Acceptance and commissioning of MRI-Linacs without 3D scanning water tanks

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Elekta

DiSCASCO

PHILIPS

Dutch Cancer Society

PTW

EMPIR

Conv. Linac VS. MRI-Linac

- Open (much space)
- Isocenter in the target
- Table movements possible in all directions
  - Correct positioning errors using table
- Field size: 40 x 40 cm²
- Isocenter: 100 cm
- Calibration rotations possible
- Cone-beam CT
- Magnetic field: 0.0005 Tesla (Earth magnetic field)
- Couch transmission (< 2%)

- Closed (small space)
- Isocenter at the body center
  - Correct positioning errors using TPS/software solutions
- Field size: 57 x 22 cm²
- Isocenter: 143.5 cm
- Collimator rotations possible
- Cone-beam CT
- Magnetic field: 1.5 Tesla (= 30000 x Earth magnetic field)
- Couch transmission (< 2%)
Considerations for measuring in an MRI-linac

- Less clearance
  - Equipment should be set up on the couch
  - 130 (length) x 70 (diameter) cm
- Divergent from conventional field size
  - MRIdian: 25.7 x 25.7 cm, Unity: 57 x 22 cm
  - Maximum field sizes set below standard detectors or Water tanks
- Different source to isocenter distance
  - MRIdian: 90 cm, Unity: 143.5 cm
- No collimator rotations
  - Conventional beam alignment procedures cannot be used
  - Gantry 0 / 180 measurements are limited due to high couch transmission
- MR imaging / MV imaging
  - No light field or (official) lasers
  - Setup of measurement equipment requires new methods
- RF safety
- Strong magnetic field
  - MRIdian: 0.35T (≈ 7000 x Earth's magnetic field)
  - Unity: 1.5 Tesla (≈ 30000 x Earth's magnetic field)
  - Detectors behave differently in strong magnetic fields

Dose delivery a magnetic field

- Photons are not affected by the magnetic field
- Electron trajectory is changed by the Lorentz force
- Therefore the local dose deposition will change
Dose delivery a magnetic field

Point spread kernels in water from 6 MV beam
Orientation: B-field perpendicular to the beam


Reference dosimetry

\[ D_{w,Q} = M_{Q}^{B} \times N_{D,w,Q_{0}} \times k_{Q,Q_{0}} \times \epsilon_{C} \times k_{B,M,Q} \]

Detector response in a high magnetic field

Detector response depends on orientation of beam and B0 (0 – 5%)

Affects Reference dosimetry & Water tank measurements
Relative dosimetry using a water tank

- Setup using projection images from on-board MV imager
- Alignment cannot rely on field edges
- Large field size. Use of two detectors
- Less clearance means shorter PDDs
- Detector response changes
- EPOM changes in B0 field and photon beam directions
- Angular variation increases: large fields and off axis fields
- The water tank, motors etc influences the magnetic field
- Continuous moving detectors induces Eddy currents
- Location of reference chamber. Mobile structures affects the scattered electrons above the tank

Issues are known and can be corrected / prevented
- Perfect reference other detector arrays / film
- Crossline symmetry is perturbed by Lorentz force

Relative dosimetry using a water tank

Detector arrays
Sun Nuclear IC profiler

- Minimal changes to the design
  - Power supply on extension
- Comparisons with/no B-field
- Detector properties
  - Short term reproducibility
  - Dose response linearity
  - Saturation and recombination
- Warm-up effects
- Chamber orientations
- Influence of ionization chamber shape
- ICProfiler versus Gafchromic EBT2

BistroMath software, Freeware by Theo van Soest
Detector arrays
PTW StarCheck maxi MR

- Minimal changes to the design
  - Power supply
  - Network connection

- Detector properties
  - Short term reproducibility (no difference)
  - Dose response linearity (no difference)
  - Warm-up effects (no difference)
  - Chamber orientations
    - Anisotropic dependence
    - Difference between AB and GT profiles (2.1% with B0, 0.4% wo B0)
    - Saturation and recombination (no difference)

Detector arrays
Issues to consider

- Air-gaps around detectors
  - Response differs between detectors
    - Higher angular sensitivity
  - Partially solvable by calibration
  - MR-compatible versions has been improved

- Full scatter condition cannot always be achieved

- Detector geometry and alignment affects reading
  - AB, GT and diagonal response differs
  - Partially solvable by calibration
  - Calibration difficult due to size of detector array

- Alignment difficult due to lack of collimator rotation
  - Used by the on-board EPID and MV beam

Film dosimetry
EBT3 suitability in magnetic field

- Very versatile
- High spatial resolution, large dose range

- Conversion of Monomers ‚Äì polymers (having a dipole moment)
- Magnetic field might influence
  - Polymerization process
  - Orientation of polymers

Evaluating EBT3 properties in 0.35T field

- EBT3 dose response curves
- B0-field orientation influence
- Real-time imaging influence

Perik, T.J. et al. PMB 63 (2018)


Courtesy to Daan Hoffmans (Amsterdam UMC) Barten et al (2017), Estro 2017 OC-231
EBT3 suitability in magnetic field
Dose response curves

Optical density (OD) as function of dose
- Measurements performed in water
- N = 4
- Dose range 100 – 800 cGy
- Red, green and blue color channels assessed

EBT3 suitability in magnetic field
B0-field orientation influence

Frontal plane B0 parallel to film
Sagittal plane B0 parallel to film

GafChromic film – magnetic field effects

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<tr>
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<tr>
<td>Raaijmakers et al. (2007)</td>
<td>0.6/1.3</td>
<td>4</td>
<td>Linac</td>
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<td>Reyhan et al. (2015)</td>
<td>1.5</td>
<td>0-8</td>
<td>Linac*</td>
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<td>Wen et al. (2016)</td>
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<td>1.18-4.74</td>
<td>Unity</td>
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<td>Roed et al. (2015)</td>
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<td>Barten et al. (2017)</td>
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<td>UMC-U</td>
<td>0-1.5</td>
<td>0-3</td>
<td>Linac</td>
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*Not irradiated in presence of a magnetic field

Slide courtesy to Bram van Asselen

Barten et al. (2017), Estro 2017 OC-231
Film processing (always convert to dose)

Film processing stages:
1. Film cassette set up
2. Film processing
3. OD to Dose conversion
4. Film dose image ready to be further analysed

Film measurement setup:
- Set to zero

Andre Mieke et al. MedPhys 2011

Linac QA measurements

Isocenter accuracy (spoke films)

“Removal” of impact B field on electrons

Dose deposition

van Zijp et al. PMB (2016)

Dose deposition

hν

hν

B₀

\[ B = B_0 \]

\[ D = D_0 \]
Linac QA measurements
Isocenter accuracy (spoke films)

Isocenter radius = 0.3 mm
(std. linac = 0.5 – 1.0 mm)

Machine QA using polymer gel

- Isocenter accuracy alignment
  - Feasibility of polymer gel-based measurements of radiation isocenter accuracy in magnetic fields
  - Take into account the shift of the magnetic field

Linac QA measurements
MLC-bank alignment and leaf position accuracy

- 11 adjacent stripes of known distance
- Film sandwiched in Cu
- Use simultaneously acquired EPID images to align film
Linac QA measurements
Beam alignment using congruence of opposed fields

- 5x5 @ G0 and 10x10 @ G180
- Film sandwiched in Cu

Difference < 0.5 mm (x) & 0.2 mm (y)

Linac QA measurements
Beam alignment using congruence of opposed fields

Magnetron replacement
- Output
- Energy
- Beam alignment (SiSo)

Beam commissioning data acquisition using film

- No flood possible in the MRI
- Easy to handle, quick setup
- 2D data instead of 2 x 1D profile
- High resolution in film plane (penumbra)
- Complete data set per field size in a single shot (300 MU)
- PDD = 25 cm (Water tank range ~ 12.5 cm)
Beam commissioning data acquisition using film

- PTW RW3 slab phantom
- 30 x 30 x 30 cm³ / 40 x 40 x 10 cm³
- EBT3 radiochromic film (20 x 25 cm²)
- SAD setup (SSD = SAD + 10 cm)
- Field size
  - 1x1, 2x2, 5x5, 10x10 and 20x20 cm²
- Depths
  - 1.0, 2.0, 5.0, 10.0 and 20.0 cm
- Axial film for High-res PDD, 3mm off-center
- Output measurements with IC in RW3 at reference depth (SAD = SSD – 10 cm)

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Beam commissioning data acquisition using film
Image processing film data

1. Digitize films
2. Convert to dose
3. OD to Dose conversion
4. Scanning and corrections
5. Image registration
6. Image processing / Viewer

Three channel (RGB) method

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Beam commissioning data acquisition using film
Results 3D processed film data
Beam commissioning data acquisition using film
Results 3D processed film data (Film vs. Water tank)

Water tank
Film

Beam commissioning data acquisition using film
Results 3D processed film data (Film vs. Water tank)

Watertank
Film

Crossline
Inline

Film dosimetry

- No significant magnetic field effects on film dosimetry
  - Film OD2Dose calibration curves within B0 field are advised
- Use water (droplets!) to avoid any possible airgaps
- Use Cu plates to capture the secondary electrons
- On a Elekta Unity system isocenter coordinate can be transferred via the on-board EPID
**Patient specific QA**

- **3D FILM**
- **3D Gel**
- **3D Digital detectors**

**Gel dosimetry**

- **Gel irradiation**
  - Different types of gels
    - Fricke gels
    - Polymer gels
    - Plastic, radiochromic gels

- **Chemical reactions**

- **3D Imaging analyses**

- **3D dose distribution**

- **... and different reading methods**
  - MRI (various sequences)
  - Optical reading
  - X-ray imaging

- **Read-out just after irradiation**
- **Can be used for complex shapes**
- **Irradiation + readings with MRgRT**

*Image courtesy to Christel Stien*
3D Detector arrays

- Current MR compatible systems on the marker
  - Sun Nuclear Arc Check
  - Scandidos Delta4
  - PTW Octavius 3D (rotates with the gantry angle)
  - Perpendicular alignment to beams; potential use for linac QA

- Remove as many ferrous components as possible
- B-field effect on electrons can cause strange behaviour, especially at interfaces between materials of different densities (e.g., air cavities of ion chambers).

- Default positioning at isocenter using frame
  - no light field or lasers
  - RF can be damaging to electronics. No MR image of device position.
- Off-axis positioning (accuracy less)

3D Detector arrays

- Systems have been tested on
  - Short term reproducibility
  - Field size dependency
  - Dose-linearity
  - Dose-rate dependency
  - Angular dependency

- Systems perform similarly in B0-field but generally need specific re-calibration

3D Detector arrays

- Most devices are developed for axial treatments
  - The center of the device at isocenter
  - Generally the high dose region

- MRI-Linac treatments do not necessarily have target in the machine isocenter
  - Many "low dose contributions" to diodes
  - Diodes have an individual angular sensitivity related to their individual orientation from the manufacturing process

- Two main aspects to consider
  - Behavior at low dose rates
  - Behavior at various gantry angles

- If device rotates with the gantry angle (PTW) then Eddy currents exist due to rotation of electronics in B-field

Houweling A C et al. PMB 61 (2016)
Ellefson S.T. et al. JACMP (2017)
Li H. et al. IJROBP (2015)
Vries J.H.W. de et al. PMB 63 (2018)
Patient QA using Delta4

- Two establish a 3D reconstruction from Orthogonal 2D planes PPD info is required
- Due to magnetic field, there is no continuous dose drop over the phantom geometry
  ➔ Electron Return Effect should be taken into account

Conclusions

- Completed the loop from commissioning to patient specific QA using film in a 1.5T MRI-Linac
- All QA can be performed using 2D detectors (film or arrays)
- B0-field affects all ion chambers and 2D and 3D detector arrays
- All detectors rely on “full scatter water conditions”, still best maintained in a water tank

Thank you for your attention!