University of Michigan Medical School

Automation of Linear Accelerator Quality Assurance

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Disclosures

- Current research projects funded by NIH, Blue Cross Blue Shield of Michigan, and Varian Medical Systems
- Roles related to Quality and Safety in AAPM and ASTRO
- Collaborative projects with industry:
  - Modus Medical
  - ImageOwl

Outline

- Example Applications of EPIDs in linac (non-patient) quality assurance
  - Acceptance Testing and Commissioning
  - Routine linac QA
  - Pre-treatment VMAT QA
  - Credentialing for Clinical Trials
- Automation of data analysis and pooling of results
- The EPID as a tool in our toolbox
- Summary and future considerations

Electronic Portal Imaging Device (EPID)

- Designs and implementation have been focused on patient imaging need
  - High contrast
  - Low monitor units
  - Spatial accuracy

721 Herman *et al.*: TG58

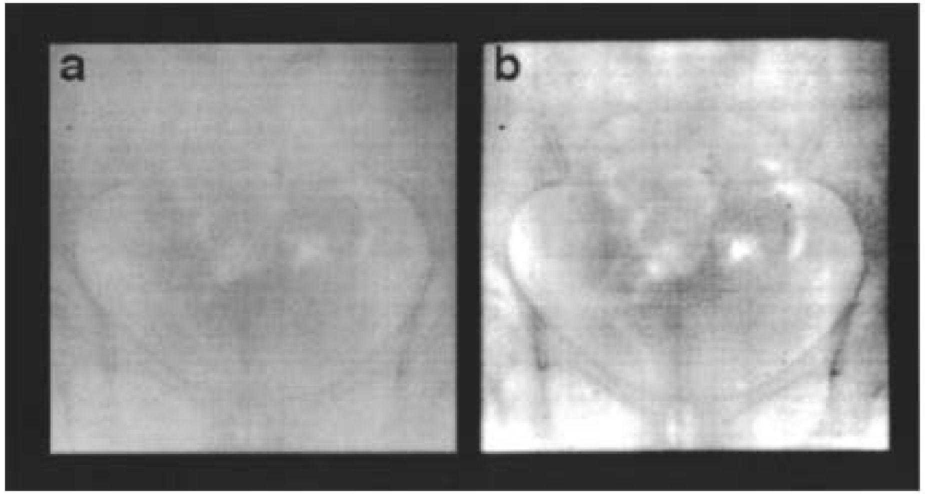


FIG. 9. Video EPID image (a) and (b) with enhancement.

Clinical use of electronic portal imaging: Report of AAPM Radiation Therapy Committee Task Group 58

Herman et al, Med Phys, 2001.

EPIDs have many other applications

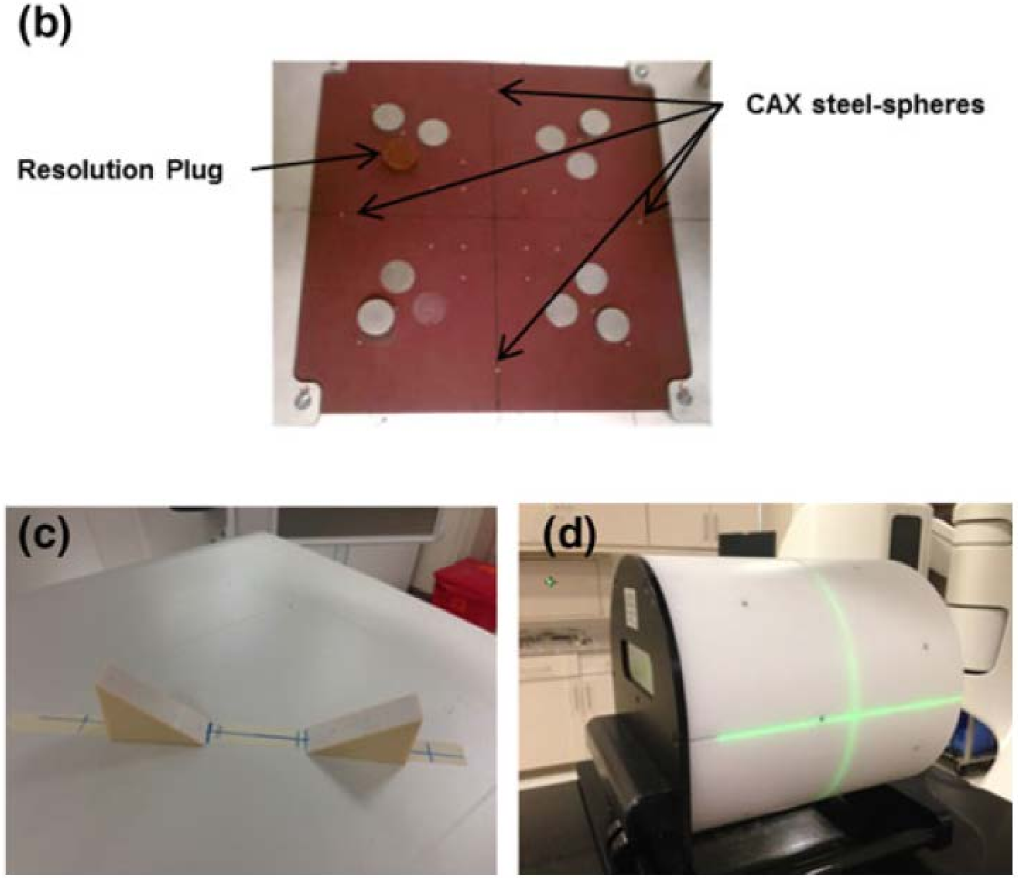
- Linear accelerator acceptance
- Routine linac quality assurance
- Pre-treatment QA for IMRT and/or VMA
- Credentialing for clinical trials

- Advantages:
  - Attached to the delivery system
  - Able to be validated against other measurement systems

Rapid Acceptance Testing with an EPID + Phantoms

Figure 1: "Phantoms used in this study;
(a) custom built in-house phantom for photon beams;
(b) phantom plate showing the steel plugs, CAX steel-spheres and resolution plug;
(c) double wedge phantom used for AT of electron beams;
(d) IsoCal phantom used with the MPC (machine performance check)."

Yaddanapudi et al, Med Phys, 2017



Yaddanapudi et al, Fig 1b, c, d

EPID + wedge phantom to assess electrons

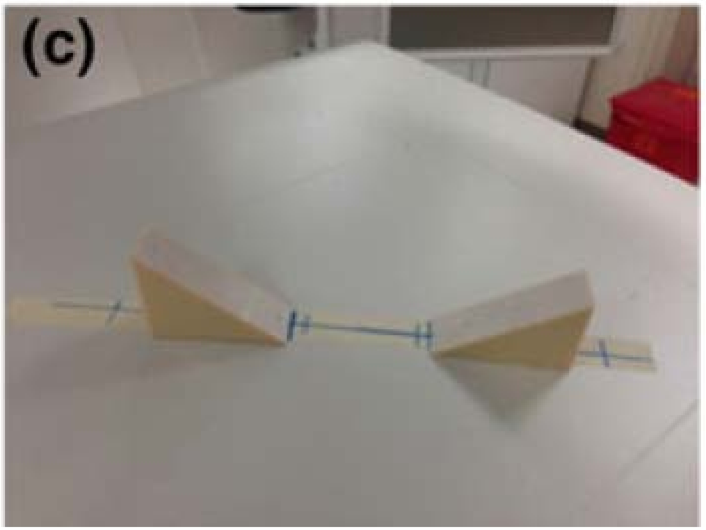


Figure 1c: wedges placed on EPID for electron analysis

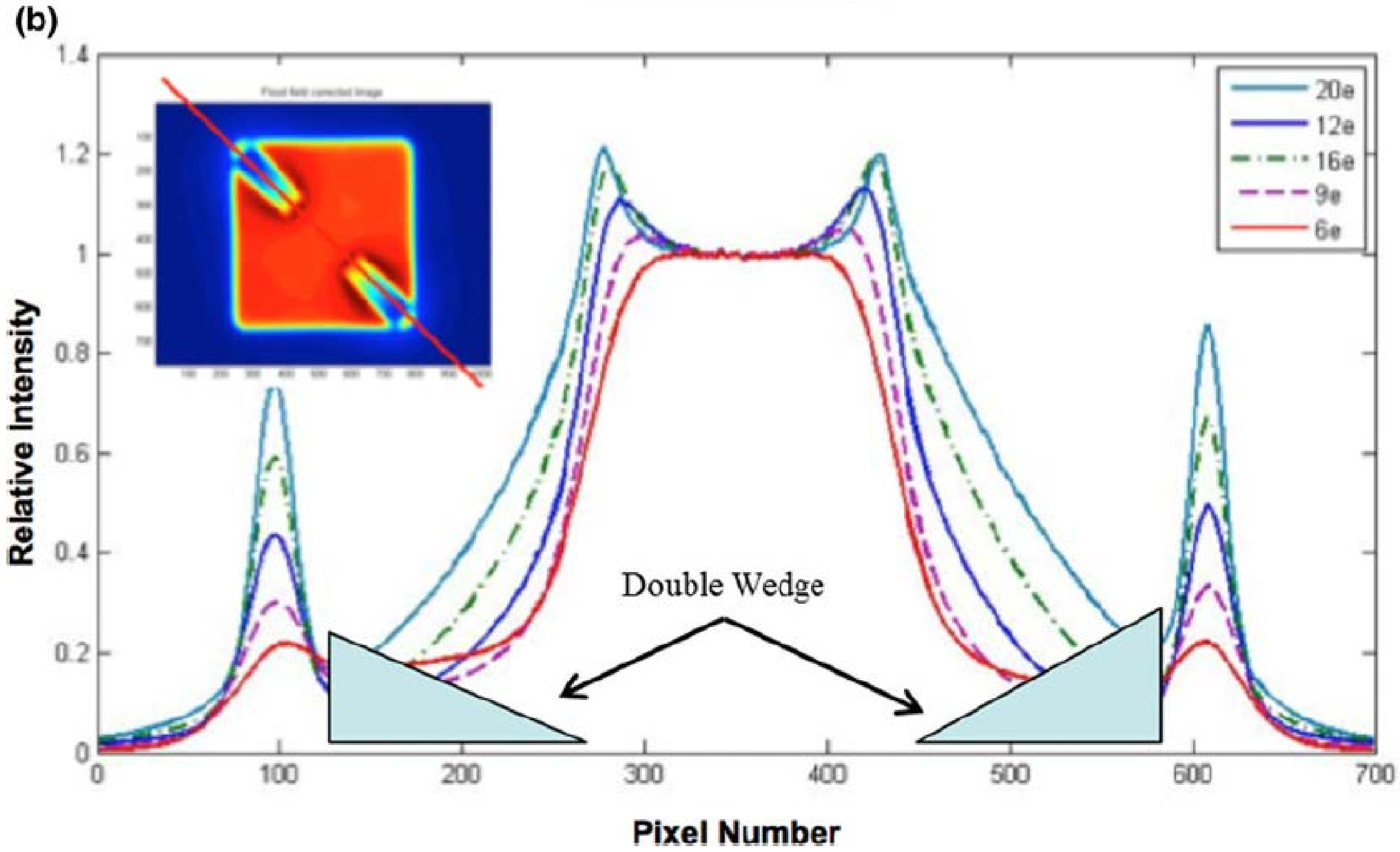
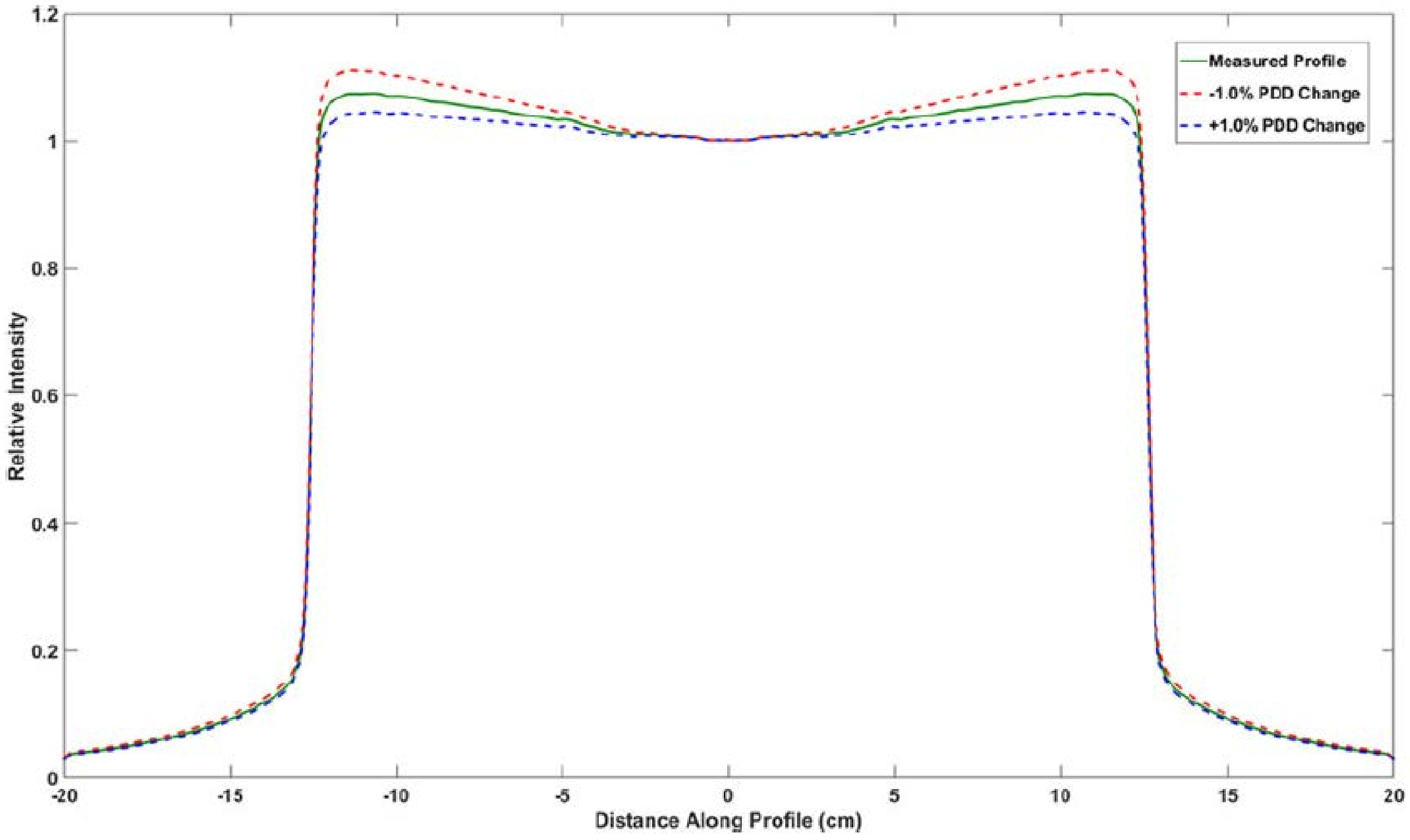


Fig. 7b: “(b) diagonal profiles of the electron beams through the double wedge phantom.”

Yaddanapudi et al, Med Phys, 2017

Profile evaluation with EPID

Figure 8: "Profiles obtained on the EPID corresponding to a 1% change in PDD (upper and lower bound profiles), which would be used as benchmark profiles to evaluate machines for photon beams, along with a measured beam profile." p. 3403



Yaddanapudi et al, Med Phys, 2017

EPID for routine QA

- Cai et al
- 5 year evaluation – measurements with a phantom locked in place
  - 0 to 23.5 mm plugs + 1 MV plug
- MV at 108 cm Source-imager-distance (SID)
- kV at 150 cm SID
- Energies: 6, 10, 15 MV + 6, 10 FFF
- Measured daily by therapists

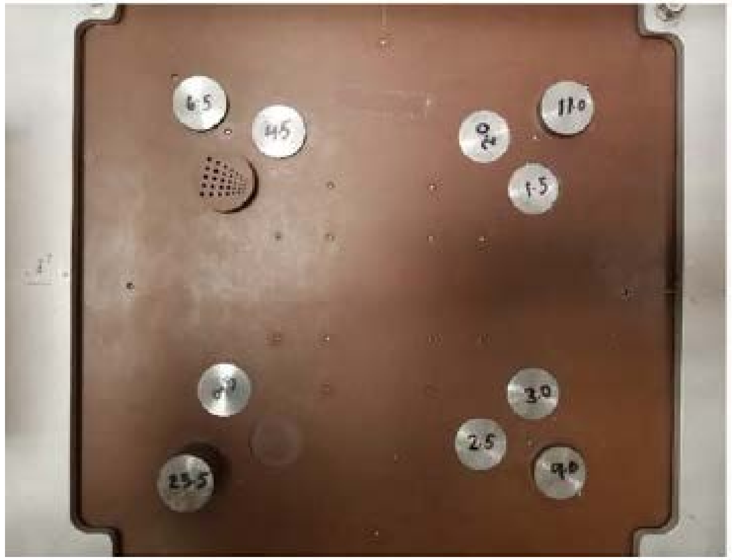


Fig 1b, Custom phantom with multiple plugs
Cai et al

Cai et al, BPEX 5 (2019)

EPID-based Daily QA vs Monthly vs TG51 Evaluated Over 3 Years

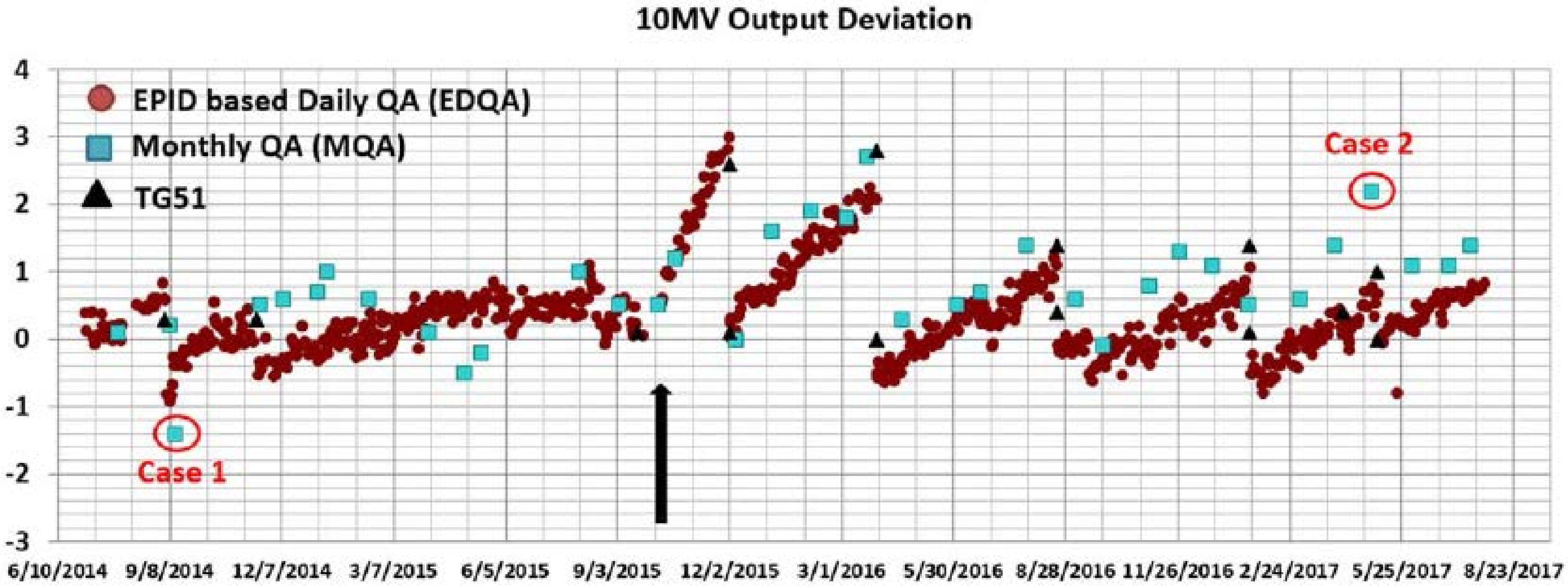


Figure 2. Trend of machine output in percentage difference compared to baseline varying with time. The top plot is the 6 MV and the bottom one is the 10 MV linac output (EDQA red points; MQA blue squares and TG51 black triagnles).

Cai et al, BPEX 5 (2019)

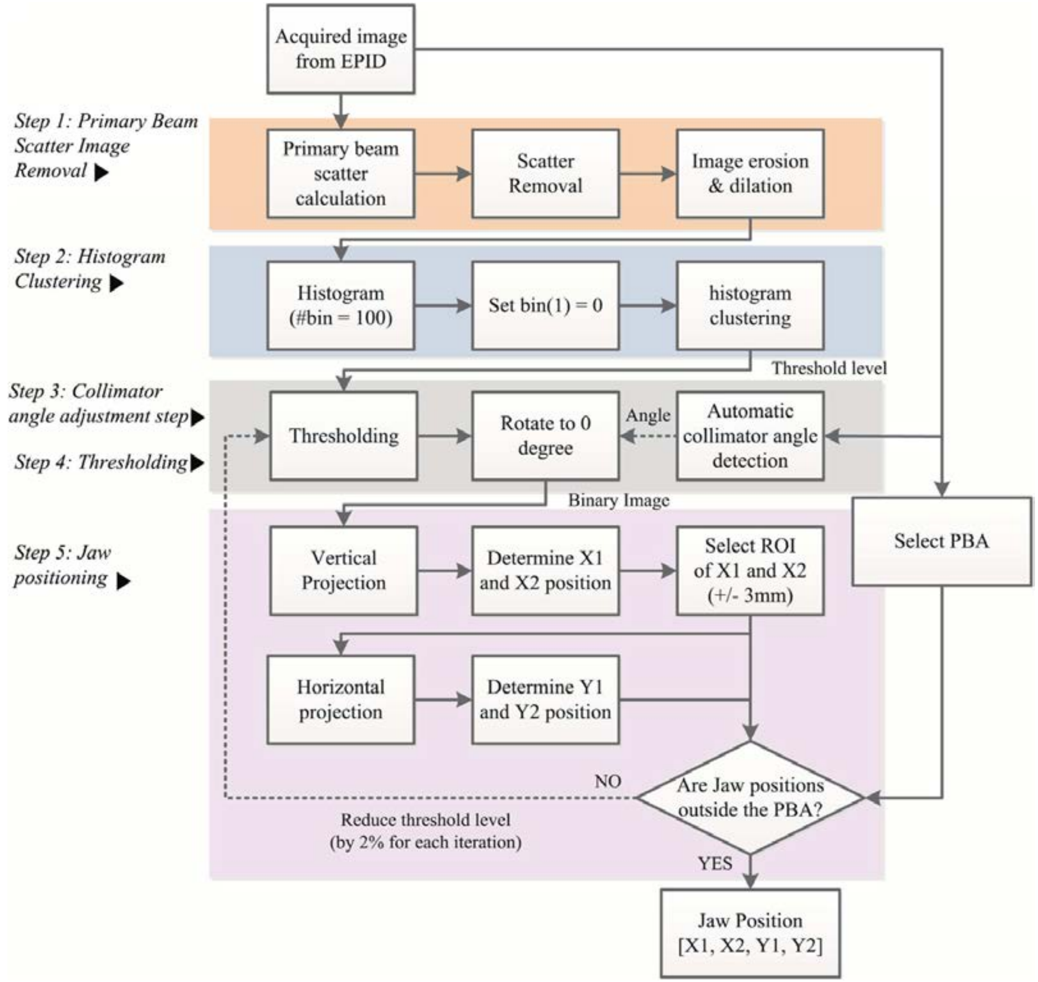
Figure 2(lower), Cai et al for 10 MV

Other applications: Pre-treatment IMRT and VMAT measurements

- EPID measurements can be used to check the deliverability of treatment plans for individual fields and/or arcs

Cine-based Analysis – Jaw Tracking IMRT/VMAT QA

Time-dependent analysis which incorporates jaw settings and MLC positions



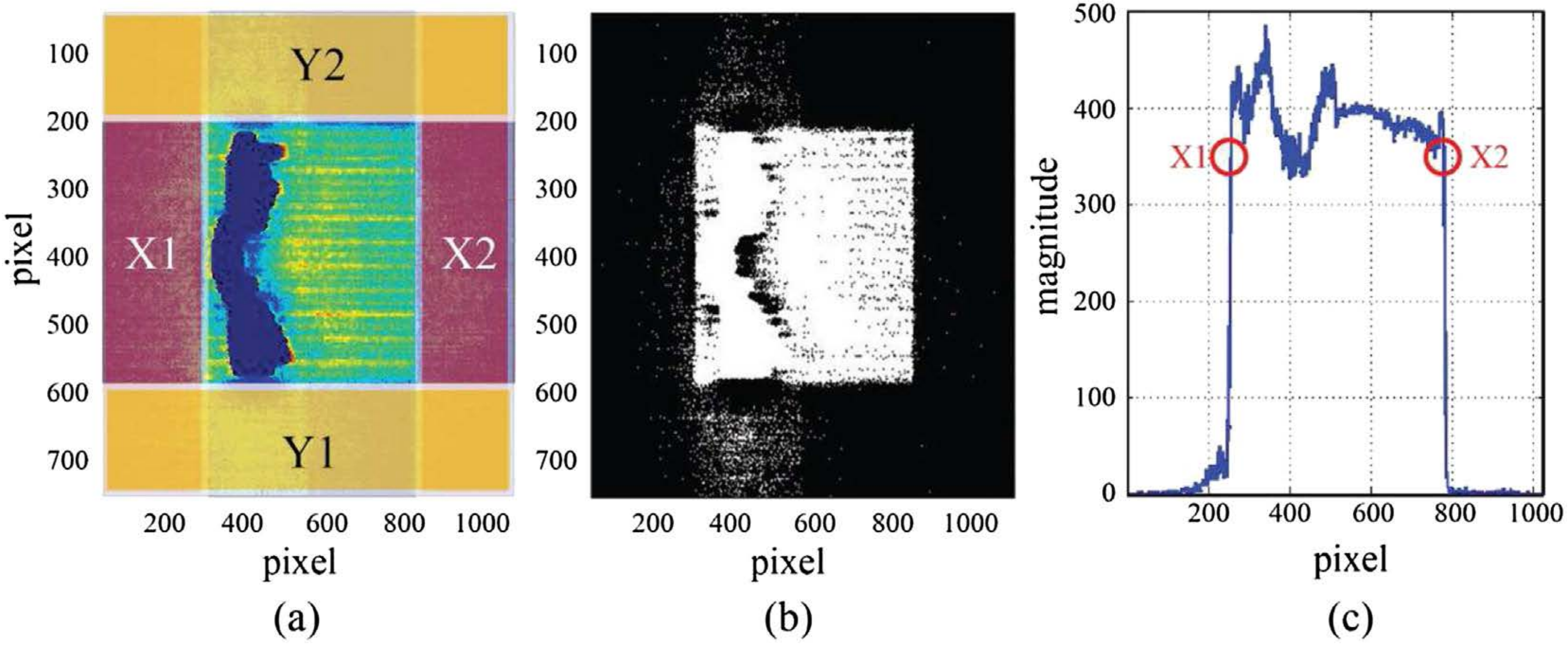
Fuangrod, et al, Physica Medica 2015

Fig. 1 Fuangrod et al. Schematic of jaw detection algorithm

EPID Method to Detect Jaws

Results for jaw position accuracy:

- Static: ±1 mm RMS error (maximum error 1.5 mm)
- Dynamic: ±1.5 mm RMS error (maximum error 3 mm)



From Fuangrod et al: "Figure 4. Sample images outlining the vertical projection process: (a) the image after PBSI extraction, (b) the binary image after global thresholding using the threshold level from the result of histogram clustering, and (c) the vertical projection and the detected X jaw positions."

Fuangrod, et al, Physica Medica 2015

Other applications: Credentialing for Clinical Trials

Virtual EPID Standard Phantom Audit (VESPA)

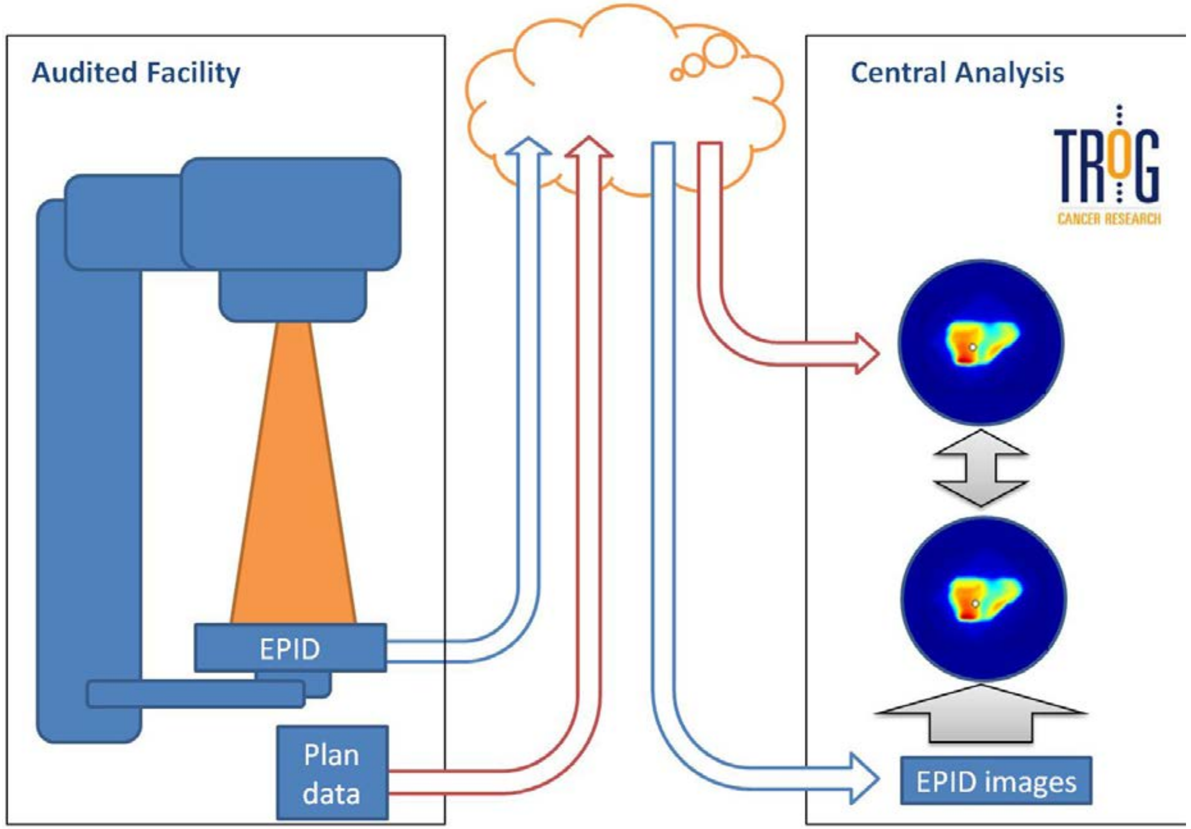


Figure 1. EPID Process for Audits with central analysis

Miri et al, PMB, 2017

- Software developed for a common analysis platform
- Corrections that were made are consistent for the different types of EPIDs for each accelerator
- Remote audit for Trans Tasman Radiation Oncology Group (TROG) clinical trials
- Facility delivers plan in air to EPID
- Data are uploaded for central analysis

Experience with Different Vendor Systems

Table 1 from Miri et al

Table 1. Summary of vendor specific or other issues encountered with the VESPA audit process.

Problem	Solutions
Transfer of images to Mosaiq results in loss of pixel scaling information to obtain integrated dosimetric image	• Varian Clinac—Images saved in Varian format in the cache on the linac used • Varian Truebeam—Image Processing Service used to store cumulative image frames. Last frame is integrated image in Varian format. Gantry angle for the image is the kV imager angle • Elekta—Images exported from iView EPID acquisition software in.his format with log file. Log file contains pixel scaling information DICOM images then created at central site for analysis
Cine Mode imaging limitations or unavailable Truebeam and Elekta cine imaging does not store dosimetric information Elekta cine imaging using Perkin Elmer software does not store gantry angle	• Varian Clinac—Requires large MU (300) for calibration of EPID signal to dose due to missing frames at start and end of acquisition • Varian Truebeam—Image Processing Service required. This stores cumulative image frames from which cine images can be derived. • Elekta—Perkin Elmer XI service software is required. Individual frames stored. Separate inclinometer for obtaining gantry angle for frames
Process and procedures	• The most common issue was incomplete data provided such as combined field 3D dose file not provided • Some images were acquired with zero collimator angle but planned at actual collimator angle, or vise-versa

Miri et al, PMB, 2017

Example problems with different vendor systems for the VESPA Audit Program (Miri et al) for TROG (Extracted from Miri et al, PMB, 2017)

Manufacturer and Model	Example Problem: Transfer of images to Mosaiq resulted in a loss of pixel scaling information to obtain integrated dosimetric image
Varian Clinac	Images saved in Varian format in the cache on the linac used
Varian Truebeam	Image Processing Service used to store cumulative image frames. Last frame is integrated image in Varian format. Gantry angle for the image is the kV imager angle
Elekta Systems	Images exported from iView EPID acquisition software in .his format with log files. Log file contains pixel scaling information DICOM images then created at central site for analysis

Miri et al, PMB, 2017

Credentialing for Clinical Trials

- Thirty audits were performed of 21 institutions
  - Intensity Modulated Radiation Therapy (IMRT) - 17
  - Volumetric Modulated Arc Therapy (VMAT) – 13
- A scoring system was developed to assess the results
- Results were analyzed for the planning and delivery system combinations

Miri et al, Radiation Oncology, 2018

Variation in EPID analysis results by delivery system and treatment planning system combinations

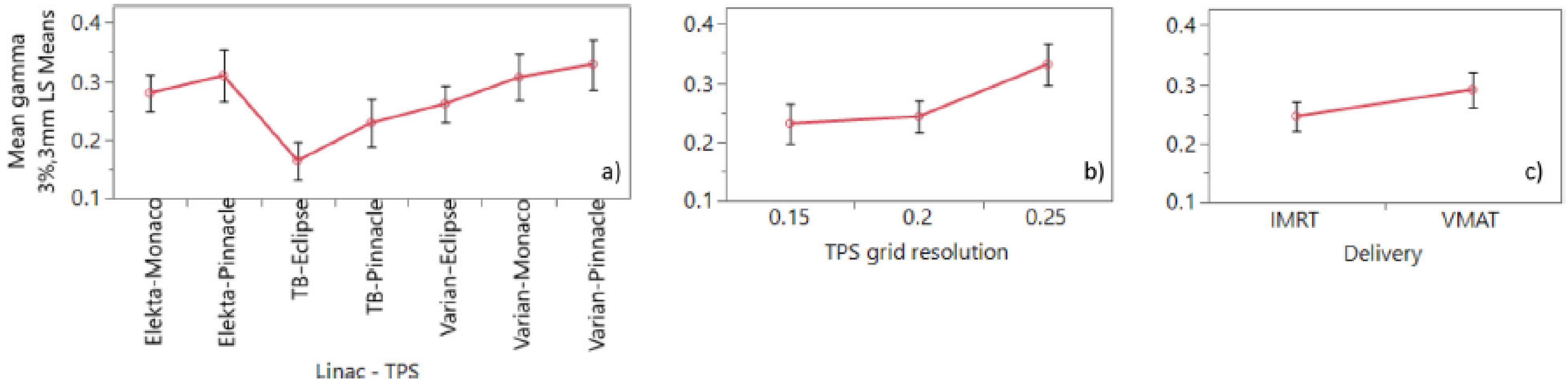


Fig. 4 Plot of GMV for the three explanatory variables that showed most influence on the audit results (Linac-TPS combination, TPS dose grid resolution and IMRT/VMAT delivery)

95% confidence intervals are shown
Results were improved with a smaller TPS grid size

Miri et al, Radiation Oncology, 2018

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Automation of Data Analysis

- EPIDs for Automation
- Leverage known orientation
  - Input is known by the machine’s treatment management system or the delivery file if DICOM-RT
  - Output is recorded in the treatment management system or may be exported
- Efficiency gains
  - Data is in a known and consistent format
  - Analysis can be automated
- Application of statistical process control

Changing how we approach QA

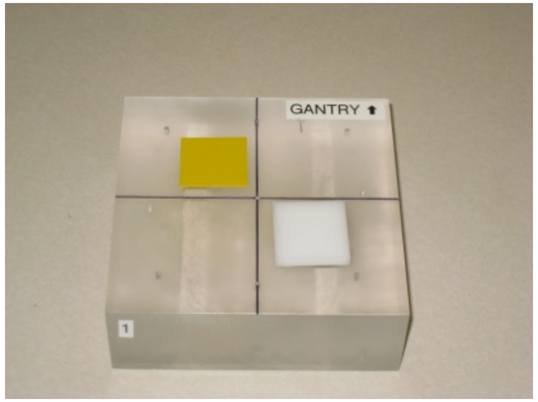
- We need to change how we approach QA for our entire process
  - Linac QA is an example
  - K Smith et al MPPG 8a (JACMP 2017)
- AAPM Task Group 100 (Huq et al, Med Phys 2016) recommends the use of tools such as Failure Modes and Effects Analysis to help identify the riskiest parts of the therapy process
  - This information can be used to identify and adopt better safety barriers

Automated QA (AQA Consortium)

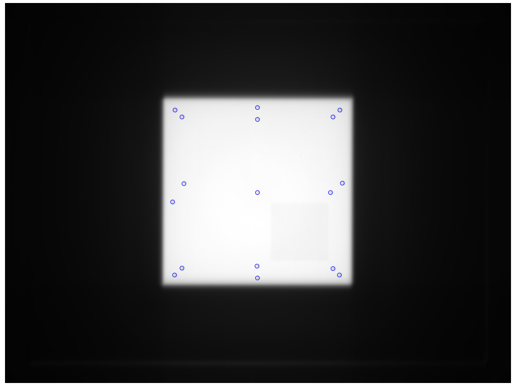
- Manufacturer funded project focused on automation of linac QA
  - EPID and trajectory log file-based
- Multi-year project which began in 2009
- Emphasis has been on collaboration since we started
- New centers have joined and contributed to aspects of the project

Phase 1 QA Test Suite

- Test suite included all MLC monthly tests in Table V of AAPM TG 142, VMAT tests, plus imaging tests
- Used both trajectory log files and EPID measurements
- The test suite was used on 8 linacs for over 6 months
- 15 minutes to deliver the test suite
- 1 minute to analyze with a customized MatLab script



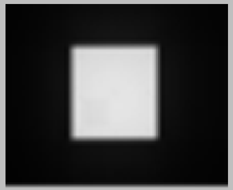
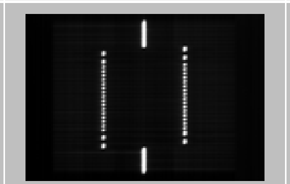
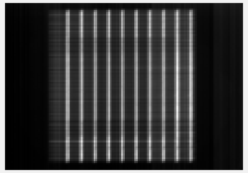
(a)



(b)

Eckhause et al, Med Phys, 2015

Emphasis of Test Suite on AAPM TG 142

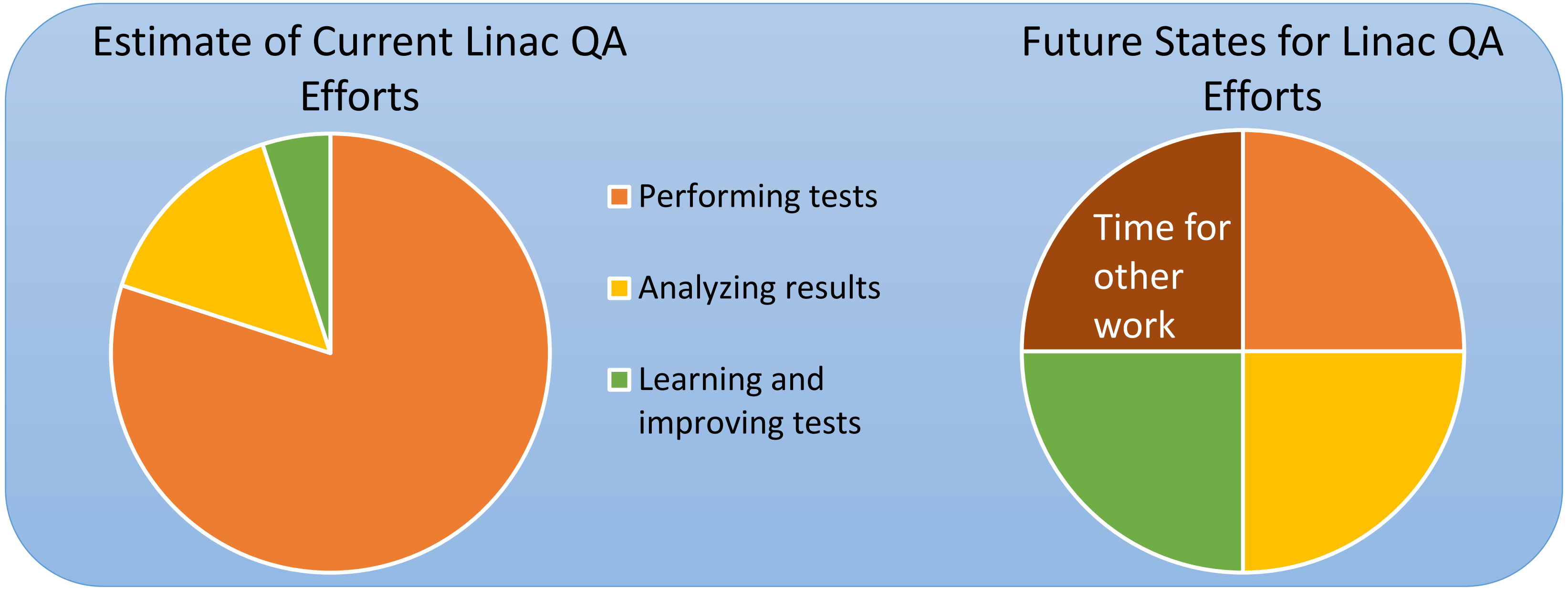
Field Description	Test Image	TG-142 Table (Klein et al[8])	Procedure(s) Tested	EPID Analysis	Log File Analysis
1.Jaw-defined field*		Table II (monthly)	Gantry sag; collimator rotation; Jaw position	Field edge, angle; phantom position	Jaw and collimator
2.MLC defined static pattern*		Table V (monthly)	Leaf positions	Leaf edge positions	Leaf position
3.Interleaf static MLC pattern*		Table V (annual)	MLC transmission	Image-to-image-comparison	Leaf position
4.Picket-fence test – static gantry*		Table V static gantry Quantitative (monthly)	Leaf position (IMRT)	Leaf positions for all pickets, cardinal gantry angles	Leaf position, velocity

Eckhause et al, Med Phys, 2015

- **+ picket fence for VMAT with variable gantry speed, variable gantry speed and dose rate**
- **Both HDMLC and Millennium MLC supported**

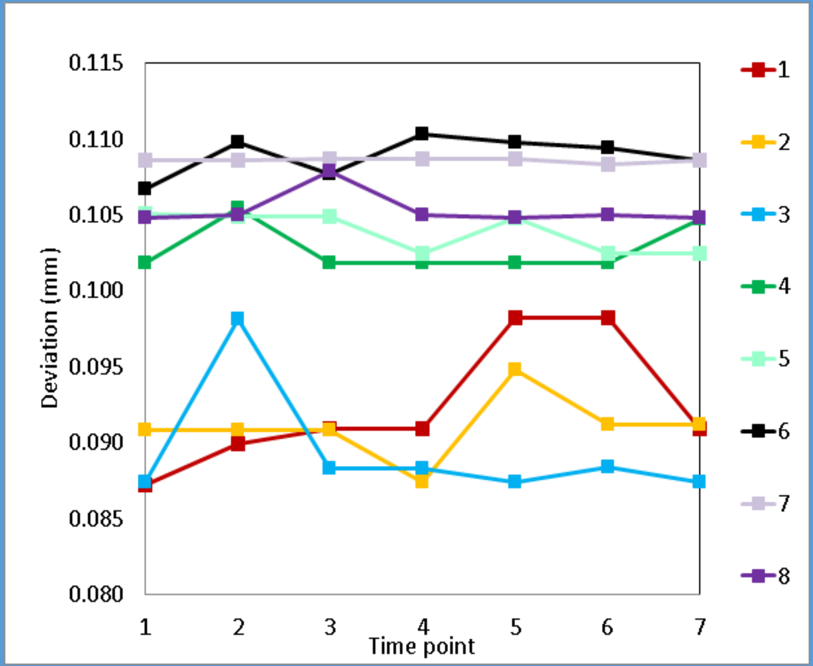
Rethinking the QA Paradigm: Improving Efficiency

- Identify key data to track
- Look for outliers
- Agree on actions when something is out of tolerance
- Standardizing our testing and analysis may lead to a more comprehensive interpretation of our results



Pooling QA results and assessing over time

- Maximum difference for leaf position accuracy over 8 same model linacs
- Very stable performance over time (submillimeter as measured with EPID)



Allows us to learn more from our QA efforts: larger data sets across institutions with standard work enables more robust analyses (statistical process control)

Gather data for our formal risk-based analysis investigations

Check of the Dosimetric Leaf Gap

Fig. 8, LoSasso et al, Med Phys, 1998

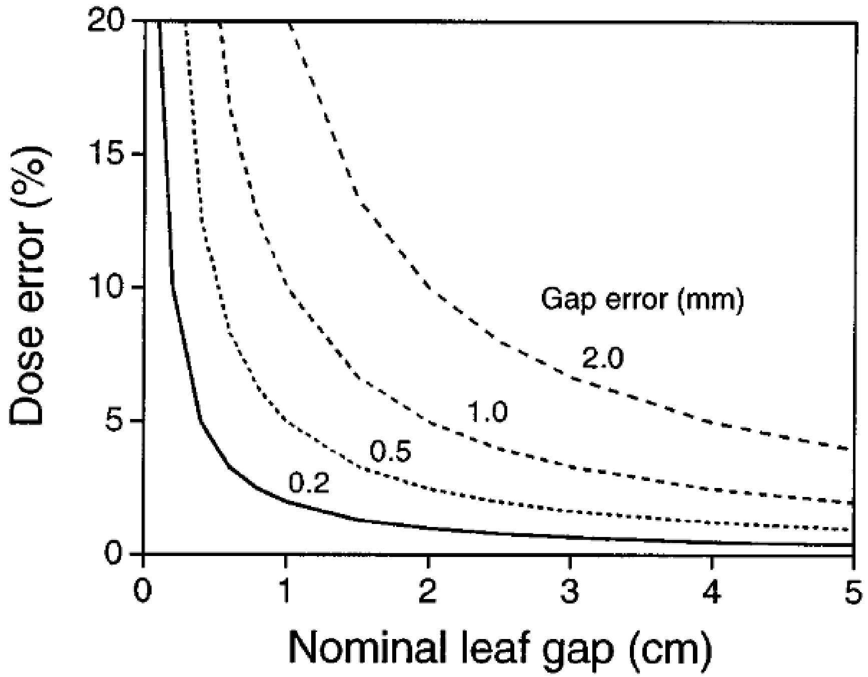


FIG. 8. Calculated results relating the error in the dose delivered to the error in the gap for a range of gap widths.

Medical Physics, Vol. 25, No. 10, October 1998

- TG 142 (Klein et al) recommends evaluation of the dosimetric leaf gap
  - Test is typically performed at the gap made by the junction of 4 leaves
  - Cumbersome to measure at multiple positions
- Goal: To devise a constancy check for the dosimetric leaf gap test:
  - Open and sweeping gap field
  - Measure with EPID and ion chamber
- To extend & automate the analysis to 2D

Automatic Evaluation of the 2D Dosimetric Leaf Gap (DLG) Measurement

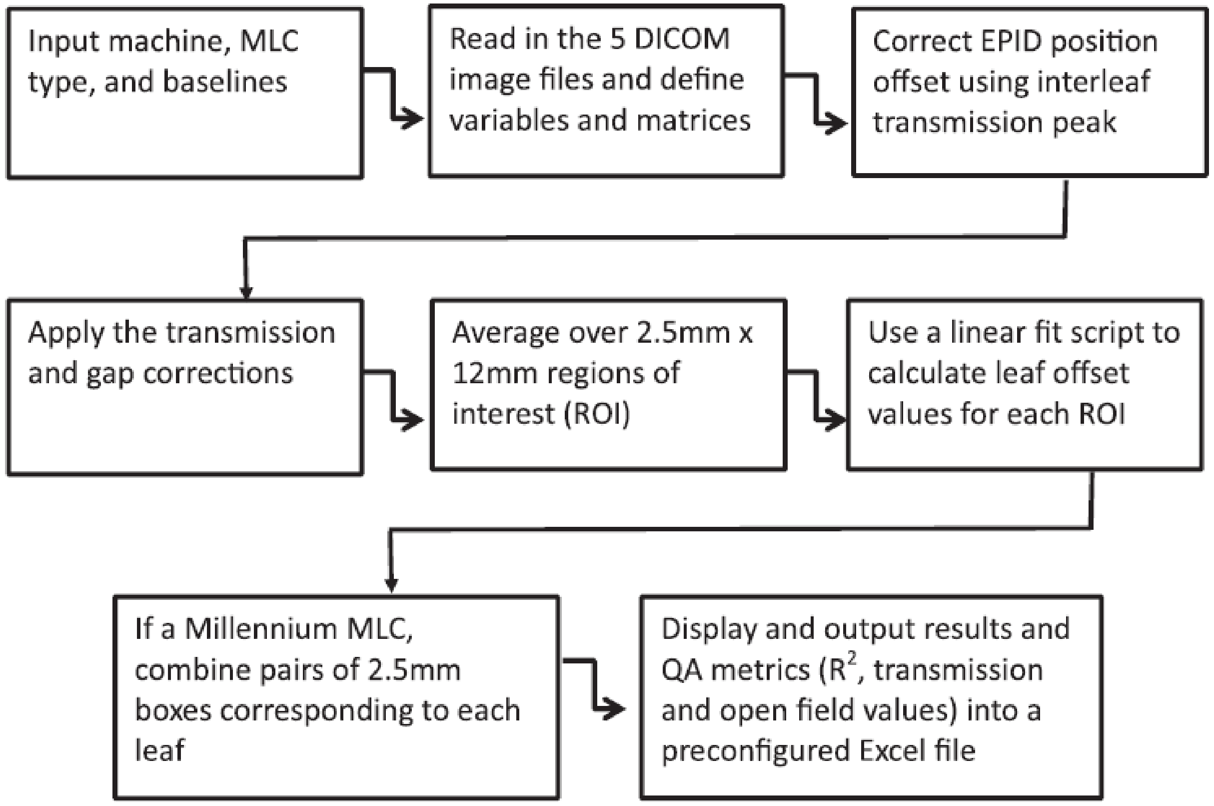


Figure 1. A flow chart diagraming the major steps in the MATLAB code.

<5 minutes to deliver all fields

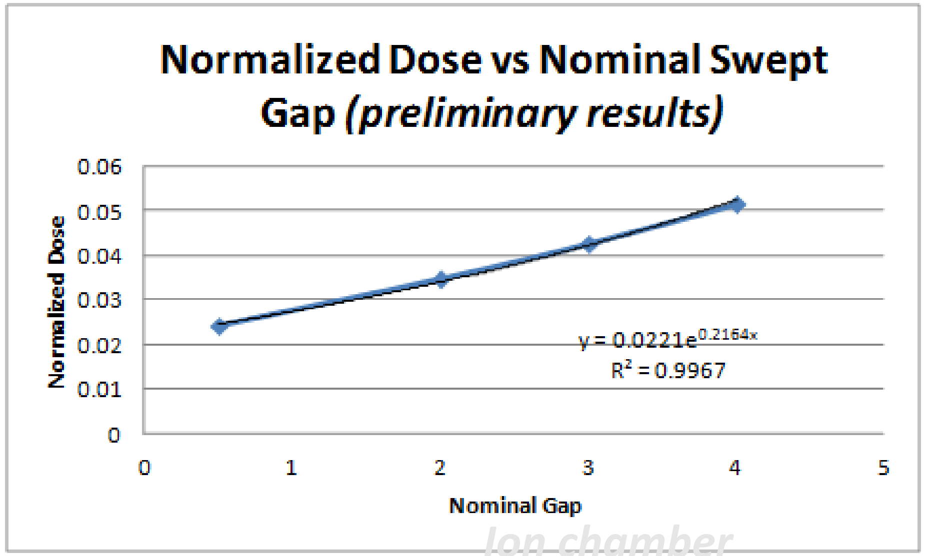
<1 minute software analysis

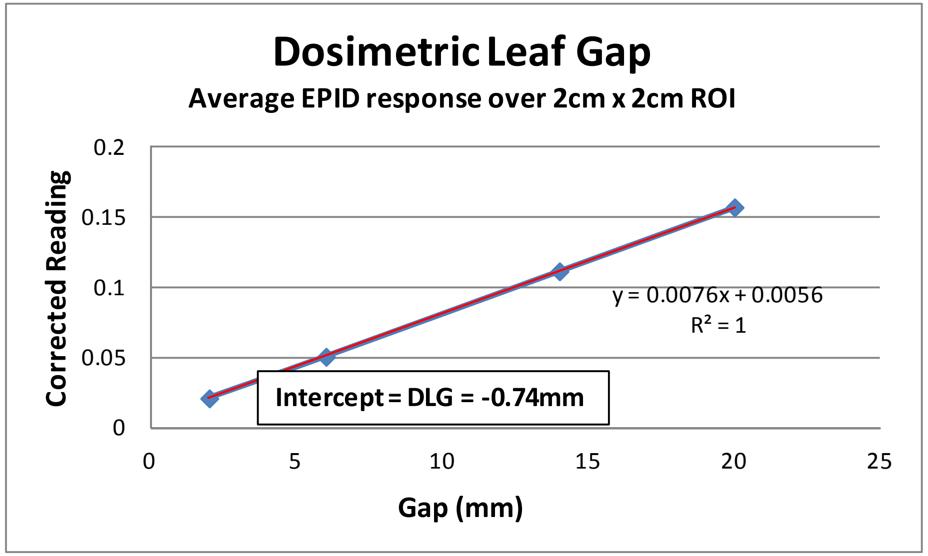
Ritter et al, BPEX, 2018

2D DLG Constancy Check

- Transmission differences can be averaged out using a 2x2 cm^2 ROI
- The DLG determined with the EPID is typically smaller than found with an ion chamber.
  - IC = 1.14 mm
  - EPID = 0.74 mm
- Results similar to those reported by Mei et al (2011).
- Validated vs ion chamber as well as 2D ion chamber array device

Ritter et al, BPEX, 2018





2D DLG Gantry Angle Dependence

- Smallest sliding field gap was delivered at gantry 90 and 270
- Differences evaluated on a leaf-by-leaf basis and set thresholds for action
- Results: 0.3 mm DLG changes were detected using a single sliding gap field – change in response is 6%
- Test and analysis only takes minutes to complete

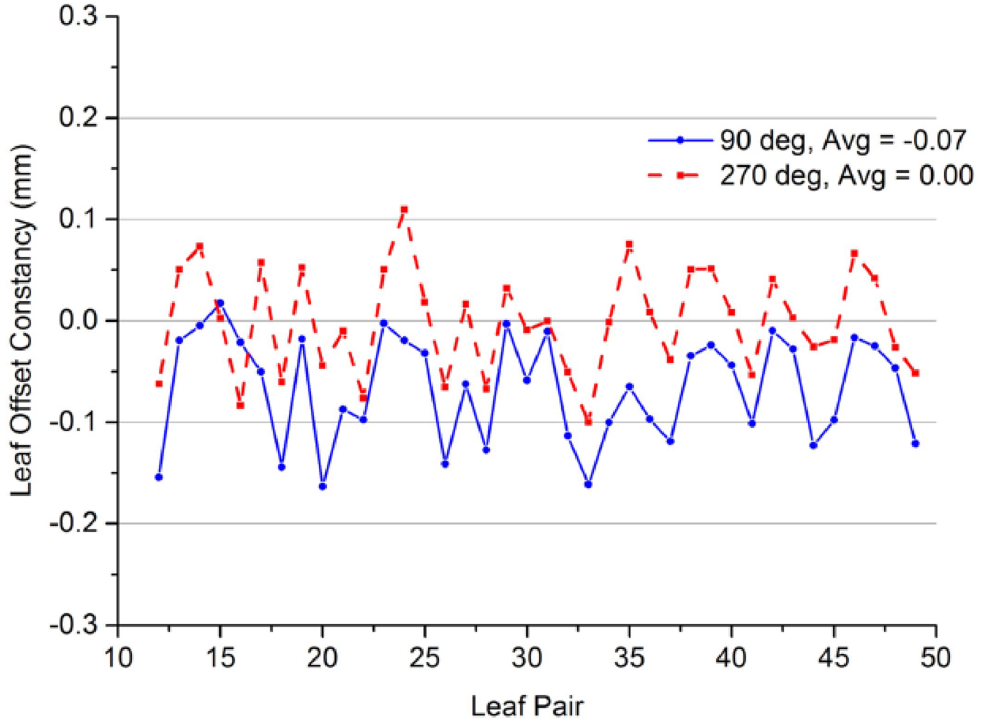


Figure 4c, Ritter et al, MLC evaluation 90 & 270 degrees

Ritter et al, BPEX, 2018

Applying Machine Learning to Linac QA Data

Can we apply machine learning to our data from different accelerators to better identify outlier measurements?

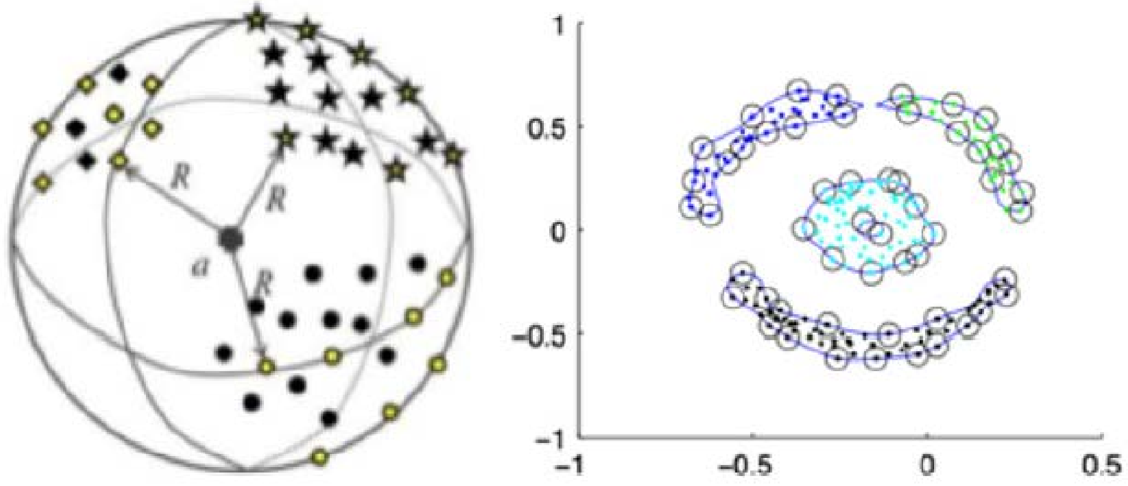


FIG. 3. The main principle of the support vector data description approach is that by first mapping input data from potentially different characteristics (e.g., normal Linac operation vs outliers) into a higher dimension and identifying the enclosing sphere (*left*), then re-mapping the sphere back into the data space, the data points can be divided efficiently into their corresponding clusters (*right*).[28]

El Naqa et al, Med Phys, In Press 2019

Evaluation of Phase 1 data: Gantry sag as a function of Gaussian kernel width

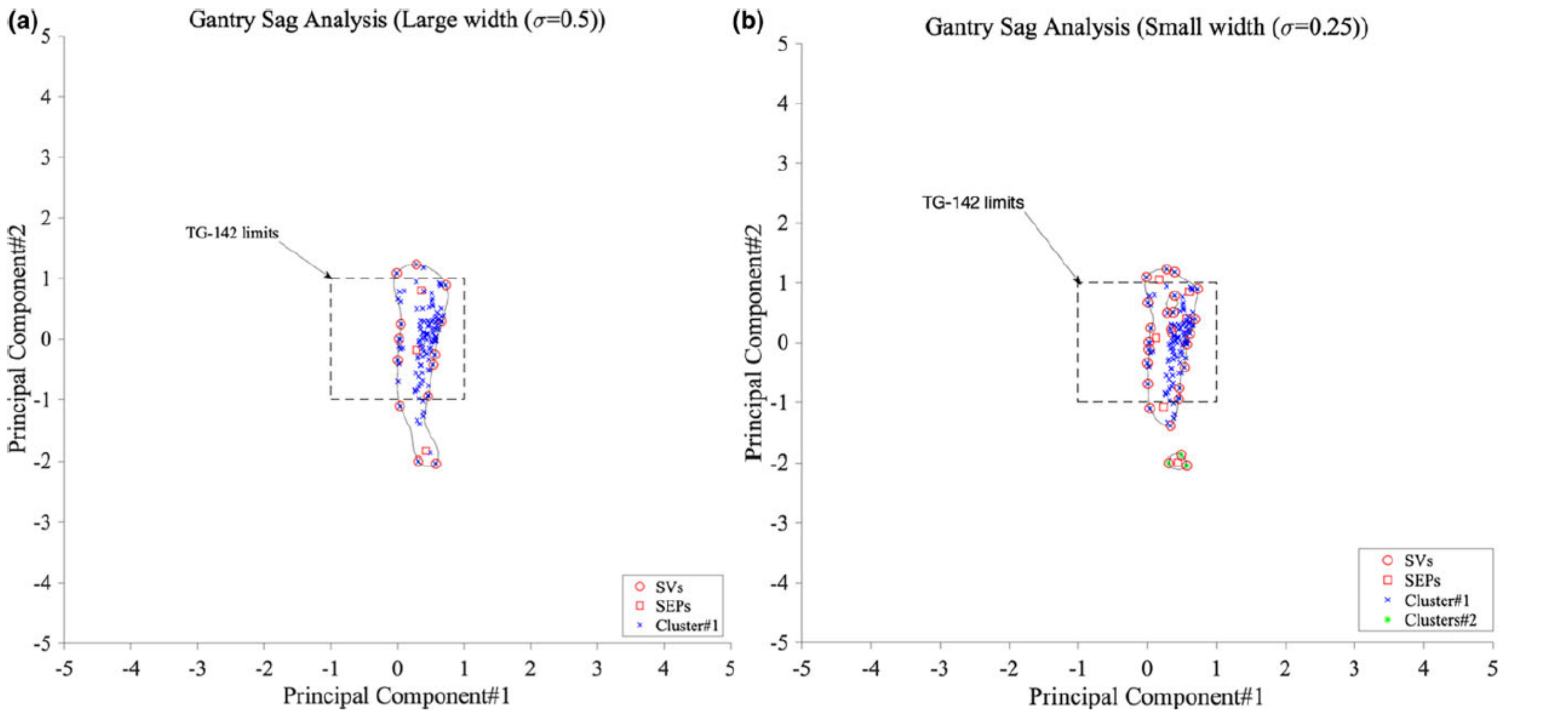


FIG. 4. Gantry sag analysis using support vector data description clustering. The principal components 1 and 2 correspond to the 0° and 180° angles, respectively. (a) Using a large Gaussian kernel width ($\sigma = 0.5$), it is noted that the cluster exceeds the bounds of the task group (TG)-142 recommendation (1 mm box) in the input data space. (b) Using a small Gaussian kernel width ($\sigma = 0.25$), it is noted the presence of two clusters of measurements, with the smaller cluster representing the "true" outliers per the shape of data which is anisotropic in comparison to the TG-142 recommendation.

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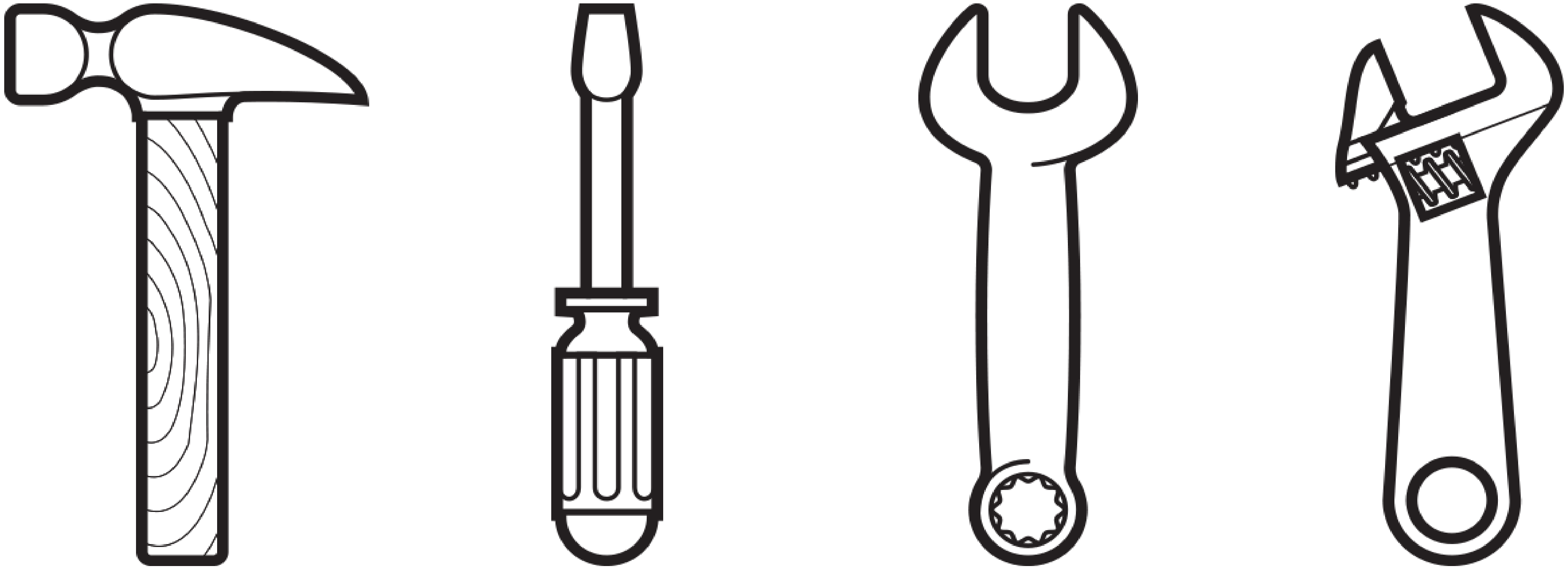
The EPID can be 1 tool in our Linac QA Toolbox – We still need other tools



Pictures

www.oxygenna.com

The EPID complements our other systems

- Ion chamber + water and/or water-equivalent plastics
- Array detectors
- Water phantom with scanning equipment

QA Needs for EPIDs

- For the EPID to be a QA tool, its response needs to be monitored
- QA should be established so that it's known when its not functioning correctly
- Be sensitive to making sure that real differences aren't washed out in the normalization of data analysis
- Determine what information is needed to confirm the stability of response

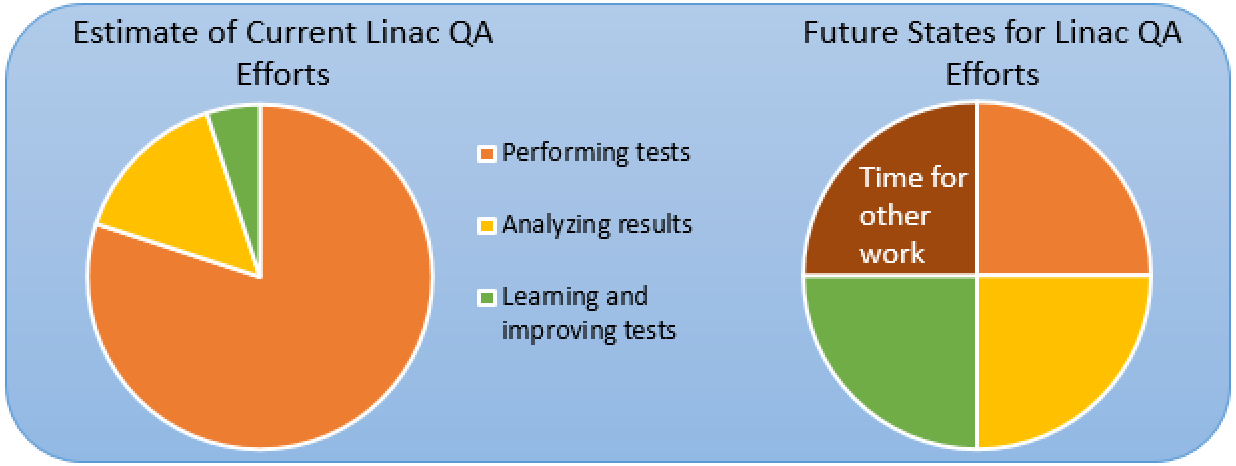
- AAPM TG 120 (Low et al) had brief mention of EPIDs

Related AAPM Guidance under Development

- TG307 on the Use of - EPIDs for Patient-Specific IMRT and VMAT QA
  - Chaired by Nesrin Dogan
- TG330 on EPID-Based Quality Assurance of Linear Accelerators
  - Chaired by Baozhou Sun
- TG 307 and TG 330 will coordinate as appropriate, especially with respect to language
- Also: TG 312 Task Group on Acceptance - Testing, Commissioning and Periodic Quality Assurance of Ion Chamber and Diode Detector Arrays (TG312)
  - Chaired by Sotirios Stathakis

Summary and Future Considerations

- EPID applications for linac QA range from acceptance testing and commissioning to routine QA
- Leveraging the EPID allows for efficiency in performing and analyzing tests
  - Change our daily and monthly QA review to automate the timely reporting of exceptions
- This will allow us to make time for other necessary work



References

- Cai et al, Three year experience of electronic portal imaging device based daily QA for photon radiation beams. Biomed. Phys. Eng. Express 5 015005, 2019.
- Eckhause et al, Automating linear accelerator quality assurance Med Phys 42: 6074-6083, 2015.
- El Naqa et al, Machine learning for automated quality assurance in radiotherapy: A proof of principle using EPID data description. Med Phys In Press, 2019.
- Fuangrod et al, A cine-EPID based method for jaw detection and quality assurance for tracking jaw in IMRT/VMAT treatments. Physica Medica, 31: 16-24, 2015.
- Miri N et al, Virtual EPID standard phantom audit (VESPA) for remote IMRT and VMAT credentialing. Phys Med Biol. 62(11):4293–9, 2017.
- Miri N et al, A remote EPID-based dosimetric TPS planned audit of centers for clinical trials: outcomes and analysis of contributing factors. Radiation Oncology 13: 178, 2018.
- Ritter et al "Automated EPID-based measurement of MLC leaf offset as a quality control tool" Biomed. Phys. Eng. Express 4: 027008, 2018.
- Yaddanapudi et al, Rapid acceptance testing of modern linac using on-board MV and kV imaging systems. Med Phys 44: 3393-3406, 2017

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