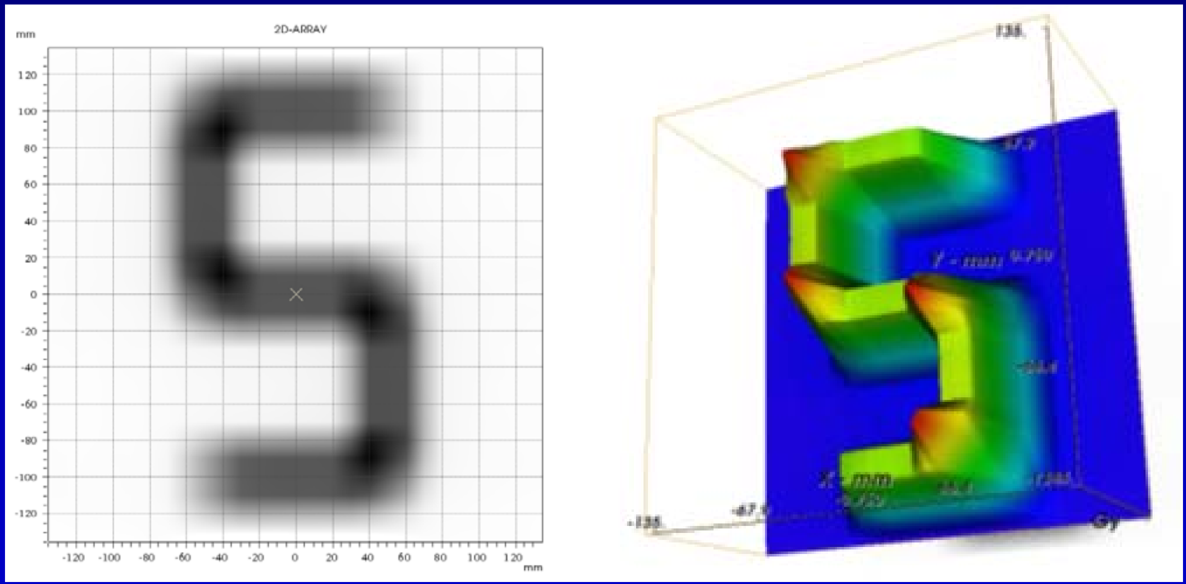
Control all motion axes, beam delivery and imaging through programmable XML Beam scripts



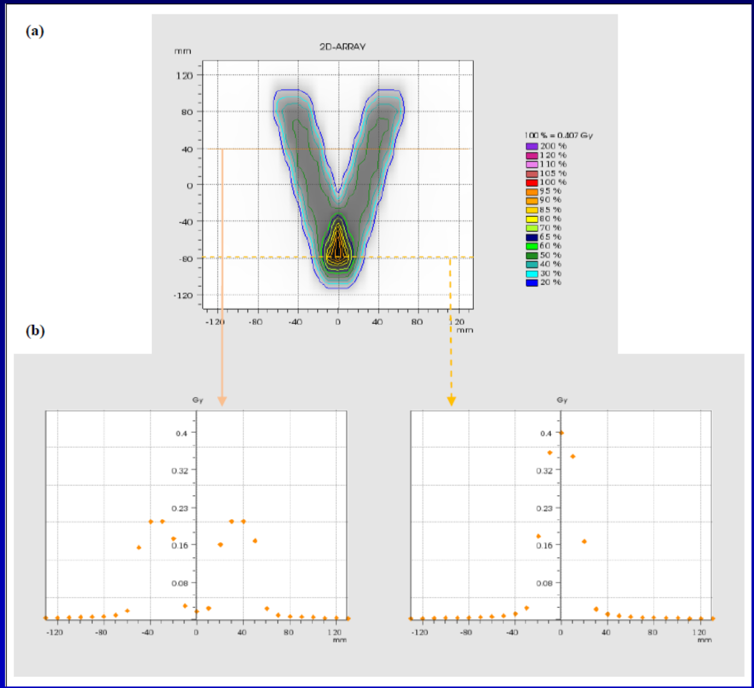


From Varian Developer mode Manual

Simple Examples



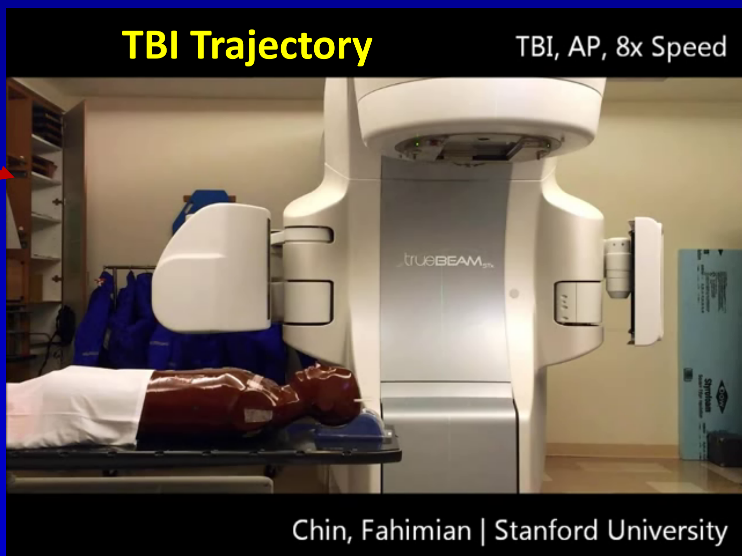
Produced by couch motion

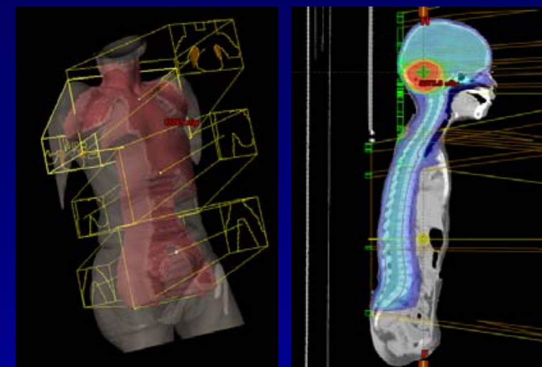


(a) Resulting radiation pattern for Varian ‘V’ produced solely by couch motion (b) The left-right symmetry indicates high geometrical accuracy and stability of the automated couch motion

Courtesy of Ben Fahimian

Complicated Examples





Courtesy of Ben Fahimian

Implementation of Autonomous QA

An Ideal Autonomous QA Process

Automatic Delivery & Data Acquisition

↓

Automatic Data Process

↓

Automatic Analysis & Reporting

Hardware + Software

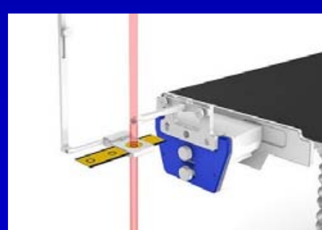
- One button QA
- Self-calibration
- Phantom pose invariant
- Reduce/Remove operator dependence
- Analyze results and generate QA report

Autonomous Imaging QA

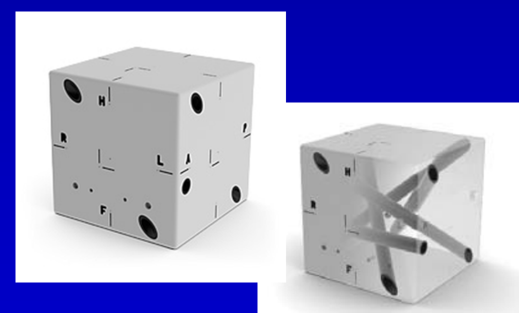
Daily Imaging QA

- *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

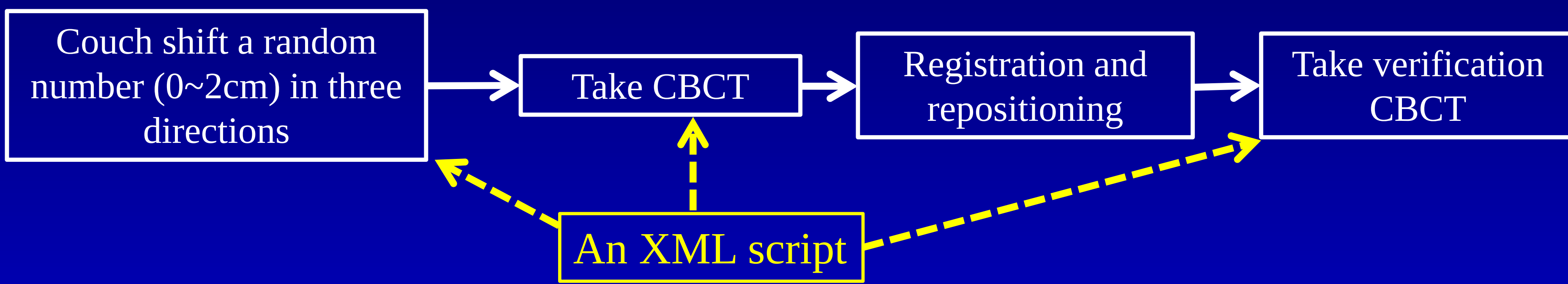


MIMI Phantom from Standard Imaging Inc.

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

Daily Imaging QA

Couch positioning/repositioning



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

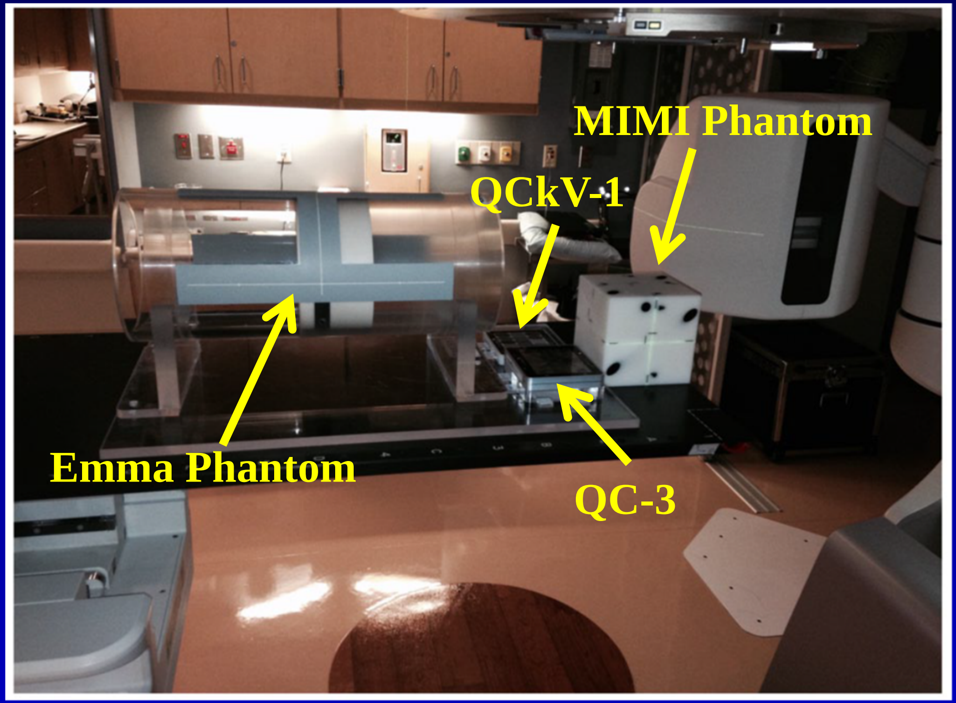
https://www.youtube.com/watch?v=JwOvALjRgqE

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

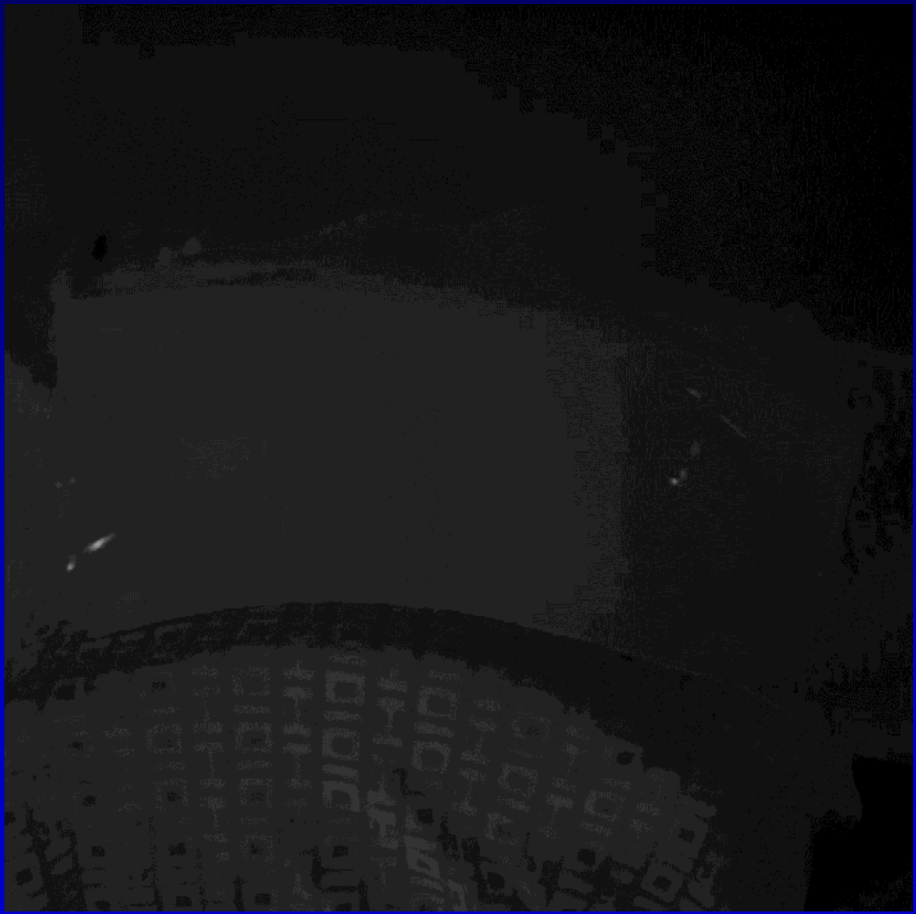
Gilmer Valdes et al, *JACMP, Vol. 16, No. 4, 2015*

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?



Courtesy of Cesare H Jenkins

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

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**

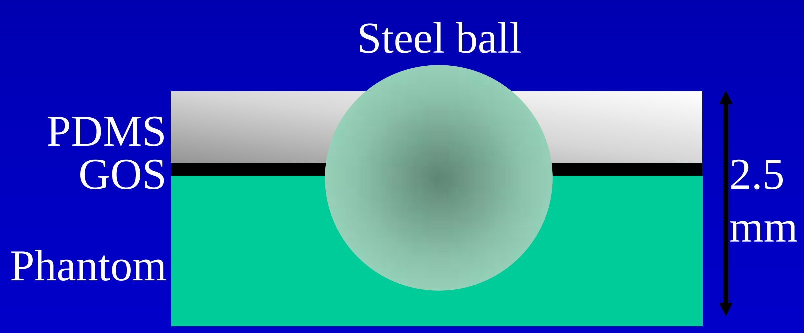
- Phantom
- Camera
- Laptop

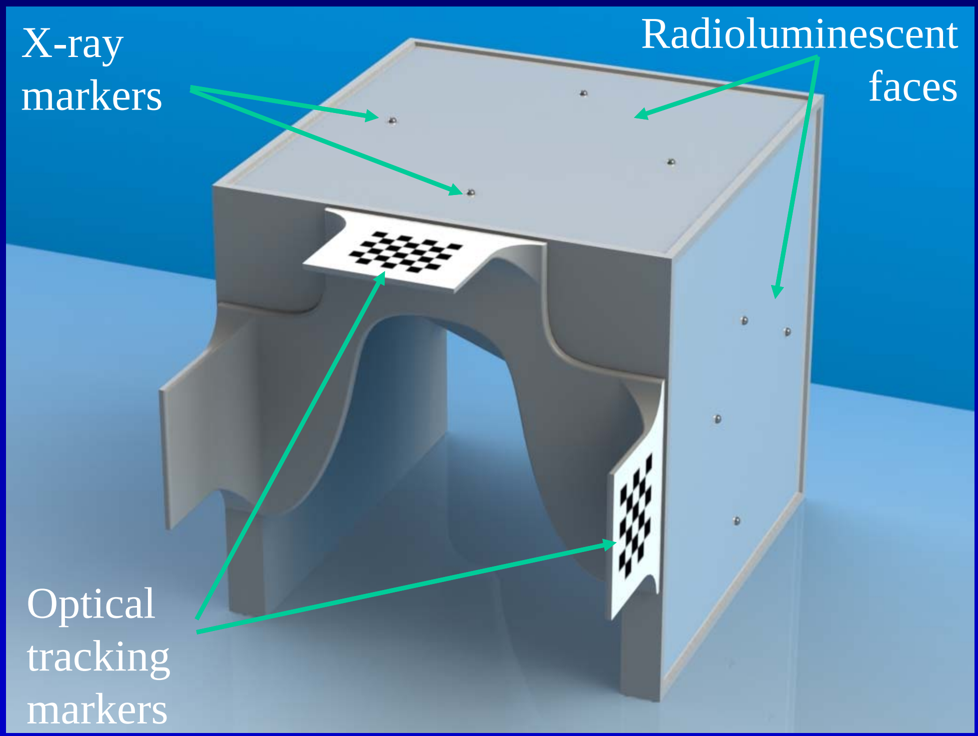
Automatic image acquisition, machine operations in Truebeam Developer mode

- Image process
- Data analysis
- Result report

Phantom

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





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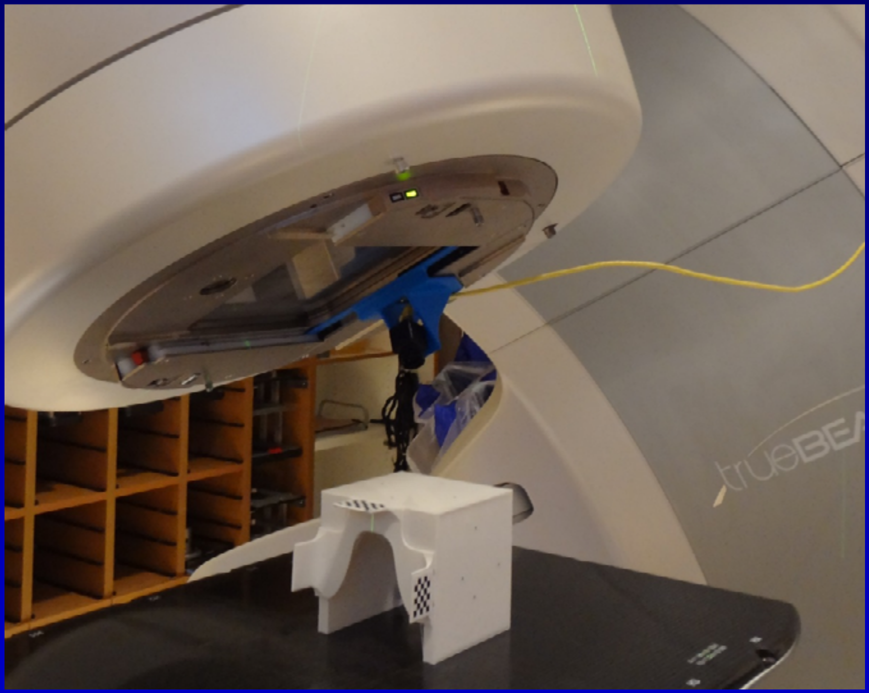
Camera

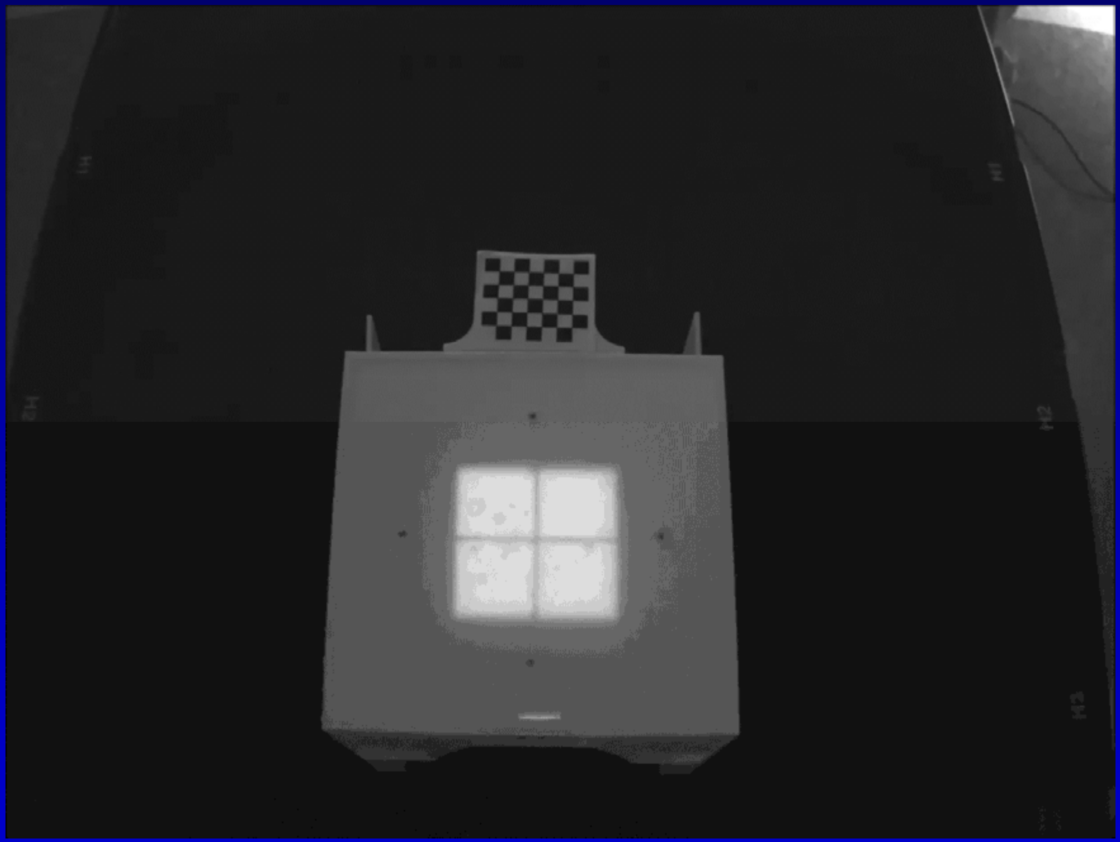
- Power over Ethernet (POE) machine vision camera
  - Single cable connection
  - 5mm f/2.5 S-mount lens
- 3D printed holder that connects to LINAC tray



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

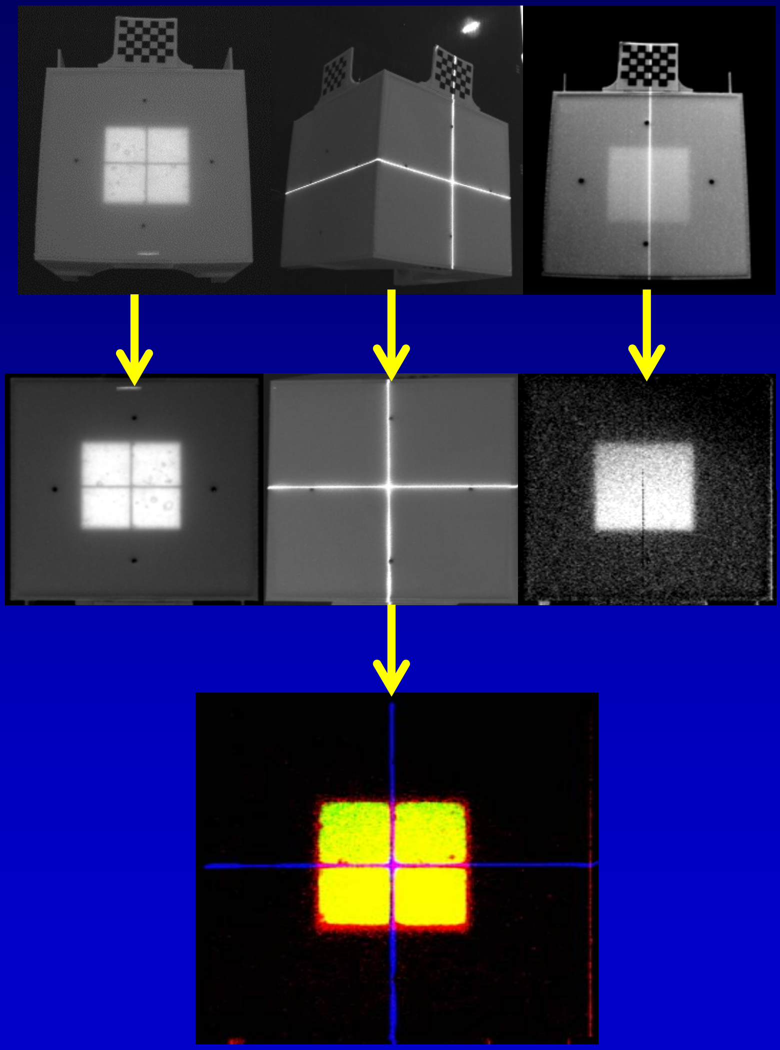
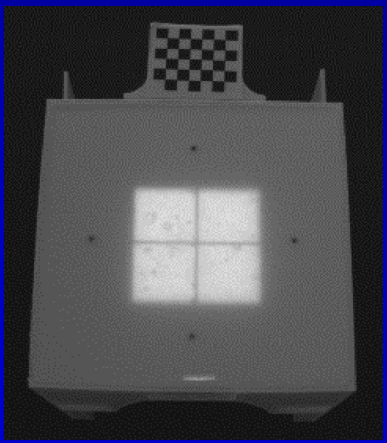


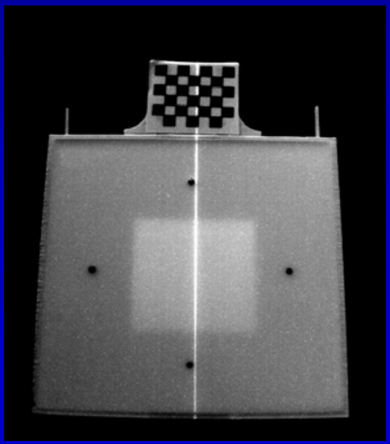
Image identification and capture

Key images were identified based on:

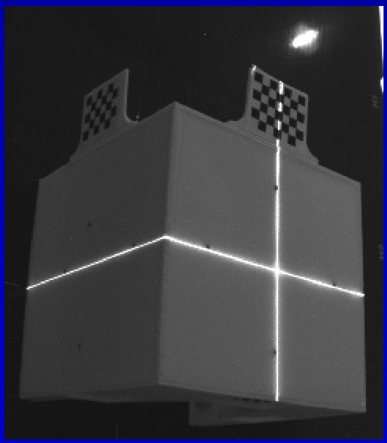
- Known delivery sequence
- Motion detection algorithm



Light Field



Radiation Field

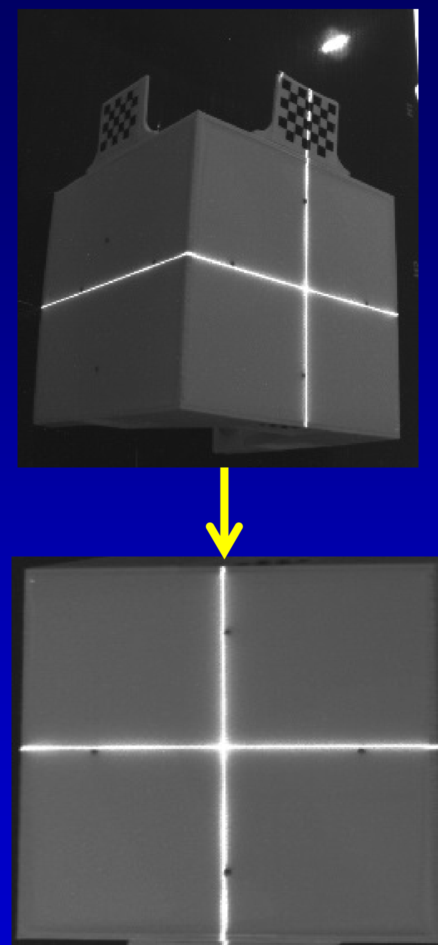


Left Laser

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

  -I*mage center is projected into the calibrated coordinate space*

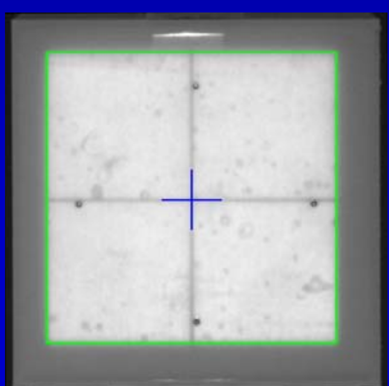
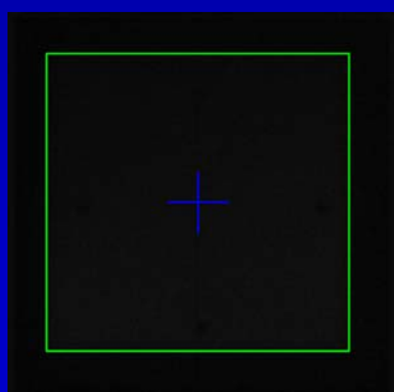
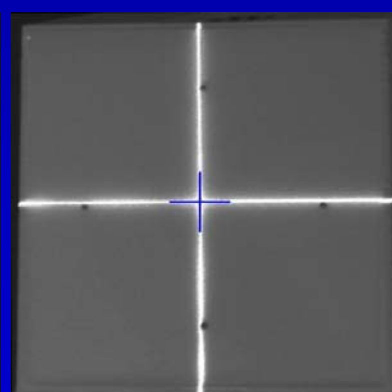
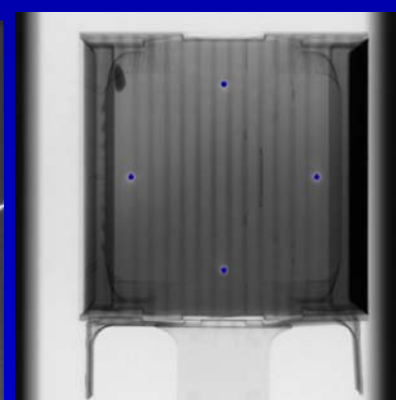
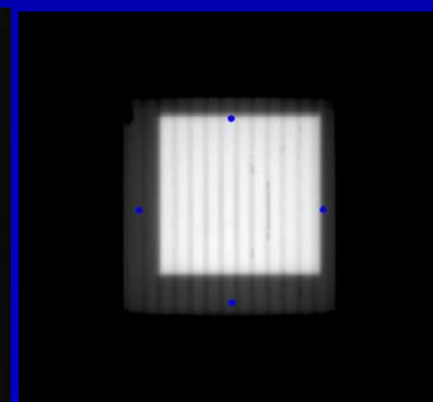
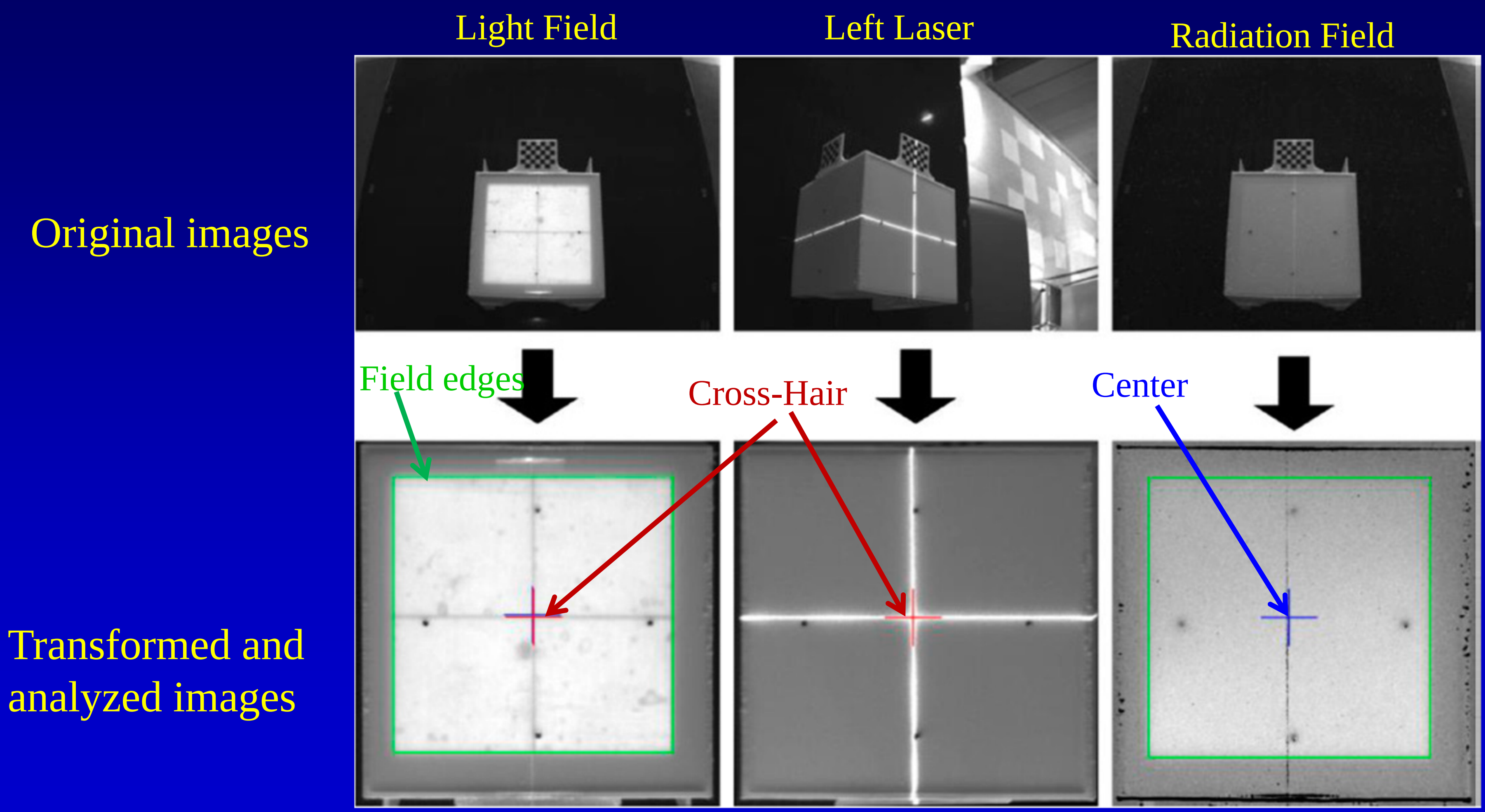






Image processing example



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Self-calibration Assessment

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

Ten measurements

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

Agree well with manual QA results

Table 2. System results compared to existing methods.

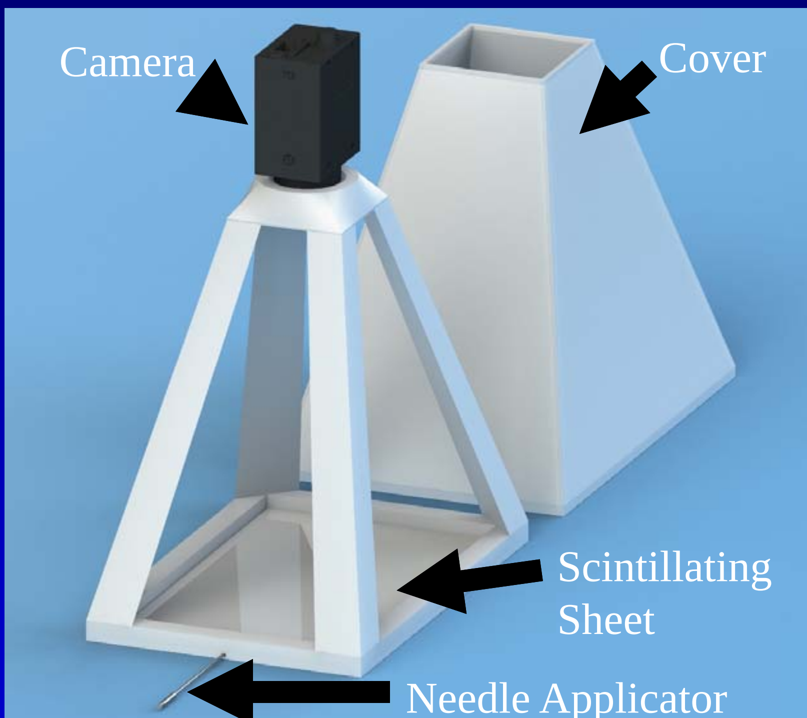
Light field/ radiation alignment	Symmetric beams	Center shift X (mm)	Center shift Y (mm)	Width difference (mm)	Height difference (mm)
Auto	5×5 cm	-0.02 ± 0.05	0.68 ± 0.11	-0.58 ± 0.05	-0.59 ± 0.09
Auto	10×10 cm	-0.21 ± 0.07	0.96 ± 0.12	-0.63 ± 0.15	-0.94 ± 0.31
FC-2	*15 × 15* cm	*−0.19*	*0.40*	*−0.30*	*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)*	*200.3*	*300.4*		
Laser localization (relative to cross hairs)	Center shift X (mm)	Center shift Y (mm)			
Auto	$0.19 \pm .30$	-0.26 ± 0.13			
Iso-align	*0.25*	*−0.25*			

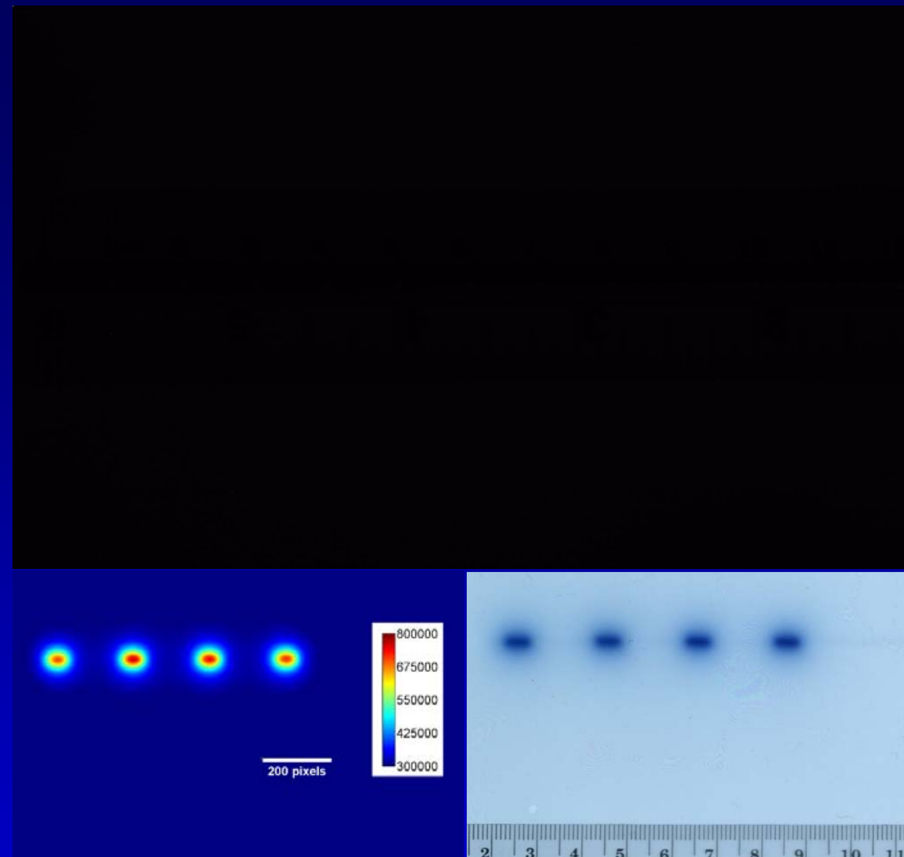
Note: Summary of tests performed by the autonomous system (mean ± standard deviation) and comparison to current QA techniques (shown in italics).

Conclusion

- 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*

Autonomous HDR QA





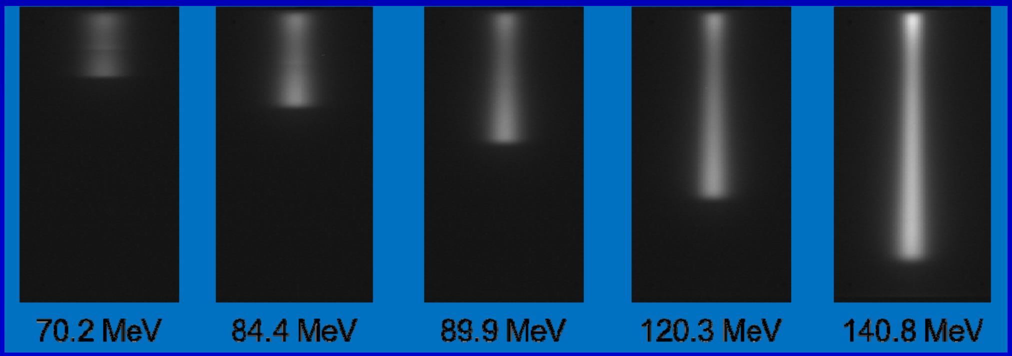
- Positioning: 1.99 ± .02 cm with the system while the result from autoradiography was 2.00 ± .03 cm
- Timing: 1 second were determined to be 1.01 ± .02 second

Courtesy of Cesare H Jenkins and Ben Fahimian

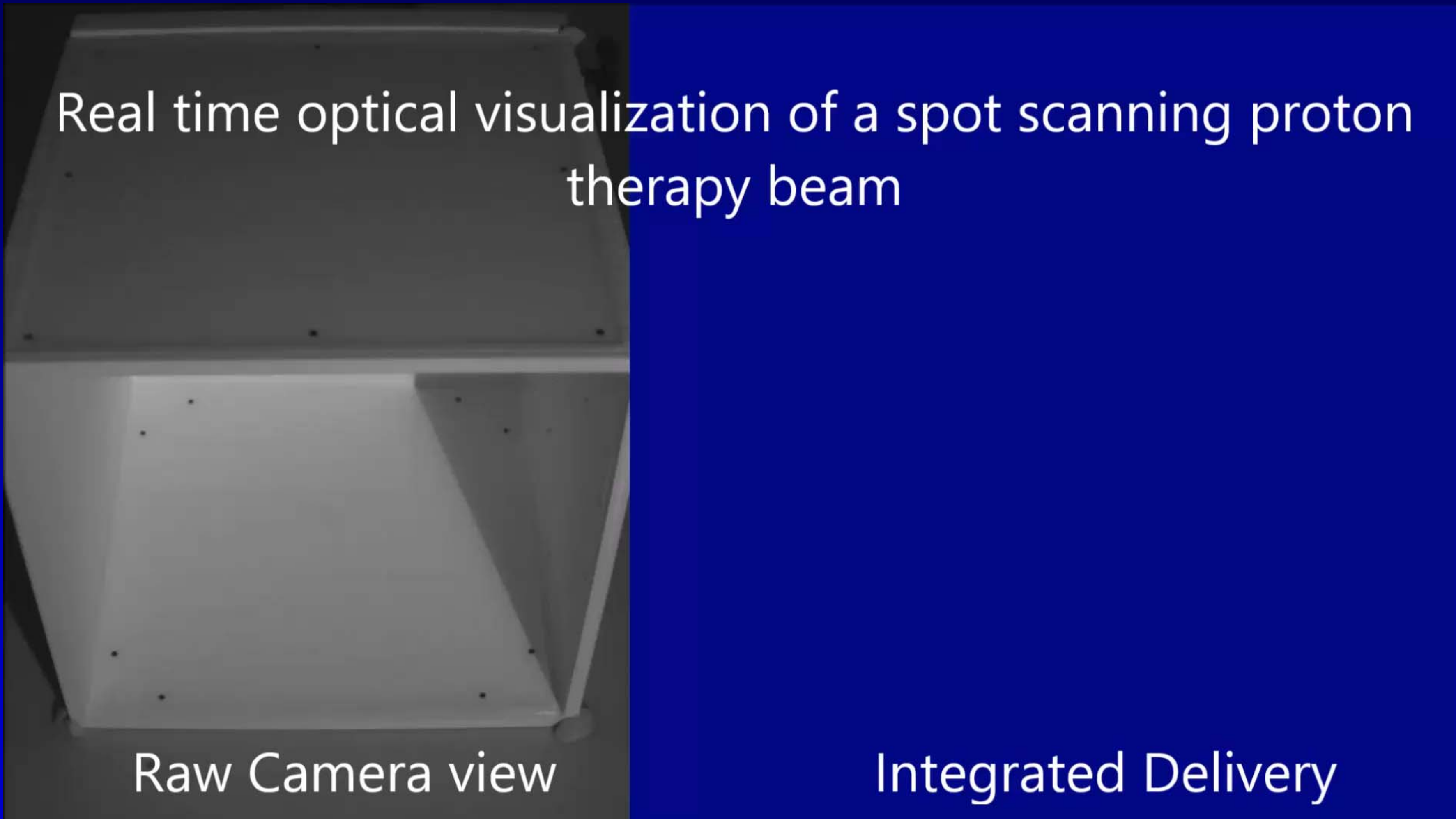
Discrete Spot Scanning Proton Beam Therapy

- 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!