Basic Physics and Quality Assurance of Proton Therapy

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Outline

- Physics of charge particle motion
- Particle accelerators
- Proton interaction with matter
- Delivery systems
  - Scattering systems
  - Uniform scanning
  - Pencil beam scanning
- Spread out Bragg Peak
- Pencil beam characteristics
- The advantage of using proton therapy

Outline

- Methodology of Quality assurances
- Type of Quality assurances
- Parameters related to Quality assurance procedures
- Daily, Weekly, Monthly and yearly Quality assurance procedures.

Physics of Charge Particle Motion

- Electric and magnetic fields influence on charge particle (CP) :
  - Electric field is used to accelerate/push the CP.
    - A charge particle (q) with mass (m) in Electric field (E), experiences force (F) and gains velocity (v)

$$\vec{F} = q\vec{E}$$

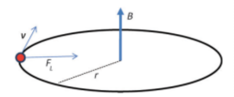
    - The kinetic energy (T)

$$T = \frac{1}{2}mv^2$$

Physics of Charge Particle Motion

- Magnetic field is used to guide/turn the CP.
  - The motion in magnetic field (B) is governed by Lorentz force (F_L).

$$\overrightarrow{F_L} = q(\vec{v} \times \vec{B})$$



- If the motion is in a plan perpendicular to magnetic field, then the centripetal force keeps the particle in a circular motion.

$$F_L = qvB = \frac{mv^2}{r} \Rightarrow B = \frac{mv}{qr}$$

Physics of Charge Particle Motion

- For constant B; as v increases, r has to increase

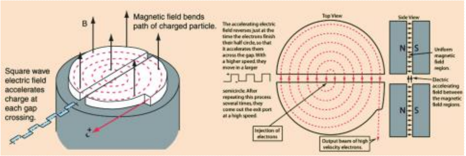
$$B = \frac{mv}{qr}$$

- For constant r; as v increases, B has to increase

$$r = \frac{mv}{qB}$$

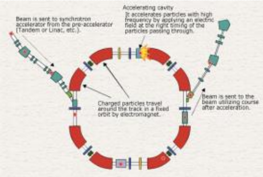
Particle accelerators

- There are Cyclotron, synchrotron, and synchrocyclotron (a cyclotron with variable RF electric field):
  - Cyclotron:
    - Maintains a constant magnetic field while increasing the energy of particles:



Particle accelerators

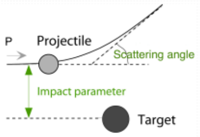
- Synchrotron:
  - Magnetic field is varied to maintain the particle in the same orbit as the energy is increased. In other word the magnetic field strength is synchronized with the increase in particles' energy, hence the name "synchrotron".



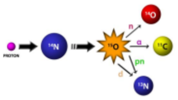
Proton interaction with matter

- Proton interact with matter by:

1. Coulomb interaction with atomic electrons leading to continues energy loss and slowing down
1. Scattering by atomic nuclei

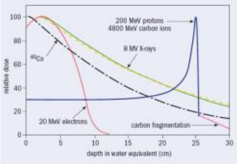


1. Head-on collision with nucleus
   - Results in nuclear reaction and productio particles (~7 MeV threshold).



Proton interaction with matter

- Proton have very low ionization density (energy loss per unit path length)
  - Range can be calculated based on continuous slowing down approximation (CSDA).
- Ionization density increases gradually to a point where a very high ionization density occurs called Bragg Peak.
  - At this point energyof most protons are 8-20 MeV.
- Proton interaction with atomic electron produces delta rays that travel a few micron and deposit their energy close to the proton's track.
- The typical ionization ration at Bragg peak to entrance dose for proton is 3:1.



Proton interaction with matter

- There is a small amount of dose due to neutron production beyond Bragg peak:
  1. This amounts depends on energy of protons
  2. Atomic number of material
     - The higher the energy of protons and higher the Z value of material, the larger the neutron-generation.
- The Stopping power (S):

$$S \mu \frac{z^2}{v^2} \log[f(v^2)]$$

Question 1

- Which statement is true about cyclotron and synchrotron?

A. In cyclotron, as the proton energy is increased, the magnetic field is also increased.
B. Proton energy increases by increasing the magnetic fields in synchrotron
C. As the energy increases, the proton radius increases in synchrotron
D. Magnetic field strength and energy are increased simultaneously to keep protons in the same orbits in synchrotron.

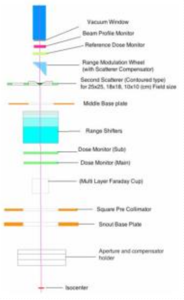
Ref: Godfrey D, Das S. K., Wolbarst A. B., Advances in Medical Physics, Medical Physics Publication, Vol. 5, 2014

Delivery system

- Scattering ssytem:
  - Single scattering and double scattering
    - Single scattering –for used eye beam treatment.
    - Double scattering- produces uniform dose distribution in transverse and longitudinal direction in water.
- Uniform scanning system
  - Single scattering with steering magnets to produce uniform dose in transvers direction. Uses energy stacking to irradiate different depth layers.
- Pencil beam scanning system
  - Positioning spot-by-spot (discrete delivery system)
  - Continuous scanning
  - Can deliver IMPT- Used steering magnet and energy staking to deliver dose.

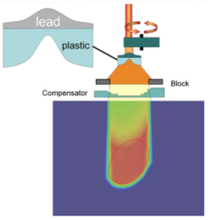
Clinical beam

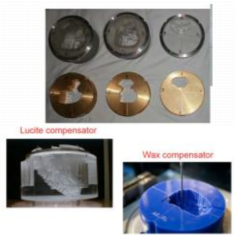
- Double scattering:
  - Single scatterer is used to spread the beam to widen the Gaussian shape beam.
  - Second scatterer is used to flatten the field
  - A Modulation wheel is used to change the range of the beam and to spread the Bragg peaks (SOBP).
  - Aperture is used to shape the field to specific target
  - Compensator (bolus) is used to limit the range to specific depth and shape the beam distally to the target.



Clinical beams

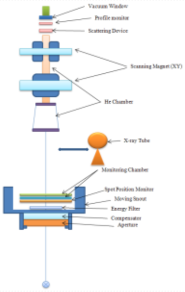
- Beam shaping device used in double scattering delivery system.





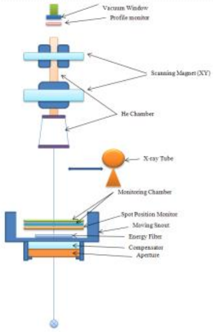
Uniform scanning Beam

- Uniform scanning
  - Scatterer is used to spread the beam to a wider Gaussian shape in order of few cm at FWHM.
  - Magnets are used to steer and move the beams along a layer at specific depth.
  - Range of protons are changed either by introducing a wedge degrader (cyclotron) or changing the energy of accelerator (synchrotron)-energy stacking.



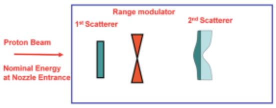
Pencil Beam

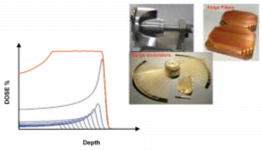
- Uses pristine Bragg peaks to deliver the useful fields.
  - Steering magnets are used to move the pencil beam to different pre determined spots for shaping the field.
  - The energy is changed to deliver beams at different layers using energy stacking system.



Spread out Bragg peak (SOBP)

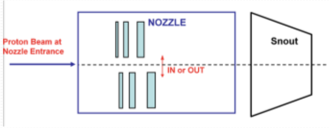
- To produce a clinical useful beam, the Bragg peaks are spread over a region of interest either by range modulation wheels or energy stacking system. The Bragg peaks depth doses are summed to produce a flat depth dose distribution (water) which covers the distal and proximal of the target. The range of proton is normally specified at depth specified by 90% distal dose and SOBP width is defines between the depths corresponding to 90% distal dose and 90/95% proximal dose of depth dose distribution.

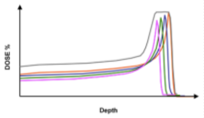




Spread out Bragg peak (SOBP)

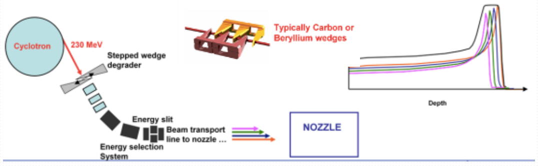
- SOBP created by inserting varying thickness of material in path of the beam:
  - ➢ Range shifter
  - ➢ Range modulation in step mode
    - ❖ Used for uniform scanning





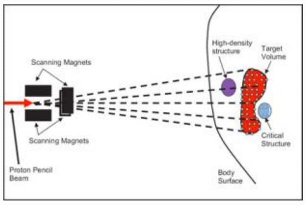
Spread out Bragg peak (SOBP)

- In active scanning; energy is changed either by changing accelerating energy (synchrotron) or by inserting degraders in the beams (cyclotron).



Pencil Beams

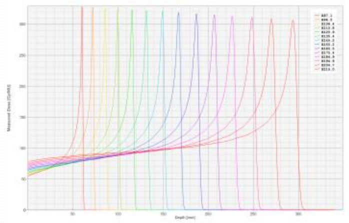
- In intensity modulated proton therapy (IMPT):
  - The pencil beam is delivered to predetermined (TPS) spots in the target.



  - The intensity of the each spot is governed by the optimization criteria to cover the target and to reduce the dose to OAR.

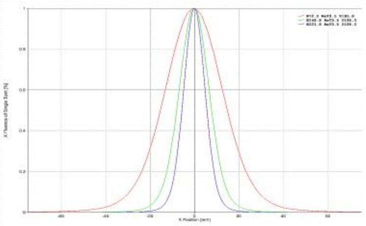
Pencil Beam Characteristics

- Proton pencil beams suffer multiple collisions when traveling through media, resulting in a slight variation in their range, referred to as range straggling or energy straggling. This results in spread of beam under Bragg peak. The higher energy proton beams suffer larger energy straggling.



Pencil Beam Characteristics

- low energy proton beams suffer more lateral scattering than high energy proton beams



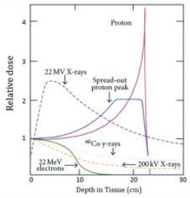
Question 2

- Which is true for different delivery systems?
  - A. Double scattering uses energy stacking to produce spread out Bragg peak.
  - B. Uniform scanning uses modulation wheels to produce spread out Bragg peak.
  - C. To produce spread out Bragg peaks, energy of protons needs to be changed.
  - D. Scanning delivery systems do not produce spread out Bragg peaks.

Ref: Paganetti H, Proton therapy physics. CRC press N.Y. 2012

The advantage of using proton therapy

1. Provides a finite range and sparing of distally organ at risk to the target.



2. Lower entrance dose (if multiple fields are used).
3. Higher linear energy transfer (LET)

Methodology of Quality assurance procedures

- It is method:
  - To prevent mistakes or defects
  - Avoid problems
  - Predict mishaps
  - To provide confidence
    - Functioning safely and accurately
- ICRU (*report 24*):
  - Dose should be accurate to within -5% to +7% of prescribed dose in order to be effective

Type of Quality assurances

- General equipment
  - Dosimetry QA procedures
    - Absolute dosimeter
    - Relative dosimeter
  - Imaging QA procedures
    - Target alignment
  - Mechanical QA procedures
    - Alignment, trueness, functionalities, interlocks, safety checks
- Patient treatment dose delivery QA procedures.
  - The dose calculation by TPS is deliverable by the equipment

Question 3

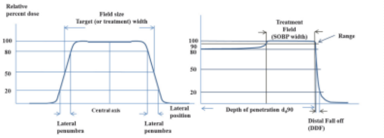
- Why quality assurance is important?
  A. ICRU report 24 states dose needs to be within +5% and -7% of prescribe dose in order to be effective.
  B. To have confidence in machine beam delivery.
  C. To minimize the probability of dose delivery errors.
  D. Because it generates revenue
  E. A, B, C

Ref: International Commission on Radiation Units and Measurements., Prescribing, recording, and reporting photon beam therapy. International Commission on Radiation Units and Measurements, 1993.

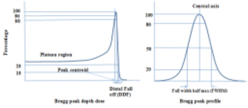
How to Check the condition of Beams ?

- Importance of clinical beam parameters
  - Clinical beam parameters are related to physical devices that controls the shape of the beams
    - Identify the vital beam parameters
    - Monitor these beam parameters
      - Monitor chambers
        - Functioning properly
        - Terminates the beams if tolerance is exceed the limits
    - On-line devices for monitoring (beam profilers)
- Most of these parameters are checked by external devices.
  - Ionization chambers, 2d detectors, multilayer ion chambers, etc.

What are the beam parameters that need to be checked?



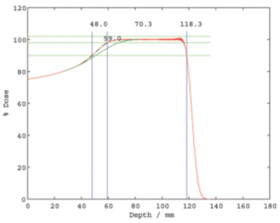
- Dosimetric parameters for scattering and scanning proton beams.

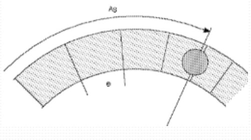


- Depth dose and lateral profiles parameters for a pristine Bragg peak

Example: Double Scattering

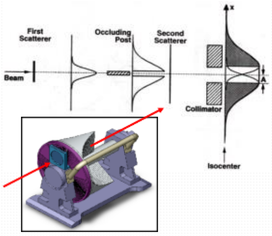
Source size effect : reduction on proximal depth dose shoulder

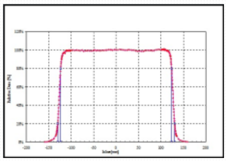


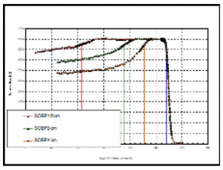


Paganetti H, Ch. 5, Proton therapy physics CRC press N.Y. 2012

Double scattering







- 70-400 RPM
- 6 Modulation per cycle
- Full modulation up to full range of beam
- Beam gated for different SOBP width
- Intensity varied to produce a flat top SOBP

Mechanical and safety Checks

- Gantry:
  - Isocentricity
    - Mechanical
    - Radiation
- Patient positioning system (PPS)
  - Couch or robotic pps
  - CBCT
    - Mechanical accuracy
    - Positional accuracy
- Safety
  - Pause
  - Emergency stop
  - Radiation indicator
  - Interlocks
  - Patients monitoring systems

Question 4

- How do we make sure that beam delivery is accurate?

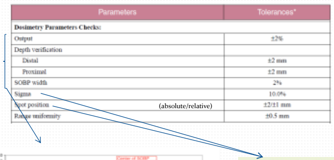
A. By checking the mechanical accuracy
B. By checking the radiation monitor in the treatment room
C. By verifying the beam parameters correspond to established baseline values
D. By making sure the imaging systems are working accurately
E. A, C, D

Ref: Paganetti H, Proton therapy physics. CRC press N.Y. 2012

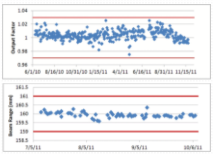
Daily Quality Assurance Procedures

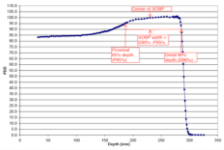
- These procedures pertain to parameters that could influence the dose distributions and cause drastic changes in dose accuracies
  - Cause harm to patients and staff
    - Need to be checked prior to patient treatments
  - On-line devices
    - Range shifters (used daily!)
    - Multi-layer Faraday cup (range verifications)

Daily QA Procedures: Dosimetry Parameters

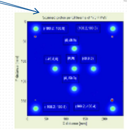


Parameters	Tolerances*
Dosimetry Parameters Checks:	
Output	±2%
Depth verification	
Distal	±2 mm
Proximal	±2 mm
SOBP width	2%
Sigma	10.0%
Spot position (absolute/relative)	±2/±1 mm
Range uniformity	±0.5 mm



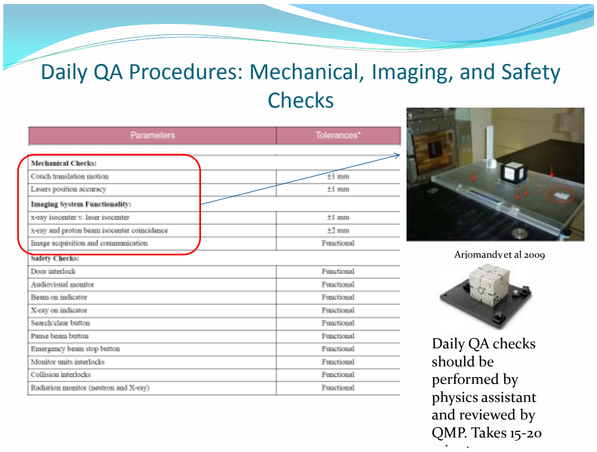


Arjomandy et al 2009



Li et al 2013

Ding 2012

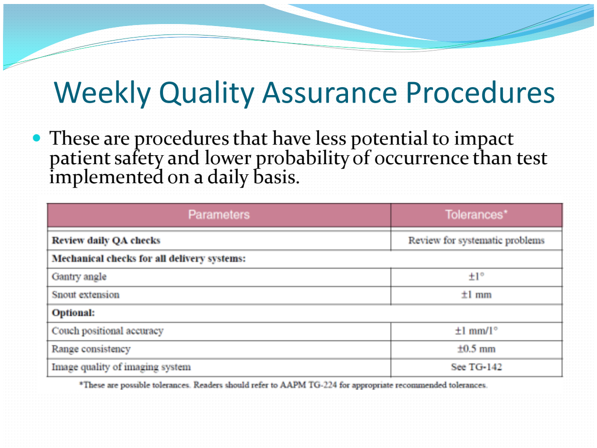


Daily QA Procedures: Mechanical, Imaging, and Safety Checks

Parameters	Tolerances*
Mechanical Checks:	
Couch translation motion	±1 mm
Lasers position accuracy	±1 mm
Imaging System Functionality:	
x-ray isocenter v. laser isocenter	±1 mm
x-ray and proton beam isocenter coincidence	±2 mm
Image acquisition and communication	Functional
Safety Checks:	
Door interlock	Functional
Audiovisual monitor	Functional
Beam on indicator	Functional
X-ray on indicator	Functional
Search/clear button	Functional
Pause beam button	Functional
Emergency beam stop button	Functional
Monitor units interlocks	Functional
Collision interlocks	Functional
Radiation monitor (neutron and X-ray)	Functional

Arjomandy et al 2009

Daily QA checks should be performed by physics assistant and reviewed by QMP. Takes 15-20

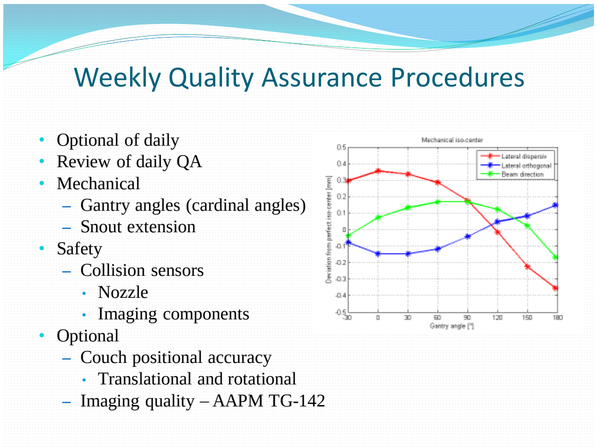


Weekly Quality Assurance Procedures

- These are procedures that have less potential to impact patient safety and lower probability of occurrence than test implemented on a daily basis.

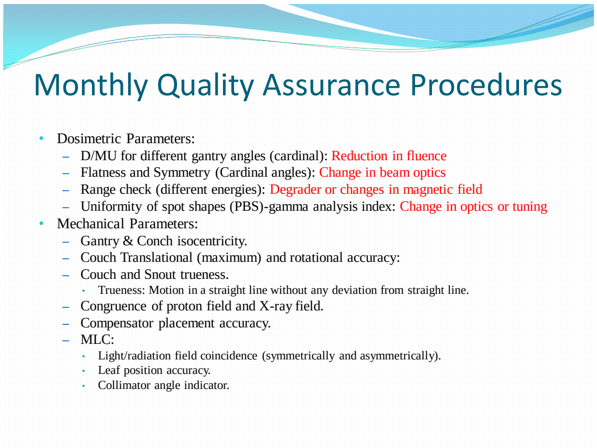
Parameters	Tolerances*
Review daily QA checks	Review for systematic problems
Mechanical checks for all delivery systems:	
Gantry angle	±1°
Snout extension	±1 mm
Optional:	
Couch positional accuracy	±1 mm/1°
Range consistency	±0.5 mm
Image quality of imaging system	See TG-142

*These are possible tolerances. Readers should refer to AAPM TG-224 for appropriate recommended tolerances.



Weekly Quality Assurance Procedures

- Optional of daily
- Review of daily QA
- Mechanical
  - Gantry angles (cardinal angles)
  - Snout extension
- Safety
  - Collision sensors
    - Nozzle
    - Imaging components
- Optional
  - Couch positional accuracy
    - Translational and rotational
  - Imaging quality – AAPM TG-142

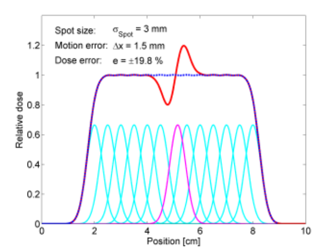


Monthly Quality Assurance Procedures

- Dosimetric Parameters:
  - D/MU for different gantry angles (cardinal): Reduction in fluence
  - Flatness and Symmetry (Cardinal angles): Change in beam optics
  - Range check (different energies): Degrader or changes in magnetic field
  - Uniformity of spot shapes (PBS)-gamma analysis index: Change in optics or tuning
- Mechanical Parameters:
  - Gantry & Conch isocentricity.
  - Couch Translational (maximum) and rotational accuracy:
  - Couch and Snout trueness.
    - Trueness: Motion in a straight line without any deviation from straight line.
  - Congruence of proton field and X-ray field.
  - Compensator placement accuracy.
  - MLC:
    - Light/radiation field coincidence (symmetrically and asymmetrically).
    - Leaf position accuracy.
    - Collimator angle indicator.

Pencil Beam Delivery

For spot size σ = 3 mm, 1.5 mm positional error will result in ± 19.8% error in dose.



Question 5

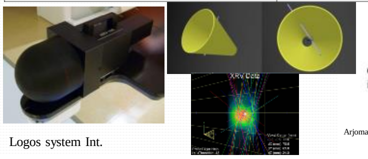
- What can cause the flatness and symmetry to change at different gantry angles?

A. Change in beam intensity
B. Insertion of wrong range shifter
C. Helium chamber being empty
D. Change in beam optics
E. None of the above

Ref: Arjomandy B, Sahoo N, Zhu XR, Zullo JR, Wu RY, Zhu M, Ding X, Martin C, Ciangaru G, Gillin MT. An overview of the comprehensive proton therapy machine quality assurance procedures implemented at The University of Texas M. D. Anderson cancer center proton therapy center–houston. Medical Physics 2009

Monthly Quality Assurance Procedures

Parameters	Tolerances*
Dosimetry parameters checks:	
Output	2%
Field symmetry and flatness	1% and 2%
Range check	1 mm
Uniformity of spot shapes	2% and 2 mm
Mechanical checks for all delivery systems:	
Gantry isocentricity	≤2 mm
Couch isocentricity	≤2 mm
Couch translational accuracy	≤1 mm
Couch rotational accuracy	≤1 mm
Couch trueness	≤1 mm
Snout trueness	≤1 mm



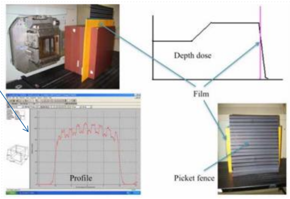
Logos system Int.

Gantry isocentricity

Arjomandy, et al 2009

Annual Quality Assurance Procedures

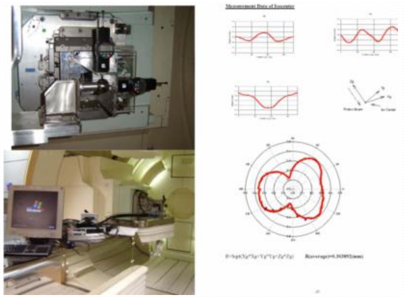
- It requires more time than monthly and it is the most comprehensive checks including:
  - Dosimetry parameter checks:
    - Standard output calibration-TRS 398 (IAEA)
    - Depth dose verifications-commissioning data.
    - Range uniformity



Annual Quality Assurance Procedures

  - Lateral profiles-Commission data.
  - Filed flatness and symmetry-compare to commissioning data.
  - Dosimetric data (MU calculations)
    - SOBP factors
    - Range shifter factor
    - Relative output factors
- Monitor chamber:
  - Linearity
  - Reproducibility
  - End effect
  - Spot position and profiles (commissioning data).
- All mechanical compared with commission and acceptance testing tolerances.
  - Gantry
  - Couch
  - Snout
  - MLC
  - CBCT

Annual Quality Assurance Procedures



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Annual Quality Assurance Procedures

- Imaging System
  - Image quality and contrast
  - Standard annual checks (State or local regulations)
  - CBCT (TG-179 & TG-142)
- Safety checks
  - All emergency button
  - Interlocks (manufacturer specified)
  - Collision sensors
  - Radiation monitoring devices
- Visual inspections
  - Modulation wheels
  - Apertures and compensator doors
- Devices:
  - Calibration update
    - Every 2 years for standard device (ionization chambers, electrometer, etc.)
  - Cross calibration of field devices (chambers, electrometers, thermometers, etc.)

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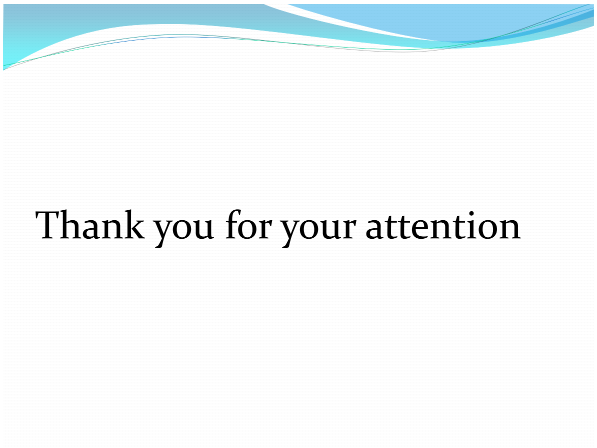

Thank you for your attention