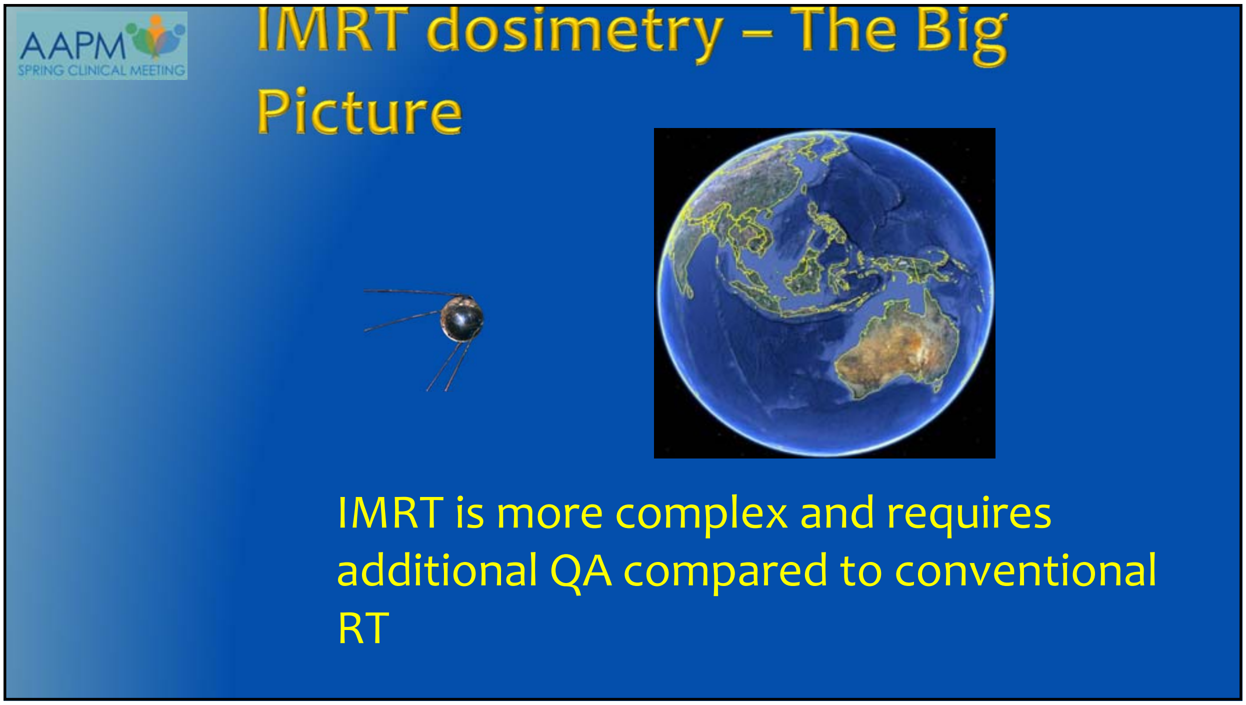
Applications of Multi-Dimensional Arrays

Clinical Needs Driving Multi-Dimensional Systems

Vladimir Feygelman
Moffitt Cancer Center
Tampa, FL

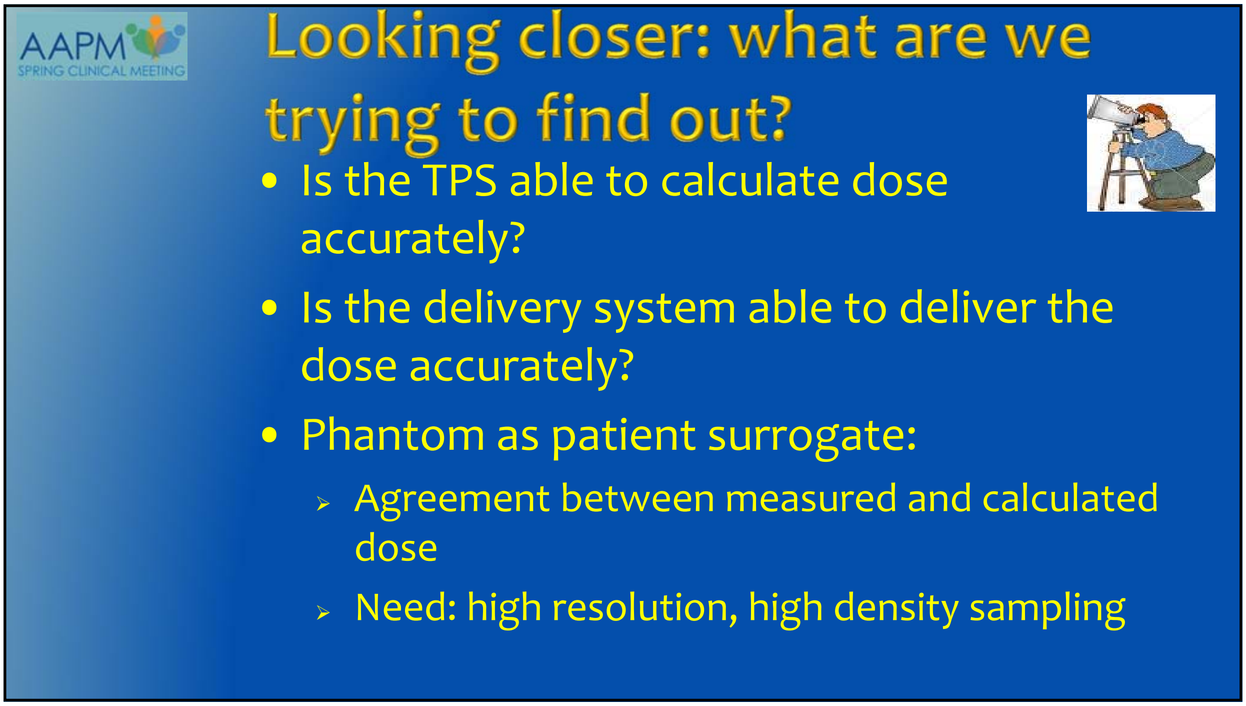
Disclosure

- VF has a sponsored research agreement with Sun Nuclear Corp.
- VF is a TG-244 contributor



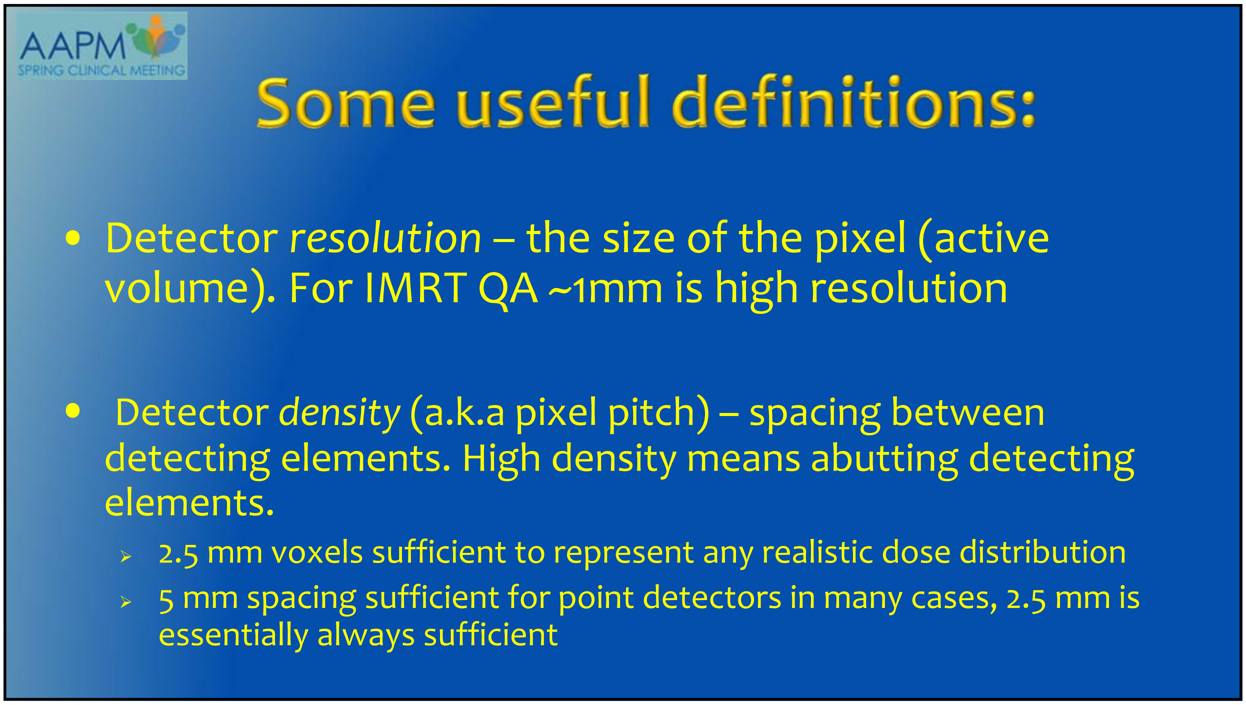
IMRT dosimetry – The Big Picture

IMRT is more complex and requires additional QA compared to conventional RT



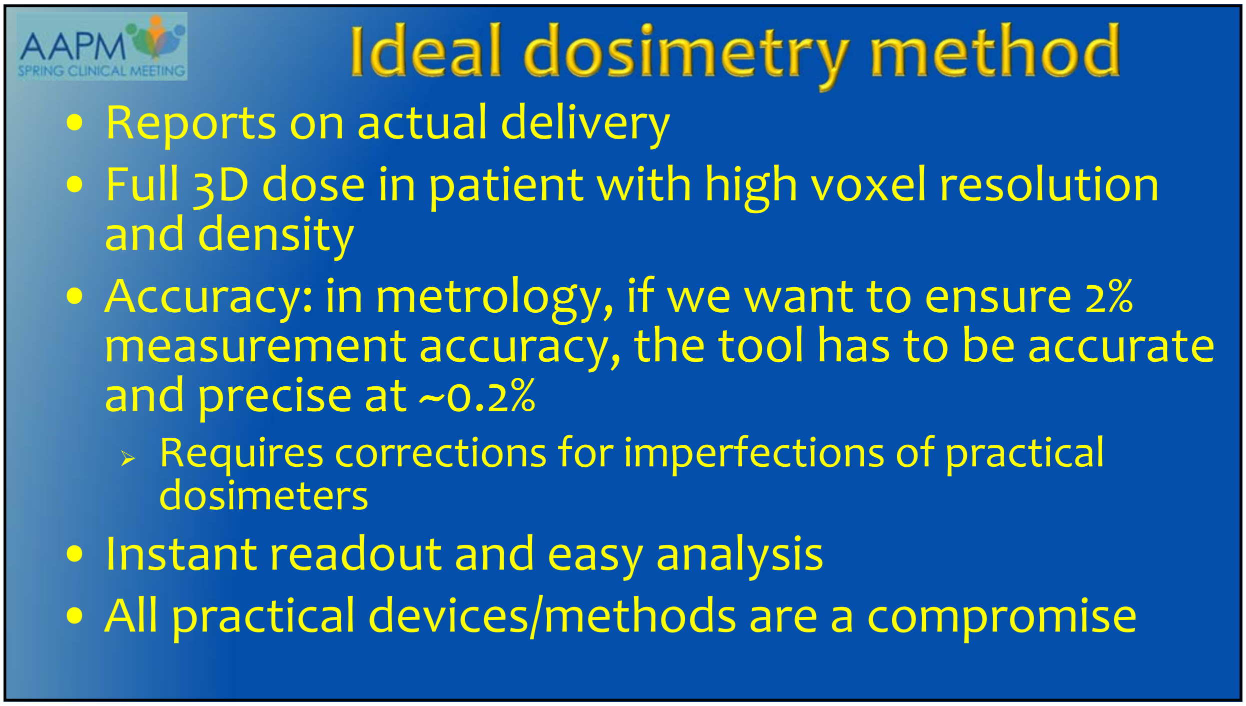
Looking closer: what are we trying to find out?

- Is the TPS able to calculate dose accurately?
- Is the delivery system able to deliver the dose accurately?
- Phantom as patient surrogate:
  - Agreement between measured and calculated dose
  - Need: high resolution, high density sampling



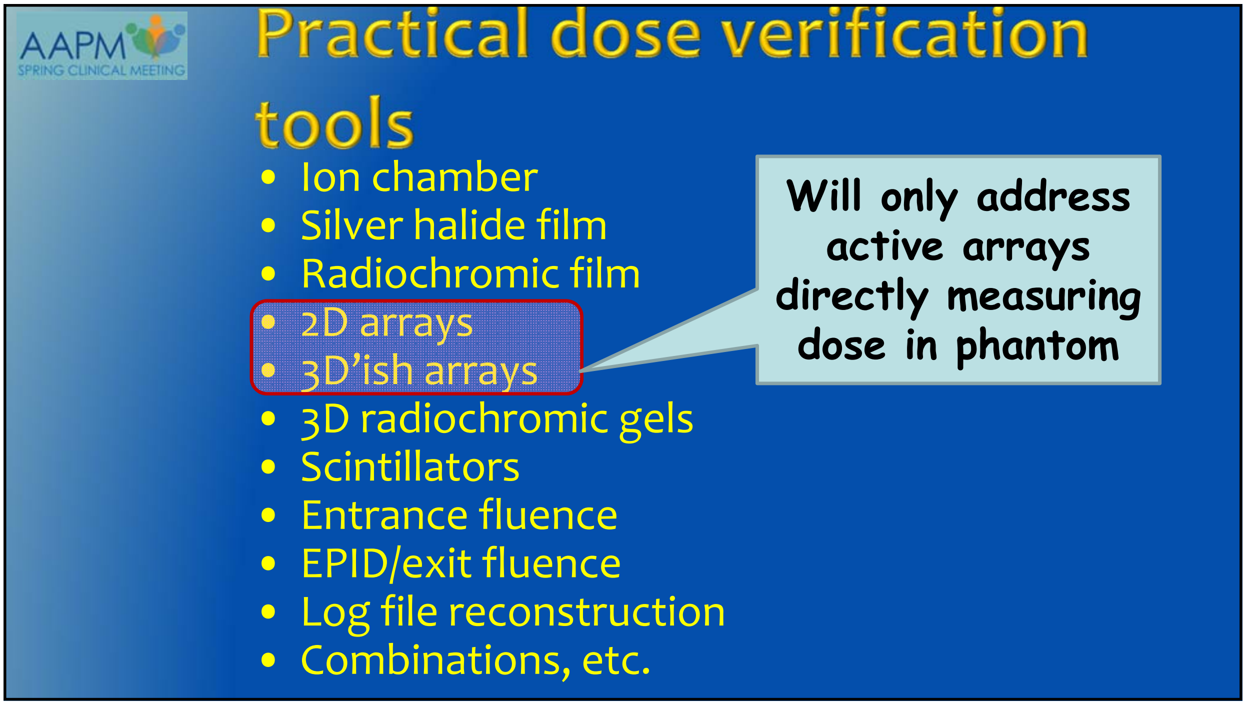
Some useful definitions:

- Detector *resolution* – the size of the pixel (active volume). For IMRT QA ~1mm is high resolution
- Detector *density* (a.k.a pixel pitch) – spacing between detecting elements. High density means abutting detecting elements.
  - 2.5 mm voxels sufficient to represent any realistic dose distribution
  - 5 mm spacing sufficient for point detectors in many cases, 2.5 mm is essentially always sufficient



Ideal dosimetry method

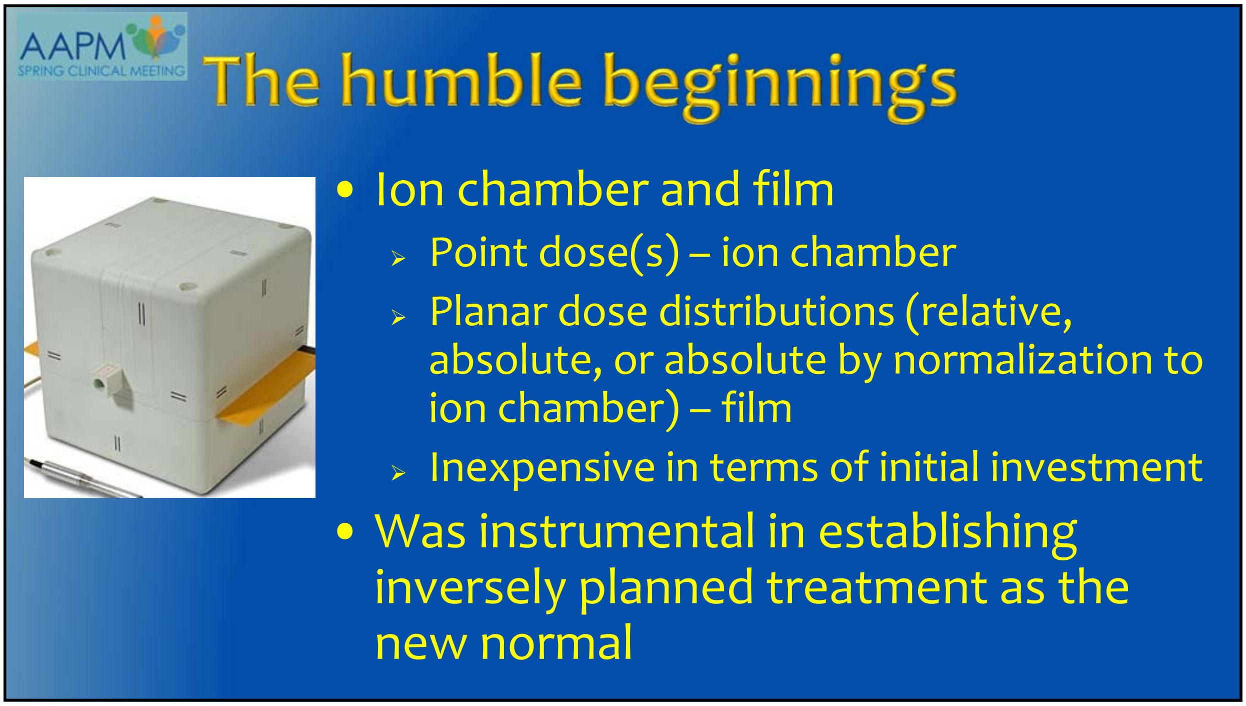
- Reports on actual delivery
- Full 3D dose in patient with high voxel resolution and density
- Accuracy: in metrology, if we want to ensure 2% measurement accuracy, the tool has to be accurate and precise at ~0.2%
  - Requires corrections for imperfections of practical dosimeters
- Instant readout and easy analysis
- All practical devices/methods are a compromise



Practical dose verification tools

- Ion chamber
- Silver halide film
- Radiochromic film
- 2D arrays
- 3D'ish arrays
- 3D radiochromic gels
- Scintillators
- Entrance fluence
- EPID/exit fluence
- Log file reconstruction
- Combinations, etc.

Will only address active arrays directly measuring dose in phantom



The humble beginnings

- Ion chamber and film
  - Point dose(s) – ion chamber
  - Planar dose distributions (relative, absolute, or absolute by normalization to ion chamber) – film
  - Inexpensive in terms of initial investment
- Was instrumental in establishing inversely planned treatment as the new normal

Ion chamber

- Absolutely indispensable for commissioning: still the gold standard
- Despite some methodology questions, this paper shows that it is quite possible to have good gamma analysis results from any number of devices and still fail 3% by ion chamber in high dose low gradient region(s)…

Medical Physics
The International Journal of Medical Physics Research and Practice

Toward optimizing patient-specific IMRT QA techniques in the accurate detection of dosimetrically acceptable and unacceptable patient plans

Elizabeth M. McKenzie, Peter A. Balter, Francesco C. Stingo, Jimmy Jones, David S. Followill, and Stephen F. Kry

Citation: Medical Physics **41**, 121702 (2014); doi: 10.1118/1.4899177

Film

- High pixel resolution and density vs. inconvenience, high maintenance and limited accuracy
- Continuous use for system commissioning strongly advocated by Pat Cadman:
  - However, he has also shown in a very useful paper that almost all commissioning tasks can be accomplished by other means (e.g. diode)
  - The only remaining item is intraleaf leakage which is hard to measure even with film and is best left to published values

Modern day QA

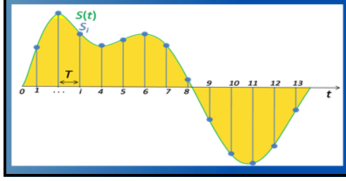
- Setting system commissioning aside for now, as IMRT usage increased, it became impractical to use chamber/film for routine patient-specific QA

Clinical need #1: Replace film for routine dose distribution measurements with a more robust dosimeter…

… Which brings us to planar electronic arrays

Ideal array to replace film

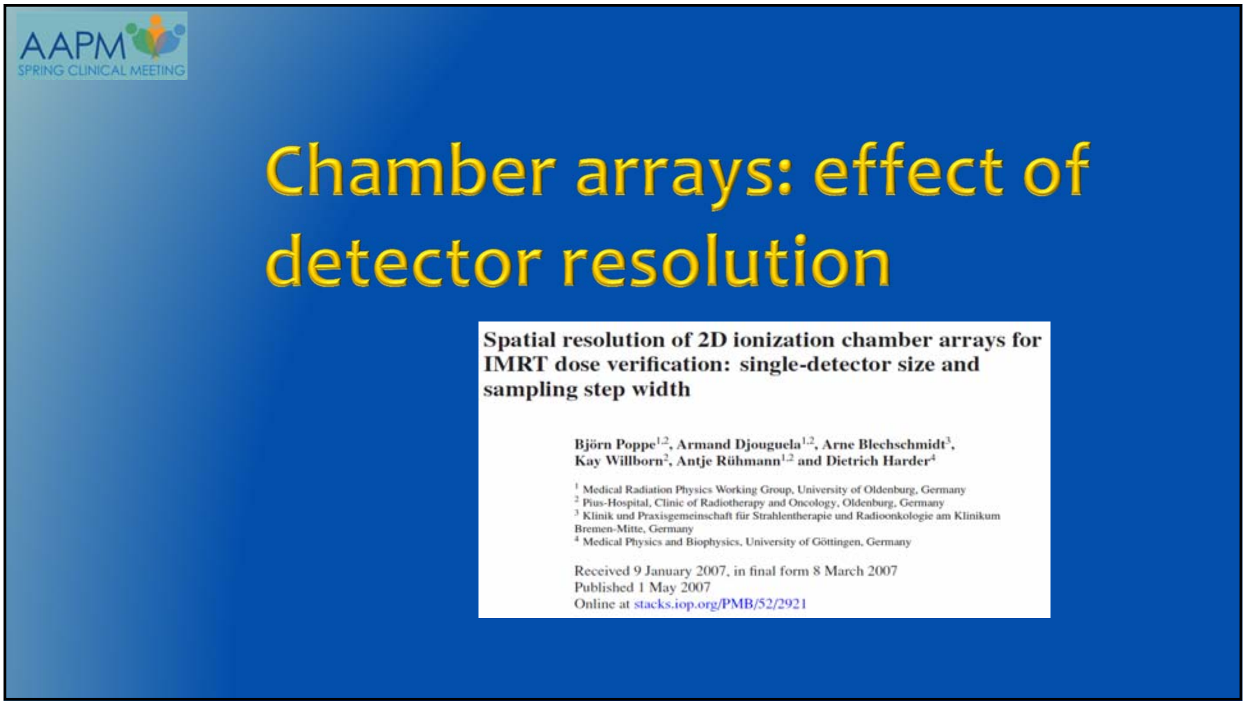
- Small detector size (pixel size). For IMRT analysis, ≤1mm is essentially a point detector
- Detectors close together (high pixel density). For IMRT analysis, point detectors spaced ~2.5 mm are sufficient from the Nyquist theorem point of view



Typical real arrays

- Chamber arrays
  - Low resolution
  - Low density
  - Energy-independent

- Diode arrays:
  - High detector resolution (~ 1 mm)
  - Low detector density
  - Energy-dependent response



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Chamber arrays: effect of detector resolution

Spatial resolution of 2D ionization chamber arrays for IMRT dose verification: single-detector size and sampling step width

Björn Poppe[1,2], Armand Djouguela[1,2], Arne Blechschmidt[3], Kay Willborn[2], Antje Rühmann[1,2] and Dietrich Harder[4]

[1] Medical Radiation Physics Working Group, University of Oldenburg, Germany
[2] Pius-Hospital, Clinic of Radiotherapy and Oncology, Oldenburg, Germany
[3] Klinik und Praxisgemeinschaft für Strahlentherapie und Radioonkologie am Klinikum Bremen-Mitte, Germany
[4] Medical Physics and Biophysics, University of Göttingen, Germany

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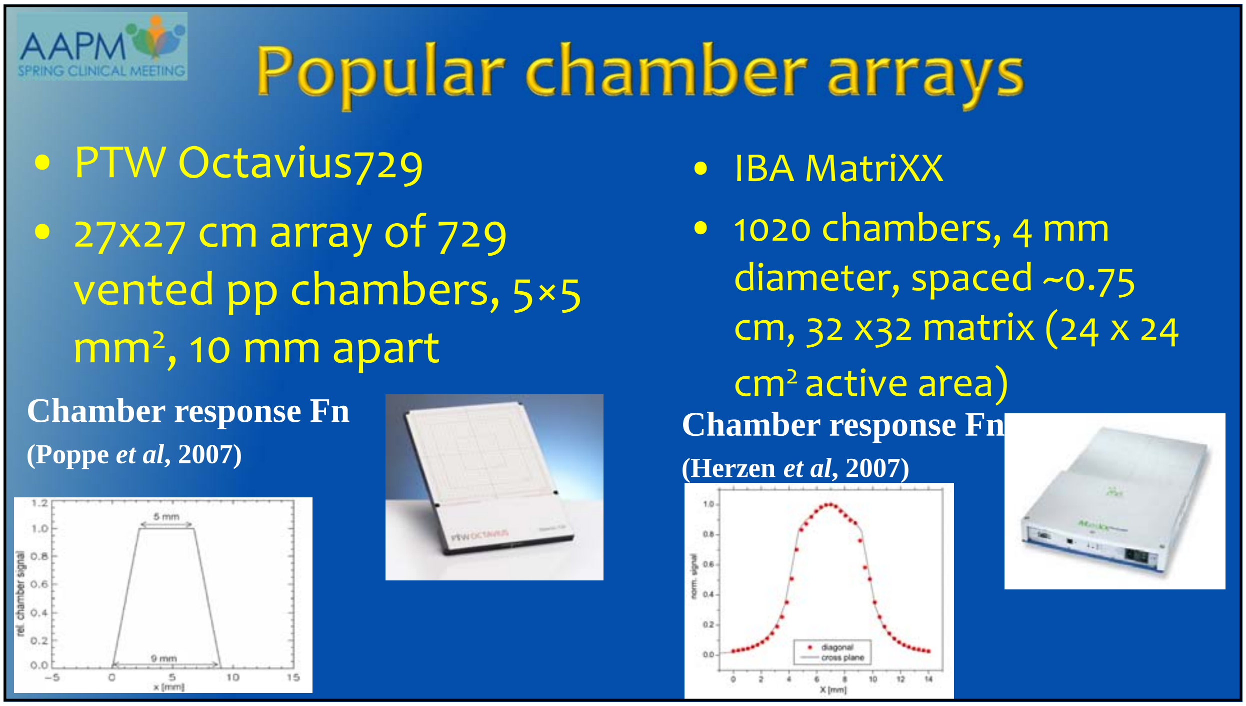

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Popular chamber arrays

- PTW Octavius729
- 27x27 cm array of 729 vented pp chambers, 5×5 mm², 10 mm apart

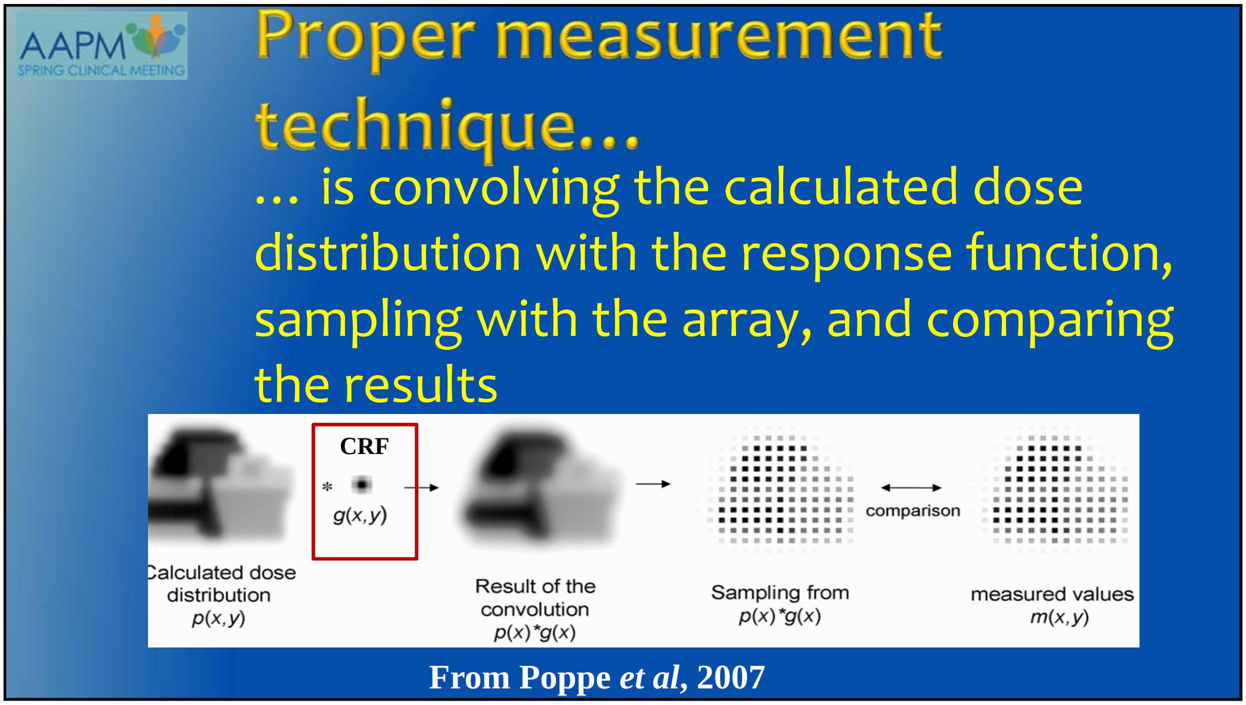
Chamber response Fn

(Poppe *et al*, 2007)

- IBA MatriXX
- 1020 chambers, 4 mm diameter, spaced ~0.75 cm, 32 x32 matrix (24 x 24 cm² active area)

Chamber response Fn

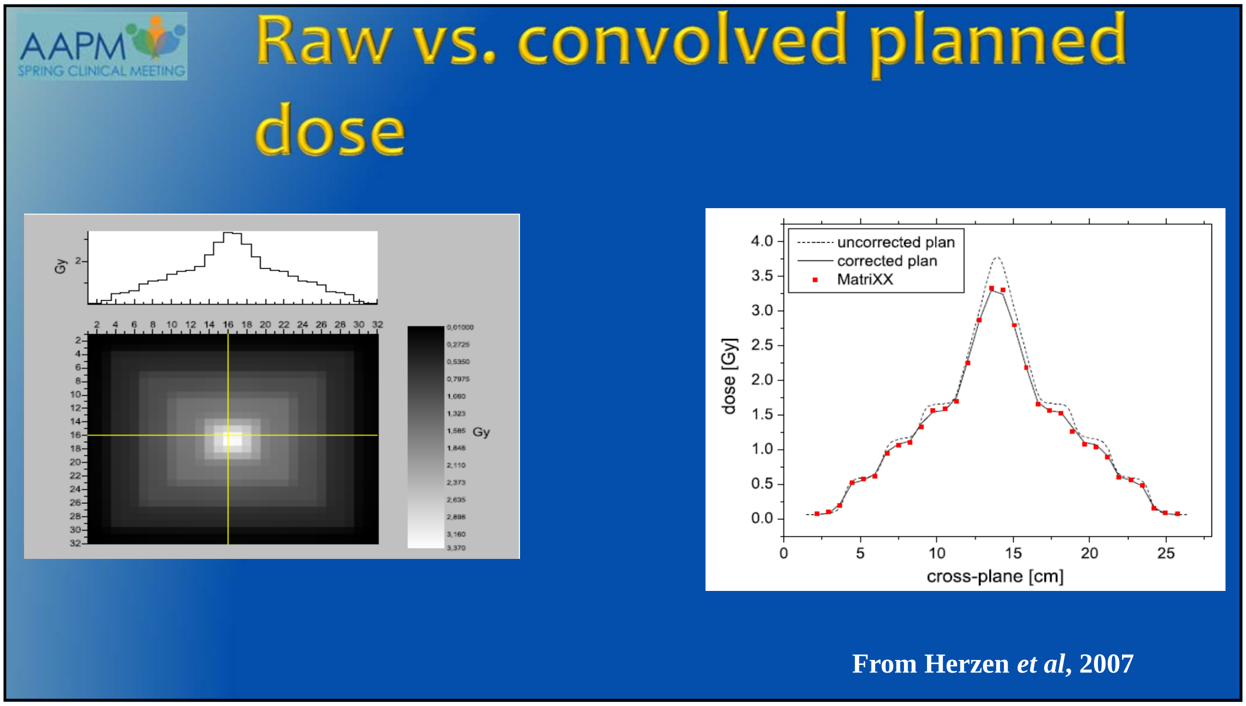
(Herzen *et al*, 2007)



Proper measurement technique…

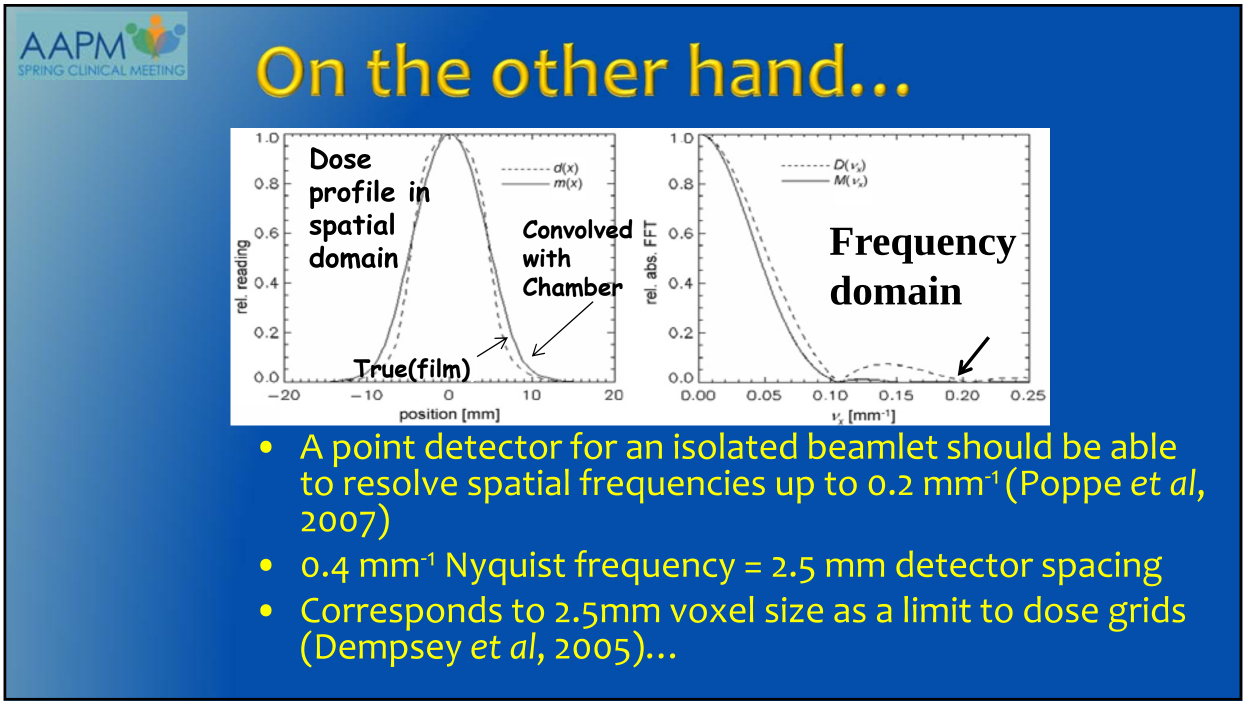
… is convolving the calculated dose distribution with the response function, sampling with the array, and comparing the results

From Poppe *et al*, 2007



Raw vs. convolved planned dose

From Herzen *et al*, 2007



On the other hand…

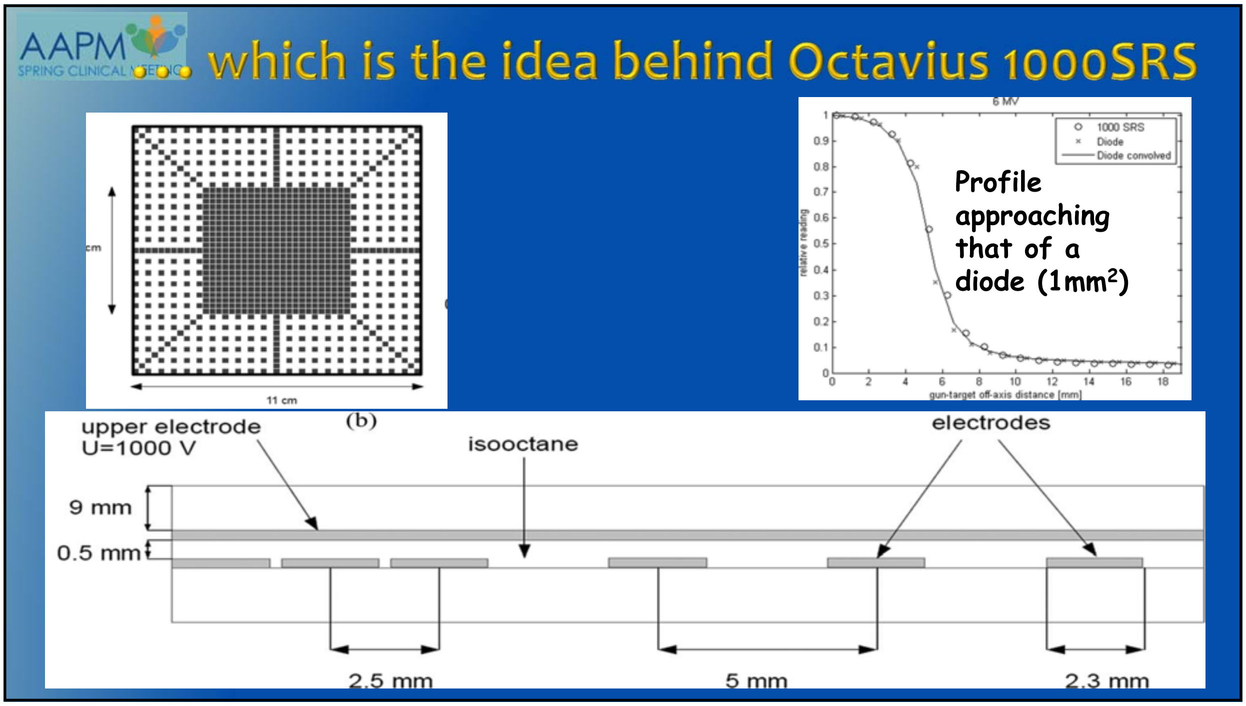
Dose profile in spatial domain

Convolved with Chamber

True(film)

Frequency domain

- A point detector for an isolated beamlet should be able to resolve spatial frequencies up to 0.2 mm^{-1} (Poppe *et al*, 2007)
- 0.4 mm^{-1} Nyquist frequency = 2.5 mm detector spacing
- Corresponds to 2.5mm voxel size as a limit to dose grids (Dempsey *et al*, 2005)…



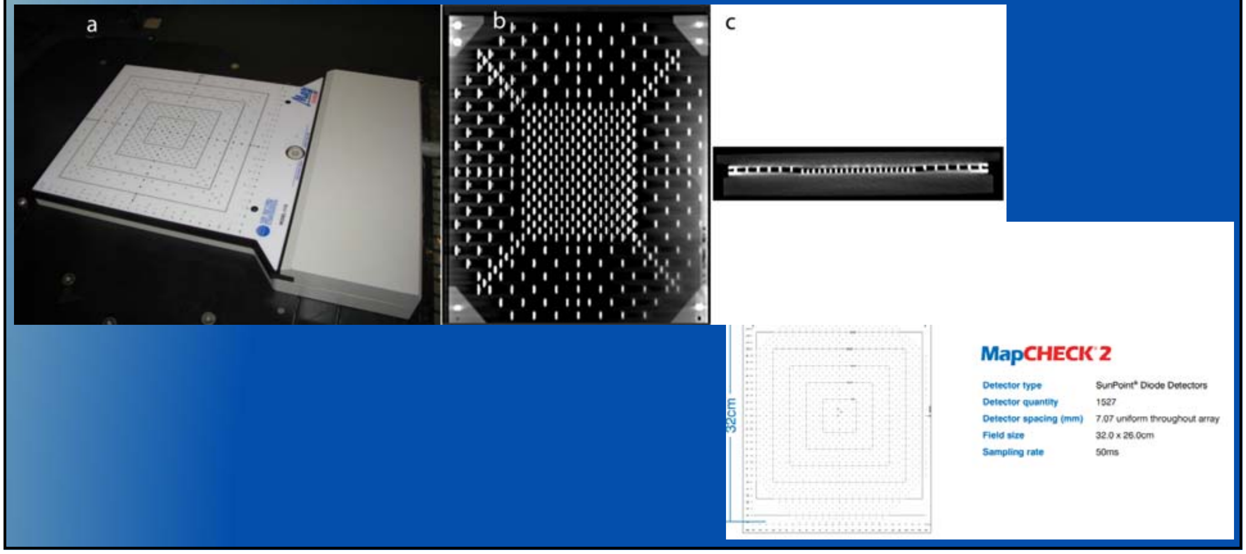
… which is the idea behind Octavius 1000SRS

Profile approaching that of a diode (1mm^2)

Diodes are point detectors

- Diode arrays produce dose distributions that do not need to be further convolved, as the detector response function is essentially a delta
- Detector density still needs to be sufficient
- Compared to chamber arrays, trade detector resolution for more complex calibration, stemming largely from energy dependence

MapCHECK/ MapCHECK2



MapCHECK®2

Detector type	SunPoint® Diode Detectors
Detector quantity	1527
Detector spacing (mm)	7.07 uniform throughout array
Field size	32.0 x 26.0cm
Sampling rate	50ms

All planar arrays have angular dependence…

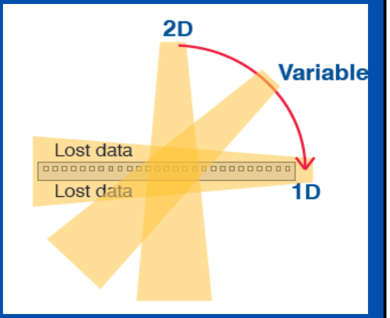
…which needs to be addressed for the true composite IMRT measurements

- Beam by beam IMRT measurements are not recommended
- And only composites are possible for VMAT…

However, even then a problem remains

2D arrays and rotational measurements

Even with perfectly isotropic response, modulation information is partially lost: 2D degenerates into 1D when beam is parallel to the array plane

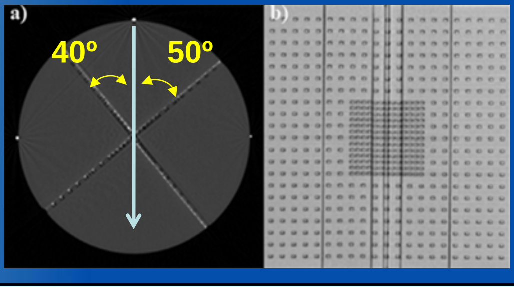


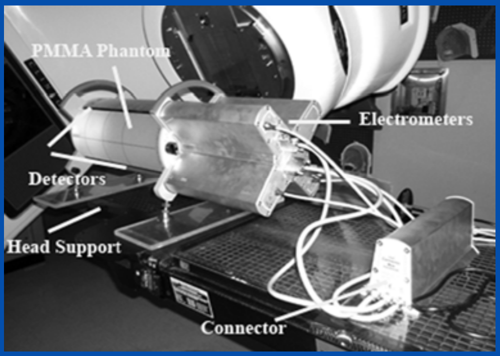
Picture: Sun Nuclear Corp.

Clinical Need #2: Develop arrays suitable for composite and rotational measurements…

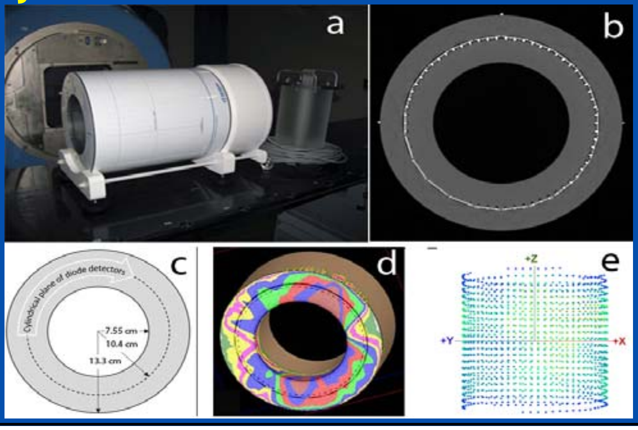
…led to quasi-3D arrays

Delta^4 – The "X" geometry





ArcCHECK – The "O" geometry



- Octavius 4D – planar array rotating in synch with gantry
- Synchronization through physical inclinometer
- Strictly speaking, a 2D array but functions rather like a Quasi-3D

Quasi-3D arrays are well suited for composite/rotational measurements

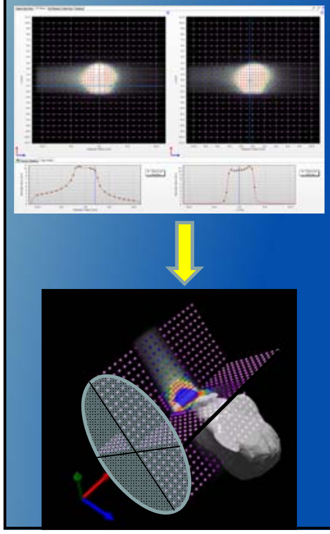
- The “X” geometry: between the two orthogonal planes, modulation information is always preserved
- The “O” geometry: the detector pattern is roughly the same in BEV from any angle
- Rotating plane: beam is always perpendicular to the array

Perhaps more importantly, Quasi-3D arrays are amenable to Clinical Need #3: Obtain 3D dose distributions in phantom

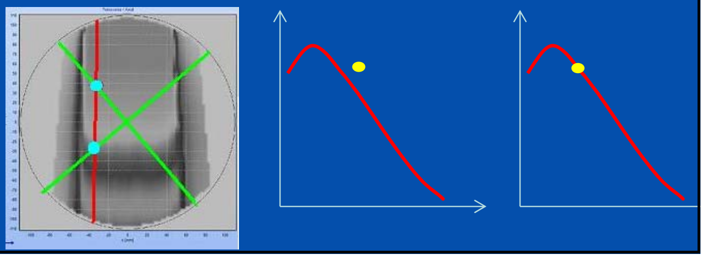
Semi-empirical 3D Dose reconstruction in phantom

- Universal among all approaches: the detector density is not sufficient to represent the dose with ~2.5 mm voxel
- Some intelligent interpolation is needed
  - Either the TPS dose is modified by measurement points, or independent calculation is adjusted to measured points, or a combination

Delta4 phantom dose reconstruction



- TPS dose on the phantom is exported at the control point (VMAT) or beam (IMRT) level
- The dose along each ray is the plan data renormalized by the measured values



ArcCHECK/3DVH phantom dose reconstruction

- The measured dose is sorted into sub-beams
- Relative dose per sub-beam is calculated with an internal convolution engine
- Relative dose per sub-beam is morphed based on the entrance and exit diode dose
- Sub-beams are added together to produce a "virtual gel" 3D dose on the phantom, with TPS voxel resolution

Octavius phantom dose reconstruction

(From Stathakis et al, 2013)

- Dose for a given gantry angle is extrapolated along the ray through every measurement point based on independently stored PDD data
- Dose is summed for all angles and can be interpolated to user's resolution

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The ability to reliably reconstruct 3D dose with high resolution (≤ 2.5 mm voxel) leads to Clinical need #4: Use fast electronic arrays for more comprehensive commissioning of the planning/delivery systems

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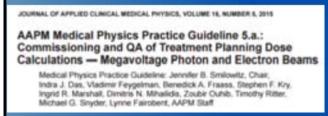
IMRT / VMAT Commissioning

Dosimetry tools and techniques for IMRT

Daniel A. Low[a]
Washington University, St. Louis, Missouri 63110
Jean M. Moran
University of Michigan, Ann Arbor, Michigan 48109
James F. Dempsey
Viewray Incorporated, Cleveland, Ohio 44106
Lei Dong
M. D. Anderson Cancer Center, Houston, Texas 77013
Mark Oldham
Duke University Medical Center, Durham, North Carolina 27710



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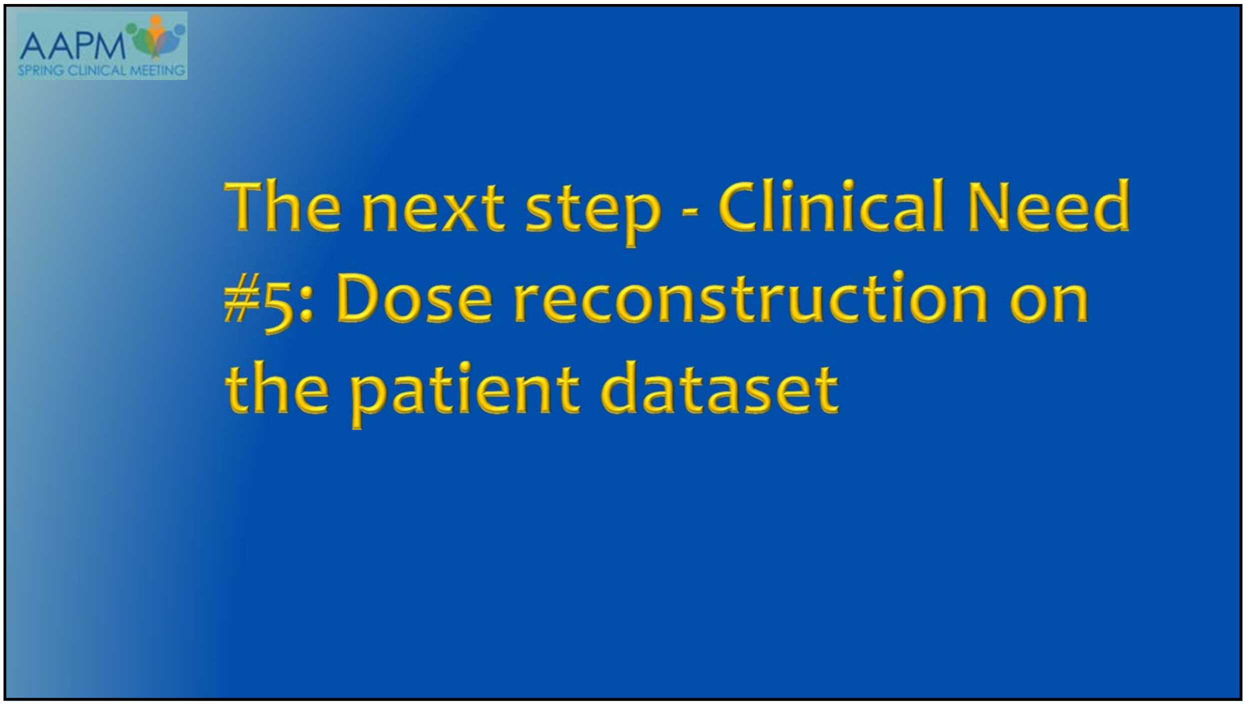
AAPM Medical Physics Practice Guideline 5.a.: Commissioning and QA of Treatment Planning Dose Calculations — Megavoltage Photon and Electron Beams

Medical Physics Practice Guideline: Jennifer B. Smilowitz, Chair, Indra J. Das, Vladimir Feygelman, Benedick A. Fraass, Stephen F. Kry, Ingrid R. Marshall, Dimitris N. Mihailidis, Zoubir Ouhib, Timothy Ritter, Michael G. Snyder, Lynne Fairobent, AAPM Staff

- Ion Chamber is still a must!
- For dose distribution, electronic arrays were discouraged due to limited spatial resolution
- TG-244 encourages judicious use of modern array systems, provided resolution ≤2.5 mm can be reliably achieved



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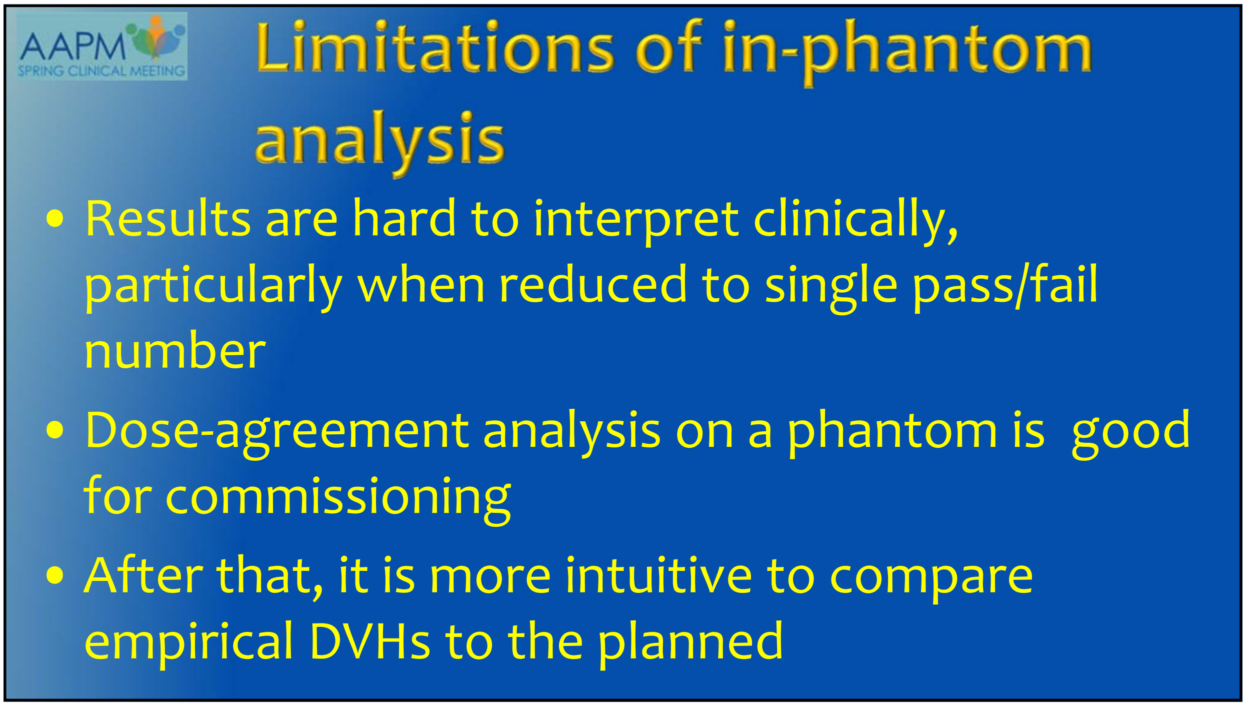
The next step - Clinical Need #5: Dose reconstruction on the patient dataset



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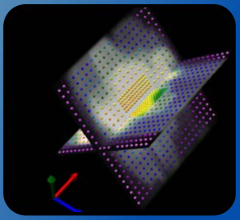
Limitations of in-phantom analysis

- Results are hard to interpret clinically, particularly when reduced to single pass/fail number
- Dose-agreement analysis on a phantom is good for commissioning
- After that, it is more intuitive to compare empirical DVHs to the planned

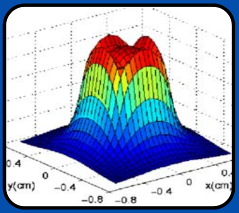
Delta4 "Anatomy"

- Totally different from phantom 3D dose
  - Extract the fluence from phantom measurement
  - Calculate the dose on the patient CT dataset based on that fluence with a Pencil-Beam algorithm
  - Requires a set of PDDs on a water phantom and in-air output factors (S_c) for each energy

Fluence estimate

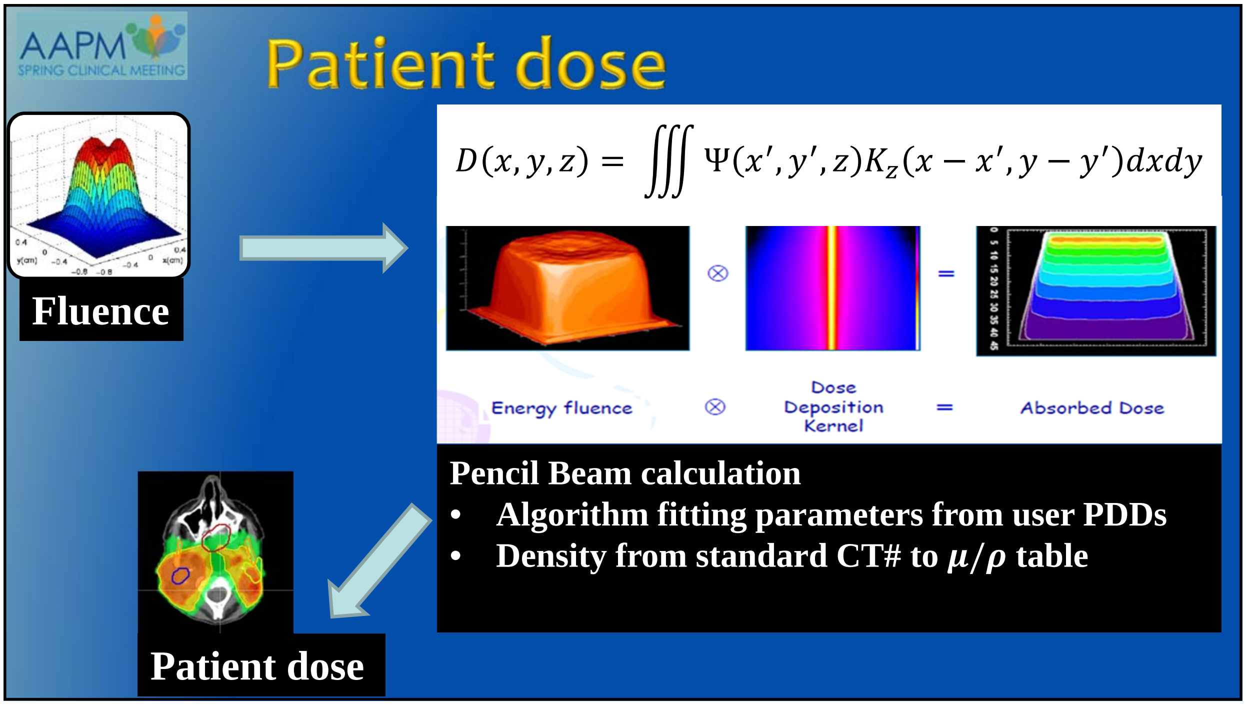


Measurement



Fluence estimate – a linear programming approach

- **Optimization problem: find the minimum area integral of the energy fluence to produce no less than measured dose at any point in phantom**
- **Resolution** $6 \times 6\ mm^2$



Patient dose

$$D(x,y,z) = \iiint \Psi(x',y',z)K_z(x-x',y-y')dxdy$$

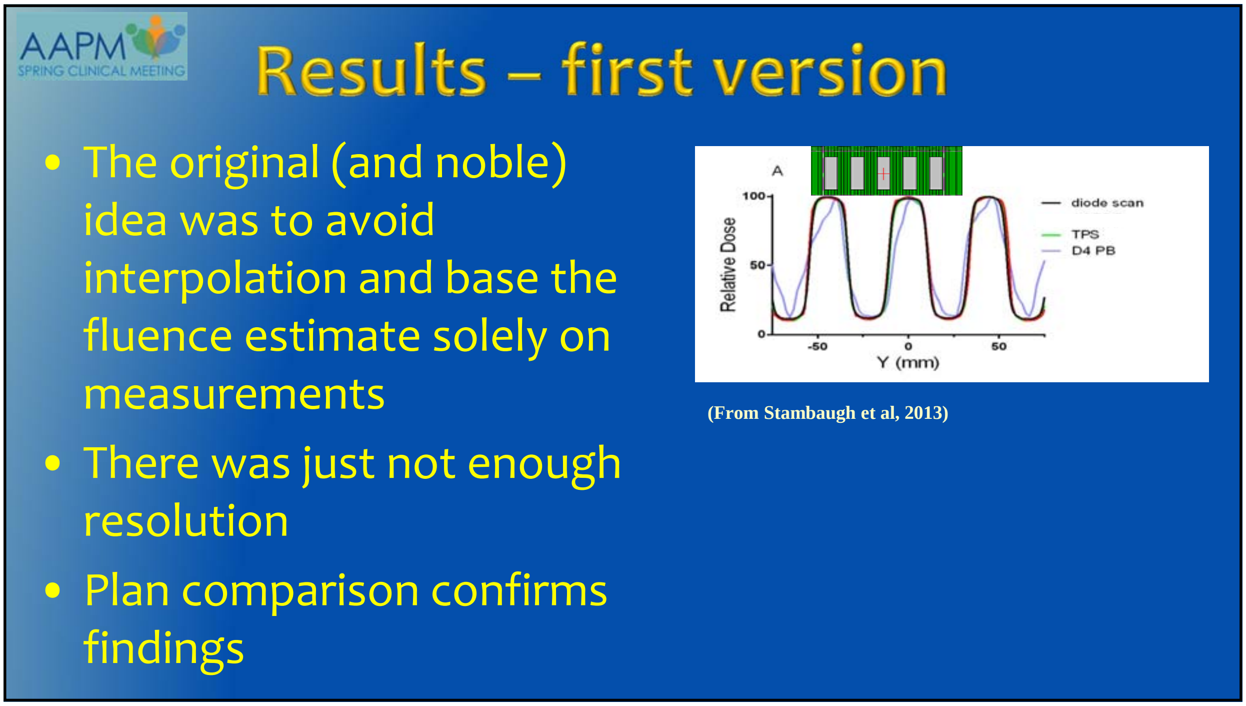
Energy fluence ⊗ Dose Deposition Kernel = Absorbed Dose

Fluence

Pencil Beam calculation

- **Algorithm fitting parameters from user PDDs**
- **Density from standard CT# to μ/ρ table**

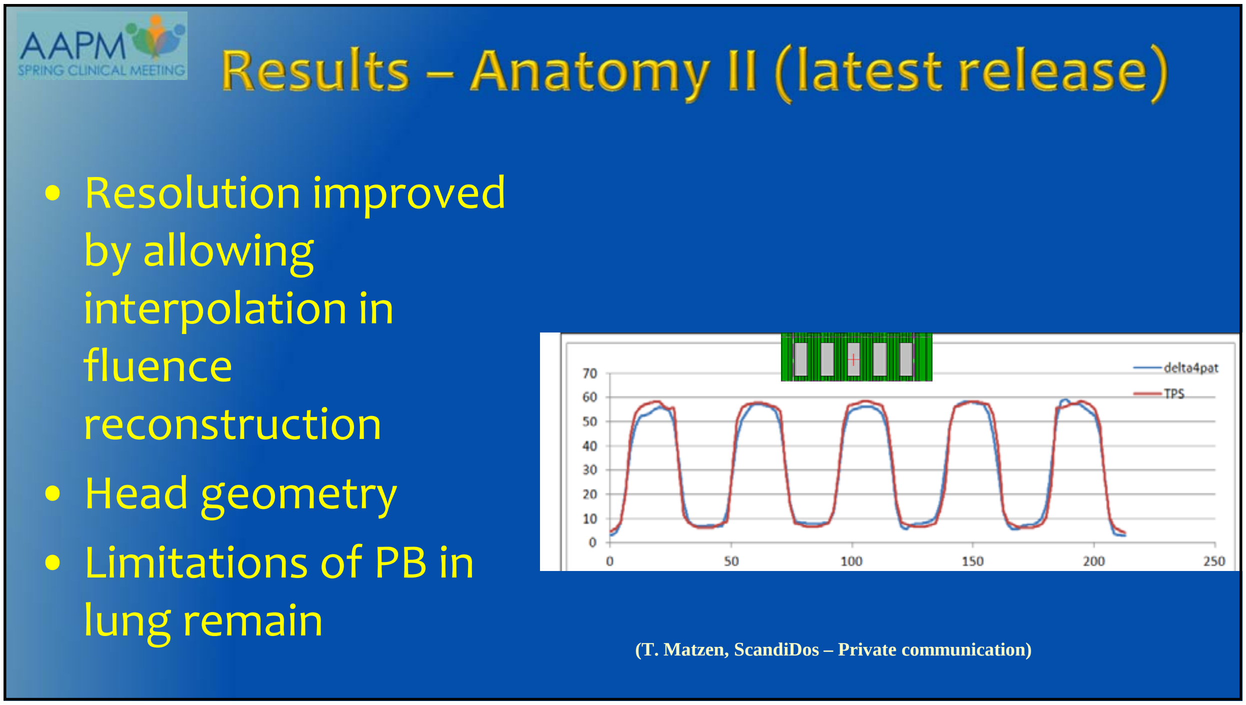
Patient dose



Results – first version

- The original (and noble) idea was to avoid interpolation and base the fluence estimate solely on measurements
- There was just not enough resolution
- Plan comparison confirms findings

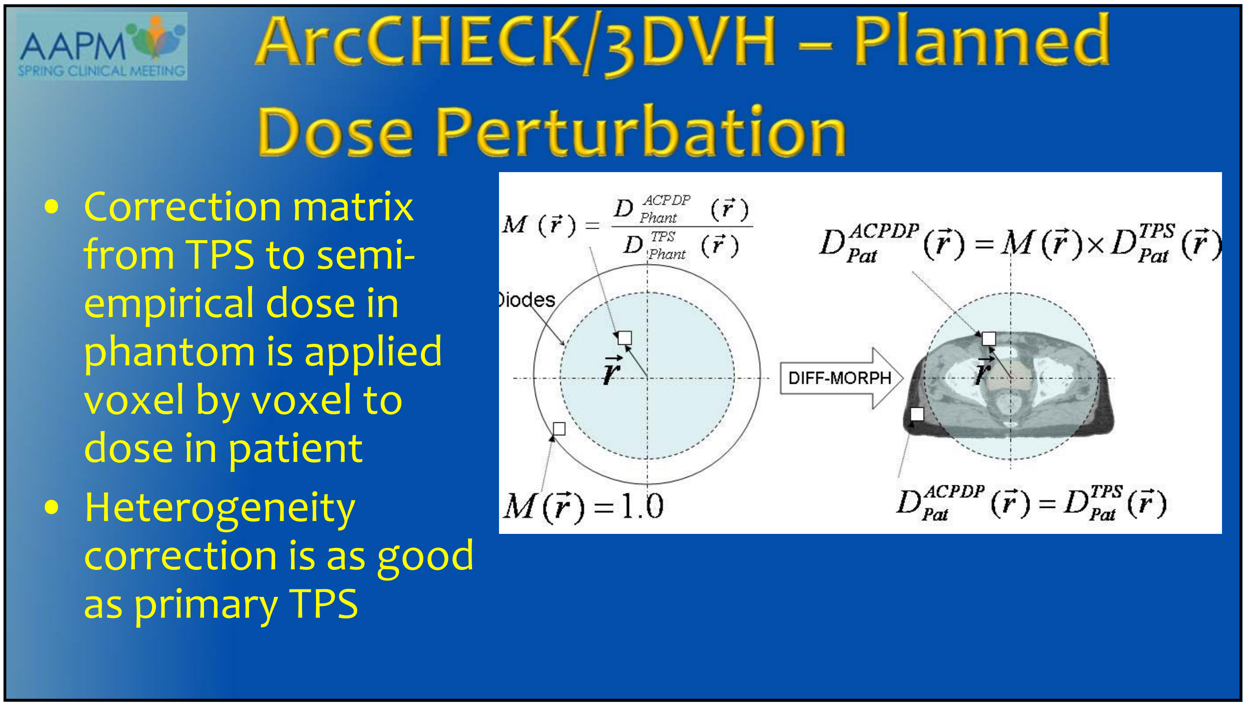
(From Stambaugh et al, 2013)



Results – Anatomy II (latest release)

- Resolution improved by allowing interpolation in fluence reconstruction
- Head geometry
- Limitations of PB in lung remain

(T. Matzen, ScandiDos – Private communication)



ArcCHECK/3DVH – Planned Dose Perturbation

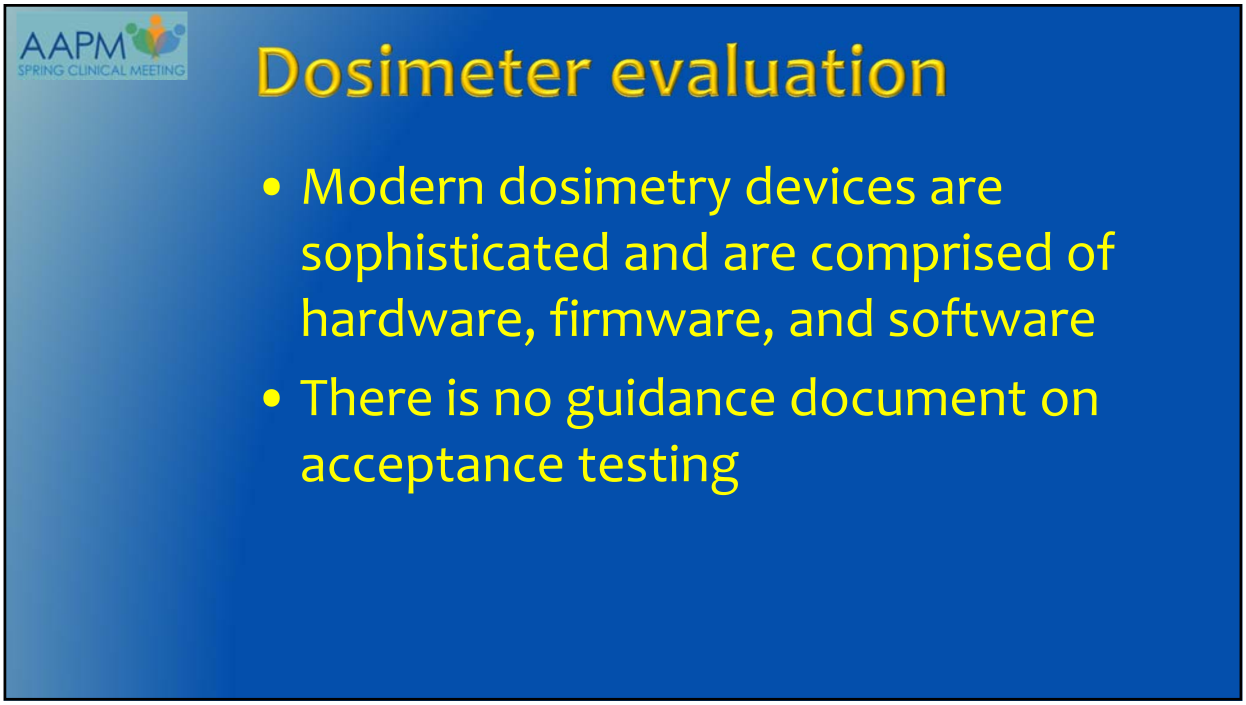
- Correction matrix from TPS to semi-empirical dose in phantom is applied voxel by voxel to dose in patient
- Heterogeneity correction is as good as primary TPS

$$M(\vec{r}) = \frac{D^{ACPDP}_{Phant}(\vec{r})}{D^{TPS}_{Phant}(\vec{r})}$$

$$D^{ACPDP}_{Pat}(\vec{r}) = M(\vec{r}) \times D^{TPS}_{Pat}(\vec{r})$$

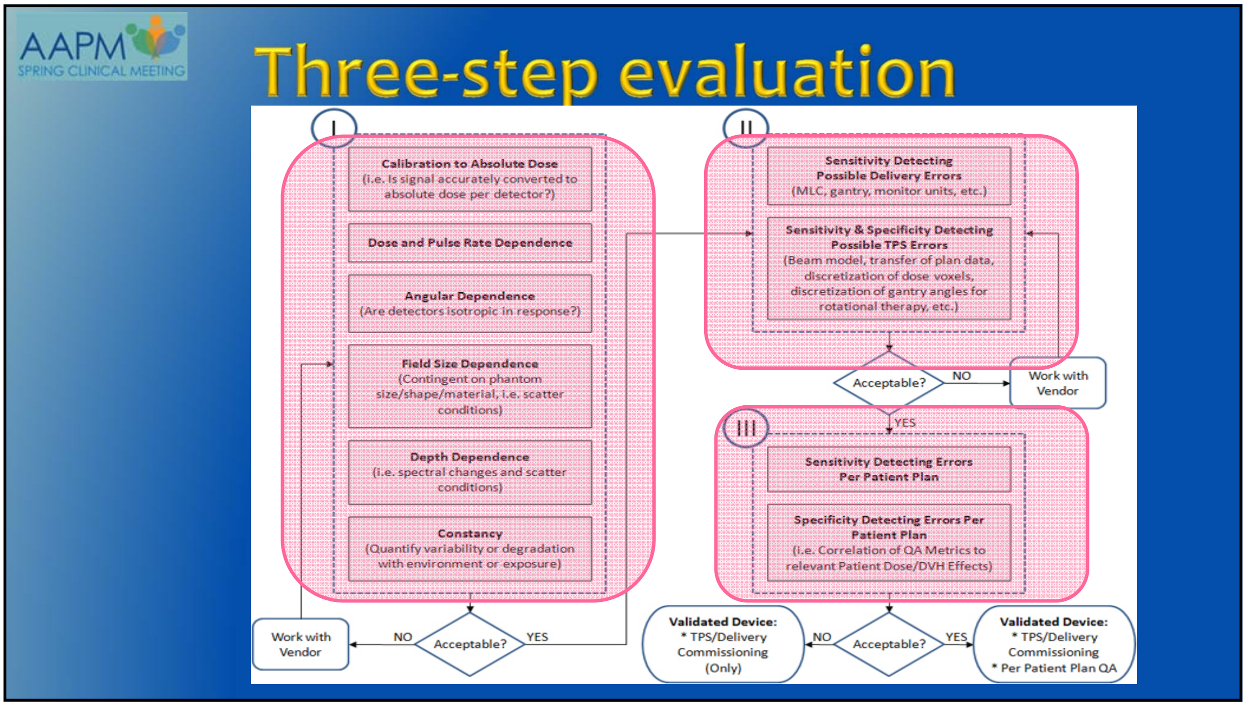
$$M(\vec{r}) = 1.0$$

$$D^{ACPDP}_{Pat}(\vec{r}) = D^{TPS}_{Pat}(\vec{r})$$



Dosimeter evaluation

- Modern dosimetry devices are sophisticated and are comprised of hardware, firmware, and software
- There is no guidance document on acceptance testing



Three-step evaluation

Calibration to Absolute Dose
(i.e. Is signal accurately converted to absolute dose per detector?)

Dose and Pulse Rate Dependence

Angular Dependence
(Are detectors isotropic in response?)

Field Size Dependence
(Contingent on phantom size/shape/material, i.e. scatter conditions)

Depth Dependence
(i.e. spectral changes and scatter conditions)

Constancy
(Quantify variability or degradation with environment or exposure)

Sensitivity Detecting Possible Delivery Errors
(MLC, gantry, monitor units, etc.)

Sensitivity & Specificity Detecting Possible TPS Errors
(Beam model, transfer of plan data, discretization of dose voxels, discretization of gantry angles for rotational therapy, etc.)

Sensitivity Detecting Errors Per Patient Plan

Specificity Detecting Errors Per Patient Plan
(i.e. Correlation of QA Metrics to relevant Patient Dose/DVH Effects)

Validated Device:
* TPS/Delivery Commissioning (Only)

Validated Device:
* TPS/Delivery Commissioning
* Per Patient Plan QA

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Basic acceptance

- Understand the phantom and how it should be represented in TPS
  - The structure of the phantom is often “calibrated out” and a homogeneous cylinder is used in TPS
  - With quasi-3D arrays the phantom material and density are very important

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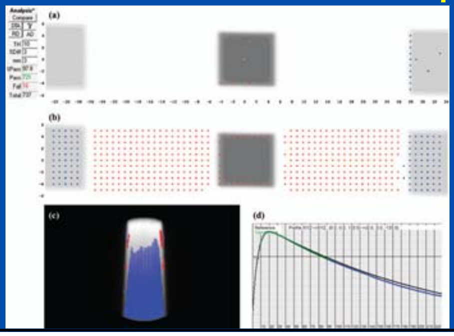
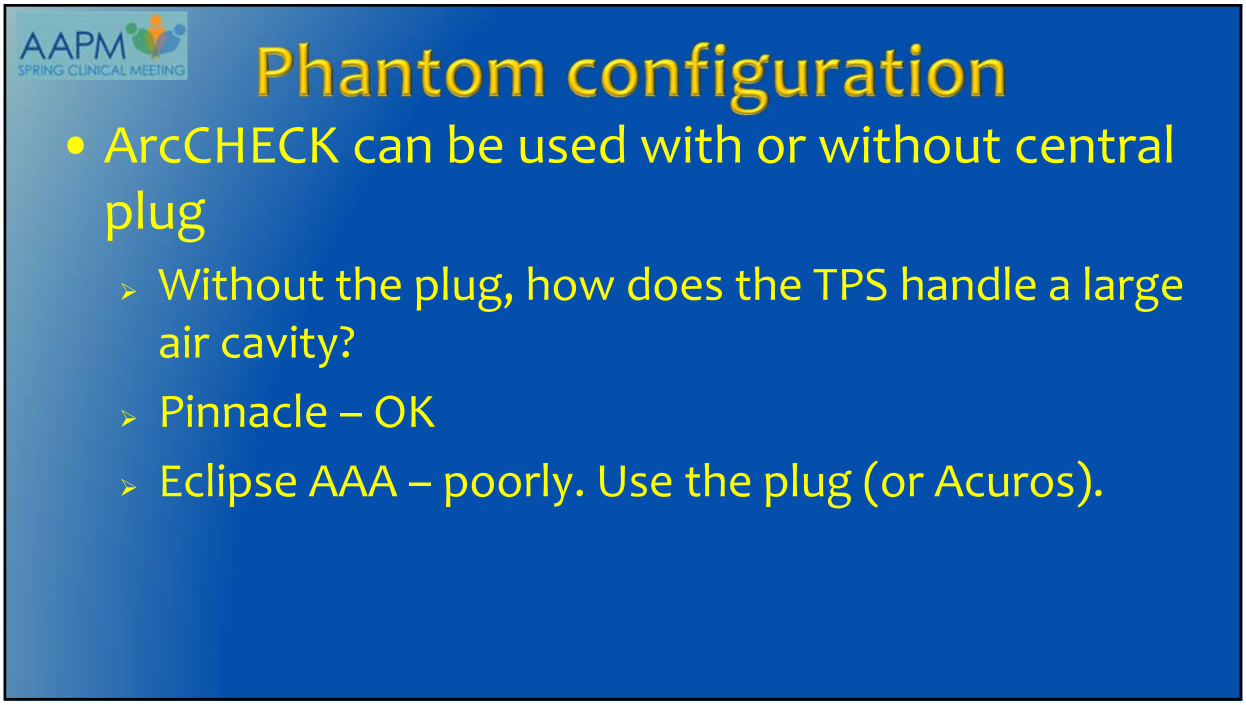
Phantom density

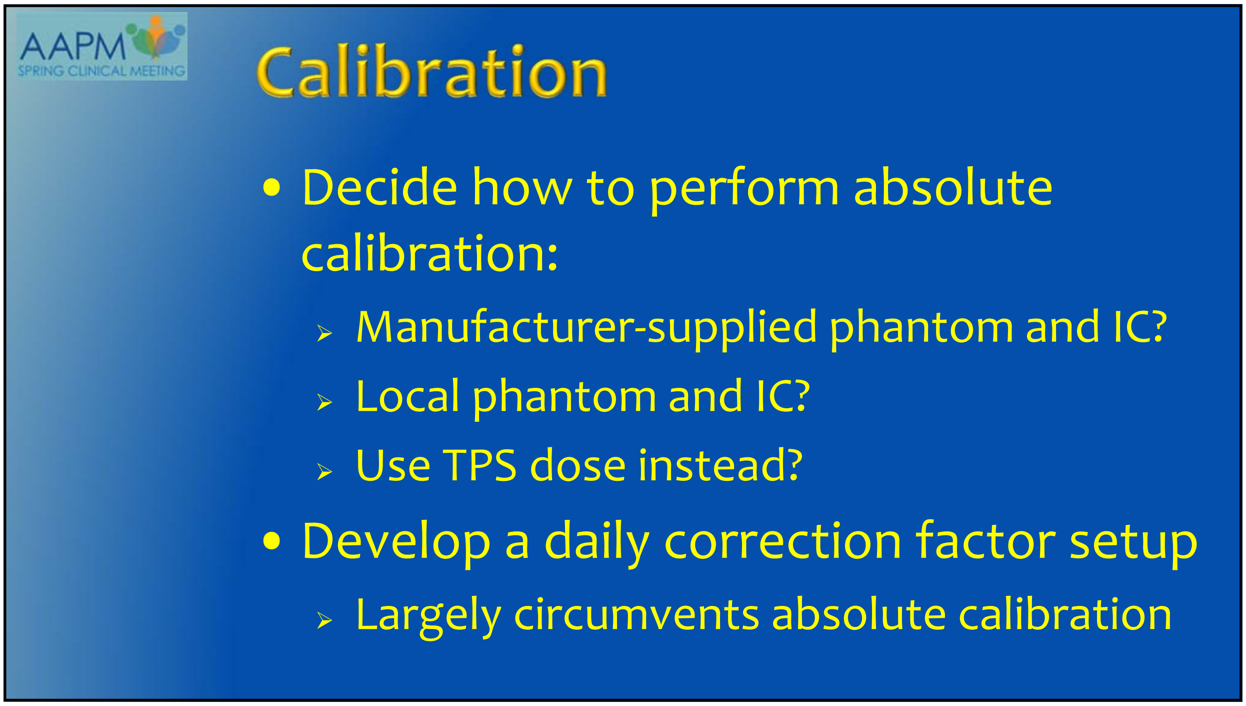
- Density assignment is not always trivial
  - There are multiple ways the TPS may interpret density information for attenuation purposes
  - Depth data should be verified with simple fields and tight criteria





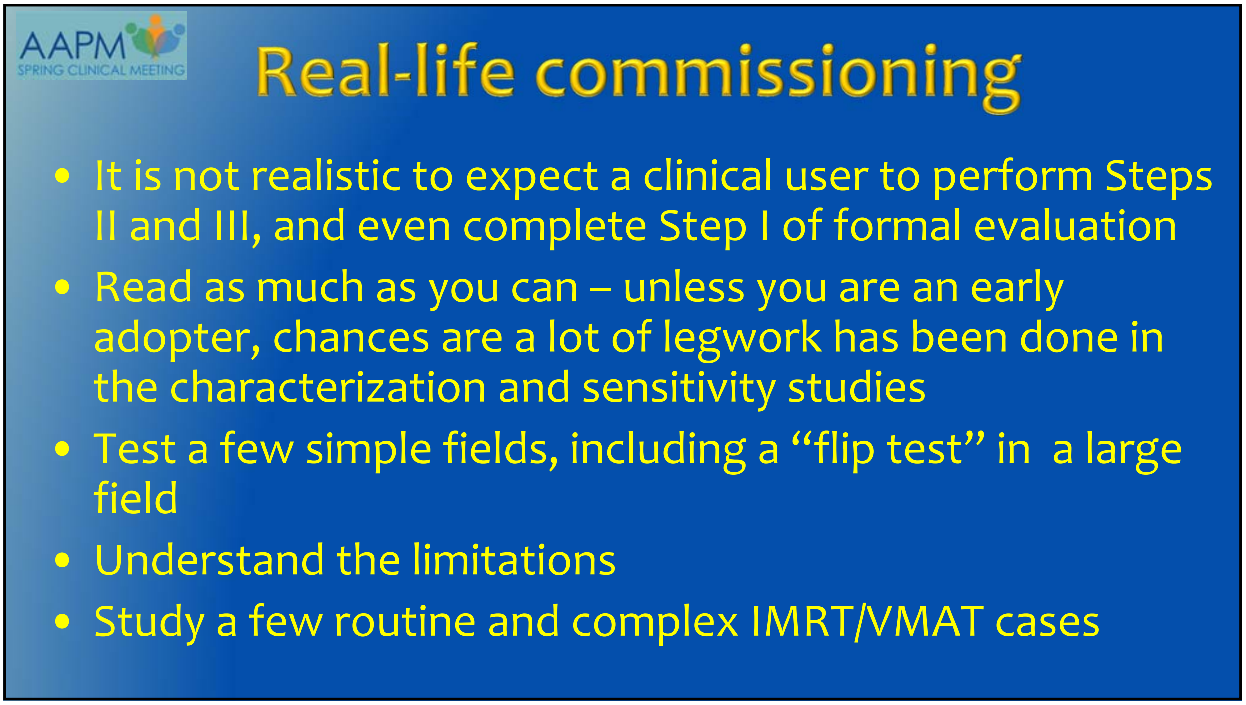
Phantom configuration

- ArcCHECK can be used with or without central plug
  - Without the plug, how does the TPS handle a large air cavity?
  - Pinnacle – OK
  - Eclipse AAA – poorly. Use the plug (or Acuros).



Calibration

- Decide how to perform absolute calibration:
  - Manufacturer-supplied phantom and IC?
  - Local phantom and IC?
  - Use TPS dose instead?
- Develop a daily correction factor setup
  - Largely circumvents absolute calibration



Real-life commissioning

- It is not realistic to expect a clinical user to perform Steps II and III, and even complete Step I of formal evaluation
- Read as much as you can – unless you are an early adopter, chances are a lot of legwork has been done in the characterization and sensitivity studies
- Test a few simple fields, including a “flip test” in a large field
- Understand the limitations
- Study a few routine and complex IMRT/VMAT cases