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Director of Clinical Dosimetry

Proton PBS Radiation Therapy and High Density Metal: Through or Around?

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Session Goal

- To understand the dosimetric impact of metallic implants in Proton Pencil Beam Scanning (PBS), establish standardized planning and equip medical dosimetrists with the planning tools, physics foundations, and procedural steps to design accurate proton plans in the presence of metallic implants.

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Session Goal

- **Core Challenge:** Protons have a finite range and inherent range uncertainties, which are highly sensitive to high-Z (atomic number) materials and image artifacts.
- Protons have a sharp distal falloff and are highly sensitive to tissue density variations, making range calculations around high-Z materials uniquely challenging compared to photon therapy.

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Learning Objectives

- Understand how to execute robust physics evaluations and plan optimizations.
- Understand the interaction of proton beams with varying high-density metals
- Identify when to treat through metal vs. when to completely avoid it.

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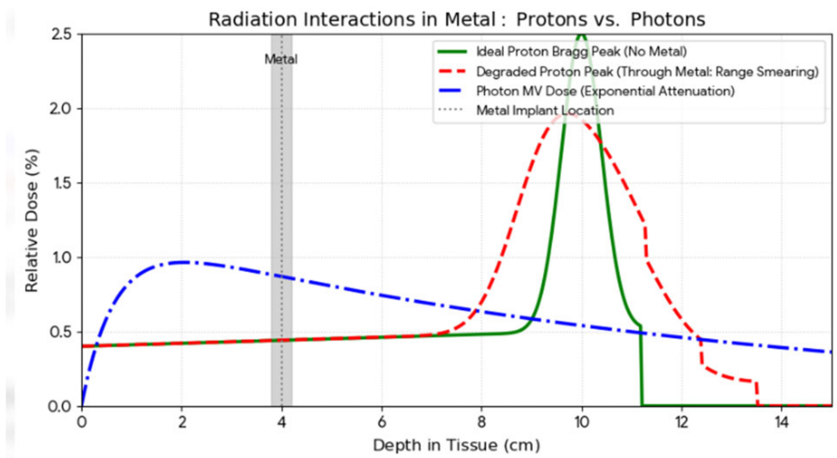
Effect on depth dose in presence of metal



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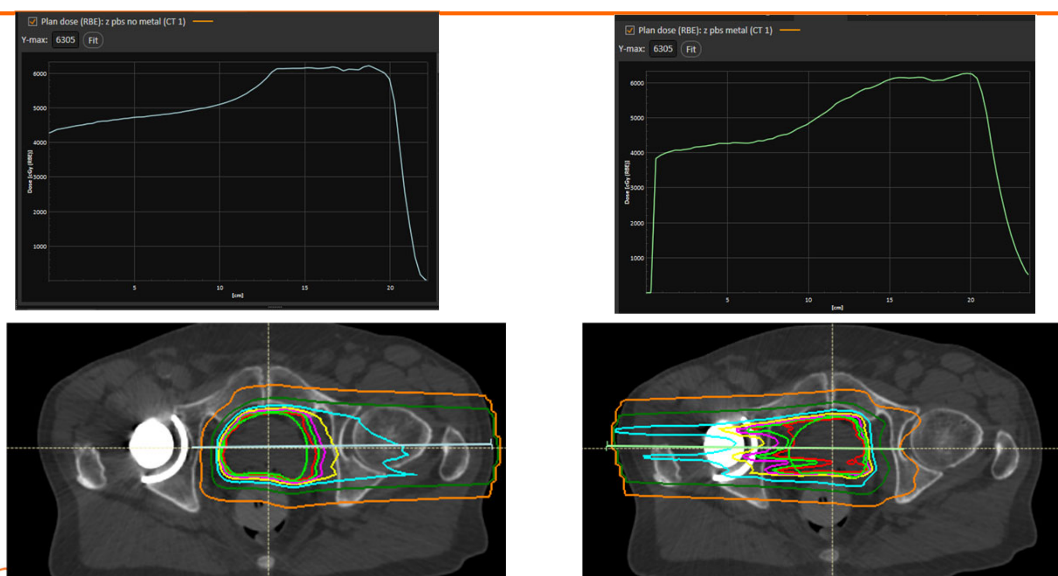
Effect on depth dose in presence of metal: PBS



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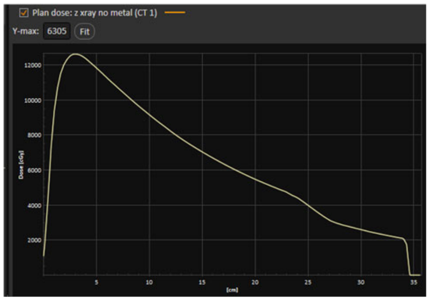
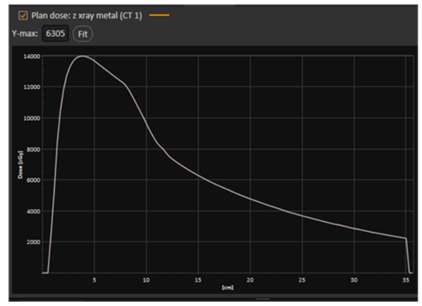
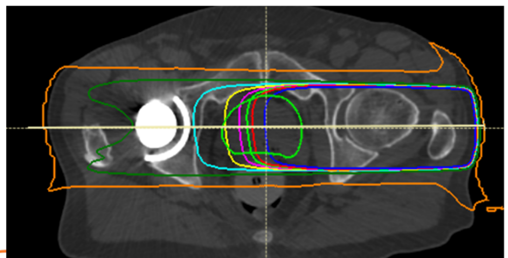
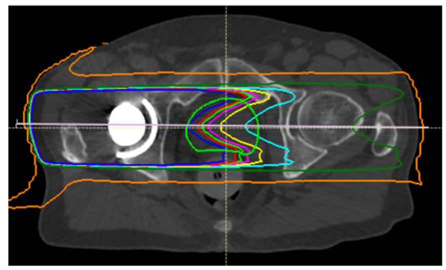
Effect on depth dose in presence of metal: 15MV Photon









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Impact of metallic implants on dose distributions

- At 15 cm depth the dose attenuation for 6 MV photons was −8.11% with titanium (object in beam path)

- The Bragg peak shift in protons, with a displacement of −4.4 cm for titanium (22% reduction)
  - in water the Bragg peak was at a depth of 19.4 cm

Bedri; Impact of Metallic Implants on Dose Distribution in Radiotherapy with Electrons, Photons, Protons, and Very-High-Energy Beams; Appl. Sci. 2025, 15, 4536

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Megavolt (MV) Photon Interactions with Metal Implants

- **Primary Interaction Mechanisms:**
  - **Compton Scattering:** Dominant interaction at MV energies (e.g., 6 MV). Photons interact with outer-shell electrons. It depends primarily on electron density, making metal dose calculations highly predictable.
  - **Pair Production:** Occurs at high energies (>1.02 MeV). This effect scales with atomic number (Z), causing localized dose enhancement near high Z metals.
- **Impact on Dose Delivery:**
  - **Exponential Attenuation:** Photons pass entirely through the patient. Metal attenuates more of the beam, but it does not stop it.
- **Clinical Implementation:**
  - **CT Artifacts:** Metal streaks corrupt Hounsfield Units (HU). Clinicians easily bypass this by manually overriding density maps in the Treatment Planning System (TPS).
  - **Beam Geometry:** Multi-field techniques (like IMRT or VMAT) easily spread out or avoid direct entry paths through dense hardware.

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Pencil Beam Scanning (PBS) Proton Interactions with Metal Implants

- Severe Bragg Peak Disruption and Stringent Range Uncertainties
- **Primary Interaction Mechanisms:**
  - **Coulomb Scattering:** Protons lose energy continuously through interactions with atomic electrons. Dense metals cause a massive, rapid rate of energy loss
  - **Multiple Coulomb Scattering (MCS):** Protons are heavily deflected by heavy nuclei (Z) in metals. This severely broadens the pencil beam slot, distorting the lateral penumbra.
- **Impact on Dose Delivery:**
  - **Bragg Peak Shift:** Because protons stop at a finite range, minor thickness errors in metal shift the entire Bragg peak forward or backward, risking severe underdosing of the tumor or overdosing of critical organs.
  - **Range Smearing:** Non-uniform implant surfaces cause different parts of the beam to stop at different depths, destroying the sharp distal dose fall-off.
- **Clinical Criticality:**
  - **HU-to-Stopping Power Calibrations:** Protons rely heavily on accurate Relative Stopping Power (RSP). Standard CT conversion curves fail catastrophically near metal, causing up to 20% range calculation errors.
  - **Pencil Beam Sensitivity:** Pencil Beam Algorithms fail to calculate MCS correctly through high Z interfaces, requiring Monte Carlo simulation codes to safely calculate the plan.

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Types of Metals, Implants, and Properties when to override density to force stopping power

– *Titanium (Z = 22):* Common, relatively low density compared to other metals. Commonly used in rods, screws, plates, and joint replacements. Lower density and fewer imaging artifacts compared to steel or gold.

- *Generally don't need to contour & override Ti on planning CT*
  - *CT density to HU conversion table is commissioned with Ti accurate*

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Types of Metals, Implants, and Properties when to override density to force stopping power

– ***Do contour** and override density for these materials*
  - *Z and densities of these materials will be saturated on the conversion table and need to be assigned density*

– *Stainless Steel / Cobalt Chrome (Z = 24-27):* High density, causes severe artifacts.

– *Gold (Z = 79):* Extremely high-Z; used for fiducial markers. Causes major beam attenuation and scatter.

– *Surgical/Bone Cement & Fillers:* (PMMA) calcium phosphate; varying densities but generally water/tissue-like, though denser than soft tissue.

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The Dosimetric Impact of Metal in PBS Treatment Plans

- **Range Uncertainty and Artifacts:** Streaking artifacts on CT scans mislead the Treatment Planning System (TPS) during Relative Proton Stopping Power (RPSP) conversion.
- Artifacts lead to inaccurate CT numbers, resulting in range errors

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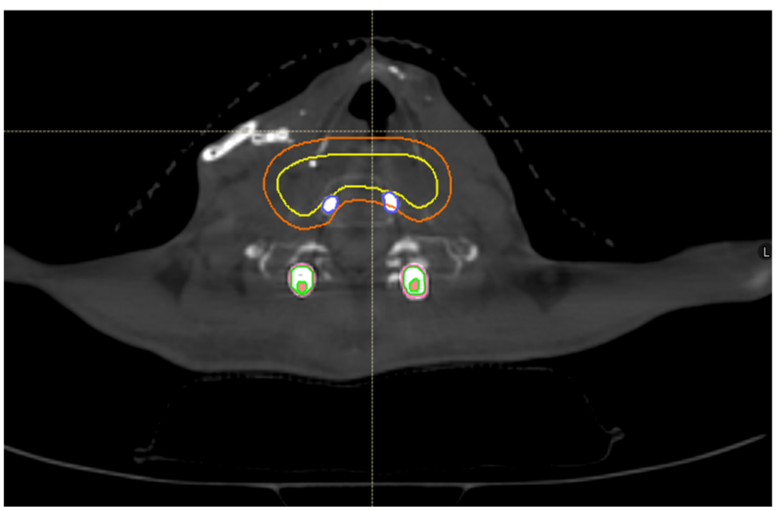
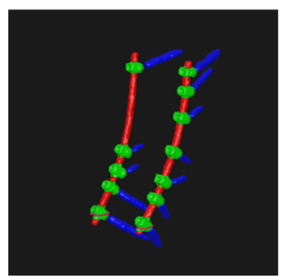
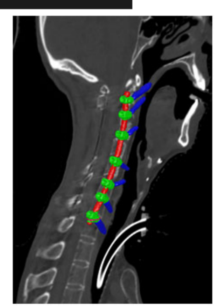
Contour yes; override?







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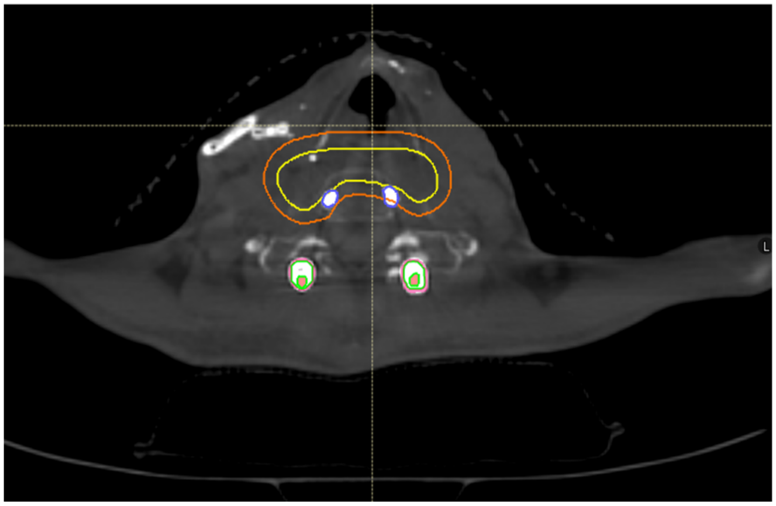
Contour yes; override?



Rods: Cobalt Chromium
 -**Override** 8.3g/cc

Screws & Tulips: Ti
 -**No override**
 -Do contour

High density artifact around metal
 -**Override** to closest matching tissue density

Low density streaking artifact
 -Override to closest matching tissue density

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The Dosimetric Impact of Metal in PBS Treatment Plans

- **The Dose Shadow Effect:** The deficit of dose (cold spot) on the distal side of a proton beam caused by the high density and stopping power of the metal. This creates an under-dosage (shadow) on the distal side of the implant.

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The Dosimetric Impact of Metal in PBS Treatment Plans

- **Spot Placement Errors:** The risk of proton spots misfiring into wrong anatomical locations if calculated incorrectly due to metal presence

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Plan Design and Beam Arrangement Strategies

- **Beam Arrangement Techniques:**
  - Utilizing numerous beam arrangements to dilute the shadow effect from a single direction.
  - Using alternating fields/angles to feather or smear out any cold spots.
  - Utilize Multi-Field Optimization MFO

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Plan Design and Beam Arrangement Strategies

- **Avoidance Principles (When to treat through metal):**
  – *Acceptable:* Small, thin hardware (e.g., small titanium screws, mesh) where the Water Equivalent Thickness (WET) can be accurately accounted for using Monte Carlo dose calculation algorithms.
  – *Unacceptable:* Large, thick implants or treating through long dimensions of the metal.

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Plan Design and Beam Arrangement Strategies

- **Why You Can/Can't Treat Through Certain Metals:** Density and thickness thresholds, and the impossibility of accurately predicting proton scatter through thick, irregular, or high-Z components.
- Some dense high Z metals would obstruct access to the target if in the beam path.

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The Role of Mixed Modalities (Protons + Photons)

- **Inherent Uncertainty:** Why it is sometimes necessary to mix in a certain percentage of photon radiation (e.g., VMAT/IMRT) around complex metal hardware.
- The role of photon VMAT/IMRT in overcoming the inherent uncertainties of proton beam delivery around complex, thick, or deeply shadowed metallic hardware.

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The Role of Mixed Modalities (Protons + Photons)

- **Clinical Rationale:** Photons are less sensitive to high-Z density interfaces, ensuring target coverage is maintained in shadowed regions where proton ranges are unpredictable.

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The Role of Mixed Modalities (Protons + Photons)

- **OAR Proximity:** Critical when organs are in or near the beam path (e.g., spinal cord, brainstem, optic chiasm, and optic nerves). A blended plan protects against meaningful target underdosage or critical structure overdosage in the event of setup errors.

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The Role of Mixed Modalities (Protons + Photons)

- **How to decide the % of proton vs photon:**
  - **No fixed rules; logical factors**
  - **Amount of metal near target**
  - **Formulate a coefficient to use of amount of beams thru metal times the uncertainty. Apply that to % split**
  - **# of beams that will avoid metal (3 beams of 4 then 30% XRAY ok)**
    - **Only ½ the beams avoid then maybe 50/50**
    - **More involvement of each beam with metal increases uncertainty/error**

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The Role of Mixed Modalities (Protons + Photons)

- **How to decide the % of proton vs photon:**
  - **Spinal cord involved**
    - **If able to do MFO (patch/thru) around the cord then approx. 15-20% photons to account for inherent uncertainties with the metal**
      - **Setup issues**
      - **Range uncertainty**

***Case study around cord will be 50/50 PBS VMAT split**

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Physics Consults & Supporting Operation Procedures (SOPs)

- **Physics Consultation Procedures:** Step-by-step workflow for when a dosimetrist must initiate a physics consult regarding material properties and hardware makeup.

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Physics Consults & Supporting Operation Procedures (SOPs)

- **Information Gathering:** Physics Consult
- Physicist shall determine, as best possible, the size composition, and physical density of the implanted material via a review of available operative notes, radiographic images, vendor provided reference materials, and if necessary, personal communication with the patient's surgeon via the attending radiation oncologist.

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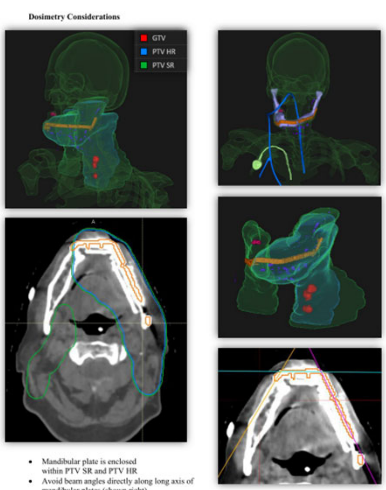
Sample information in physics consult



Implant/ID Cards [redacted]

[redacted]

Implants

+ New Implant

Implant	Type	Status	Implanted on	Explanted on
SCREW - CROSS DRIVE MINI 2.0MM X 9MM MFG#25-872-09-91	IMPLANT (IMPLANT	Explanted		3/25/2022
SCREW - LOCKING CROSS DRIVE 2.0MM X 7MM MFG#25-882-07-91	IMPLANT (IMPLANT	Implanted	3/25/2022	
SCREW - LOCKING CROSS DRIVE 2.0MM X 5MM MFG#25-882-05-91	IMPLANT (IMPLANT	Implanted	3/25/2022	
SCREW - LOCKING CROSS DRIVE 2.0MM X 11MM MFG#25-882-11-91	IMPLANT (IMPLANT	Implanted	3/25/2022	
Mandible plate		Implanted	3/25/2022	
COUPLER - MAC SYSTEM PURPLE 3.5MM (GEM2755) MFG#GEM2755	IMPLANT (IMPLANT	Implanted	3/25/2022	

Op/Procedure Notes [redacted] (Dr [redacted] UF Health Jacksonville):

The prefabricated custom reconstruction plate was secured to the native mandibular segments and secured in place through the predrilled holes with bicortical KLS locking screws, according to the VSP plan. Following transfer of the free flap to the head and neck field, the fibula was inset into the surgical defect. The fibula was secured to the custom reconstruction plate and the native mandible with monocortical KLS locking screws, according to the predrilled planned screw holes.

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Physics consult directive

- Based on the findings above, recommendations for the treatment planning approach shall be provided to dosimetry including applicable standing guidelines and/or patient-specific requirements.

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Sample planning guidelines

– For titanium implants (Z = 22):
  - Ok to treat through thin plates, meshes, small screws (length $\lesssim$ 1.0 cm), and small dispersed material. Increase range uncertainty during robust optimization to 4%.
  - For longer screws, create a metal avoidance structure using a 1 mm margin and avoid treating through the long axes of the screw; It is ok to treat through the cross-section of the screws and rods (diameter $\lesssim$ 1.0 cm), but range uncertainty should be increased to 4% during robust optimization.

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Sample planning guidelines

- For titanium implants (Z = 22):

- For larger implants:
  - Create a metal avoidance structure using a 1 mm margin and avoid treating through the implant if at all possible.
  - **If there is a critical need to treat through the implant**:
    - » Attempt to use beam angles and per-beam blocking that minimize long path lengths through metallic materials.
    - » Consider delivering 1/3 – 1/2 of prescription using VMAT based on level of uncertainty.
    - » Increase robust optimization settings, e.g., 4 mm, 4.5%.

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Sample planning guidelines

– - For metal implants w/ suspected Z > 22:
- Ok to treat through thin plates, meshes, small screws (length ≲ 0.5 cm), and small dispersed material, e.g., fiducial markers, clips. Increase range uncertainty to 4% during robust optimization.
- For larger implants:
  - Create a metal avoidance structure using a 1 mm margin and avoid treating through the implant if at all possible.
  - If there is a critical need to treat through the implant:
    - » Attempt to use beam angles and per-beam blocking that minimize long pathlengths through metallic materials.
    - » Consider delivering 1/3 – 1/2 of prescription using VMAT based on level of uncertainty.
    - » Increase robust optimization settings, e.g., 4 mm, 4.5%.

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Sample planning guidelines

- - For implants with CFR-PEEK:
  - Ok to treat through screws and rods. Use standard range uncertainty.
- For dental hardware
  - Create a metal avoidance structure using a 1 mm margin and avoid treating through the implant.

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General planning guidelines in presence of metal(s)

- -General planning recommendations:
  - For treatment planning w/ PBS always utilize **Monte Carlo.**
  - Consider using higher priorities on robust objectives.
  - Robust evaluation should be utilized during physics review.
  - Use multiple beams to average out range uncertainties.
  - Keep large angles between beams; Consider using non coplanar beams.
  - Use different angles for boost phases.
    - Also consider "feathering" beam directions (+/- 5-10 degrees) half-way through the treatment course
  - Avoid long pathlengths through metallic material, i.e., keep physical pathlengths $\lesssim$ 1 cm).
  - Use BEV, w/ 'metal contours' on to determine the best treatment angles.

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Physics Consults & Supporting Operation Procedures (SOPs)

- **CT Override Procedures:** Establish protocols for dealing with CT artifacts. Methods for contouring hardware and manually assigning/overriding physical densities

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CT Override Procedures:

- **CT Override Procedures:**
  - **Ti: no need to contour & override; HU assigned correct on CT**
  - **Due to saturated density of any material with a higher Z than Ti**
    - **If treating thru the implant the should contour and override density value**
    - **If not treating thru (avoiding) no need to override**
    - **Need to consider Stopping-Power Ratio (SPR)**.
      - ratio of a material's stopping power (how much energy a proton loses as it passes through) to the stopping power of water. The TPS uses SPR to calculate where the proton beam will stop in material.

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CT Override Procedures:

- **CT Override Procedures:**
  - *Stainless Steel assign density~7.95 g/cm^3*
  - *Gold (Z = 79): assign density~ 19.3 g/cm^3*
  - *Surgical/Bone Cement & Fillers: lower density but the material doesn't read the correct HU so need to override*
    - *See product specs to make estimate of density value*

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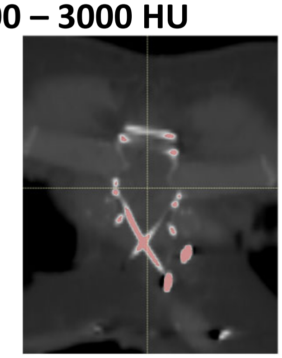
CT Override Procedures:

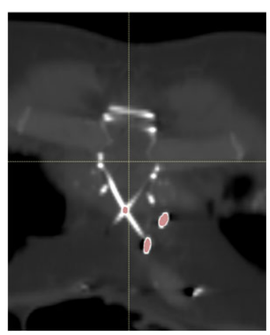
Careful not to over-contour: Could over-estimate a implant size because the actual object may be thinner than what we can contour (~less than 1mm diameter)

- Use Auto threshold contouring vs manual contouring

~2800 – 3000 HU



1000
vs
2800



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CT Override Procedures:

- **CT Override Procedures:**
  - **What if we are uncertain of material or best approach to override or not?**
    - **After plan optimization copy CT then +/- assigned density value**
      - **- on copied CT with +/- values a**
      - **Evaluate robustness of different scenarios**

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CT Override Procedures:

- CT Override Procedures:
  - converting streak artifacts back to muscle or bone density in the TPS
  - **OMAR**
    - **Orthopedic Metal Artifact Reduction**. software algorithm used in CT scanning to remove the dark bands and bright streaks caused by dense metallic implants (like hip replacements, surgical hardware, or dental fillings)

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OMAR

- **Improved Tumor Delineation:** Metal artifacts blur images and cast shadows, making it difficult to see where the cancer ends and healthy tissue begins. OMAR clarifies these obscured areas.
- · **Corrected Hounsfield Units (HU):** Radiation dose calculations depend on the tissue density numbers (Hounsfield Units) derived from the CT scan. Metal artifacts falsely alter these numbers. OMAR restores HU accuracy so the treatment planning system (TPS) can accurately predict dose delivery
  - In some cases, the algorithm can over-correct, causing secondary visual distortions or erasing fine bone details which degrades planning CT image quality

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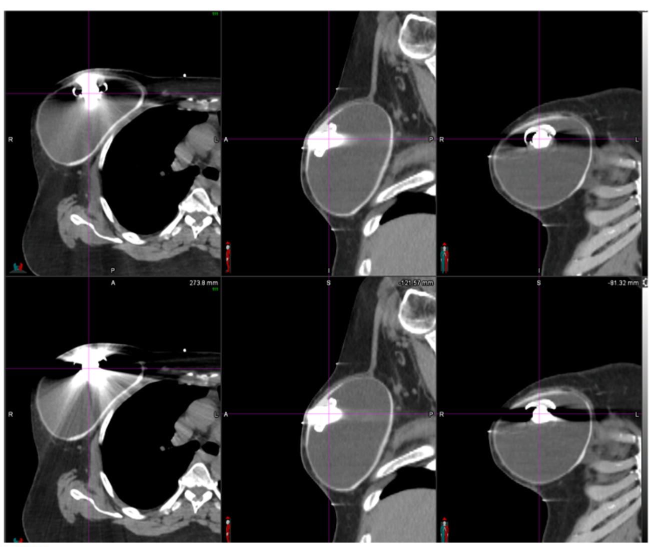
OMAR vs non-OMAR



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Robust Evaluation & Physics Validation

- **Robust Evaluation Approaches:** Validating the planning approach by testing specific scenarios, such as overriding the implant to multiple material densities (e.g., steel vs. titanium) and computing dose variations.

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Robust Evaluation & Physics Validation

- **Uncertainty Parameters:** Setting robustness parameters in the TPS to account for (3.5-4%) range uncertainty and (2-3mm setup uncertainty
- **Robust Evaluation Tools:** Using the Treatment Planning System (TPS) to validate the planning approach against the above robust optimization parameters

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Clinical Case Studies (Cervical spine)

- **Case Study:** *Spine (e.g., chordoma with titanium spinal rods and pedicle screws near cord).* Strategy: Multi-field optimization (IMPT) avoiding beam entry directly down the axis of the rod.

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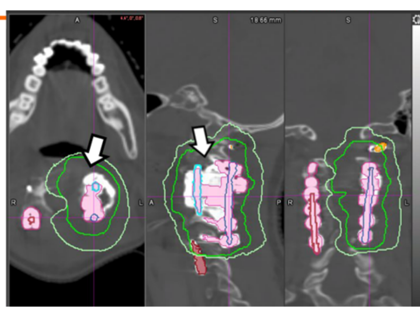
Chordoma C1-5 Spine



Titanium rods/screws/small cage/tulips take close to 15% of the CTV7380 volume

Fig.1. Implanted objects (Ti hardware, vertebra-reconstructing polymer ('surgical cement') and Embolization areas vs RT targets:

Cervical reconstruction hardware:

- **3 thin Titanium rods with long screws and center Ti cage (pink filled contour): Rt Ti rod (brown line), Lt ANT Ti rod (light blue), Lt POST Ti rod (dark blue);**
- **2 areas of embolization: Inferior embolization area (dark red filled contour) and Superior embolization area (filled orange contour).**
- **Hyper-intensive area marked with the arrow: vertebral column reconstructive methylmethacrylate (aka "surgical cement").**

Targets: PTV7380 (bright green) and PTV 5040 (light green).

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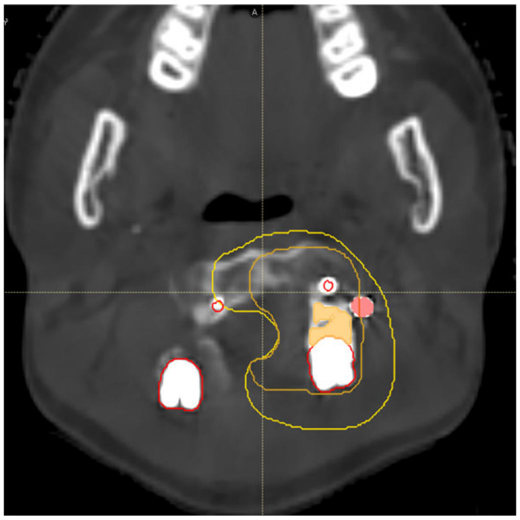
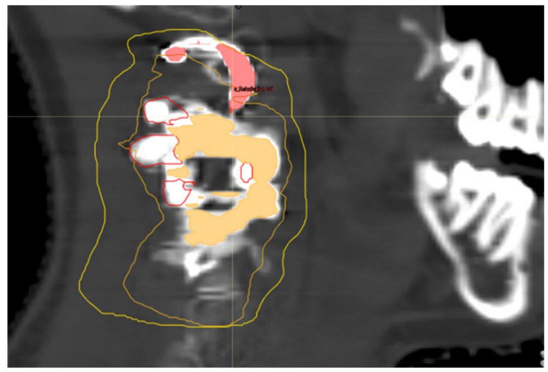
Chordoma C1-5 Spine



CTVs: Yellow outline
Orange filled: Surgical Cement (1.19 g/cc)
Ti hardware: Red outline
Embolization coil: red filled (16.65 g/cc)
-platinum



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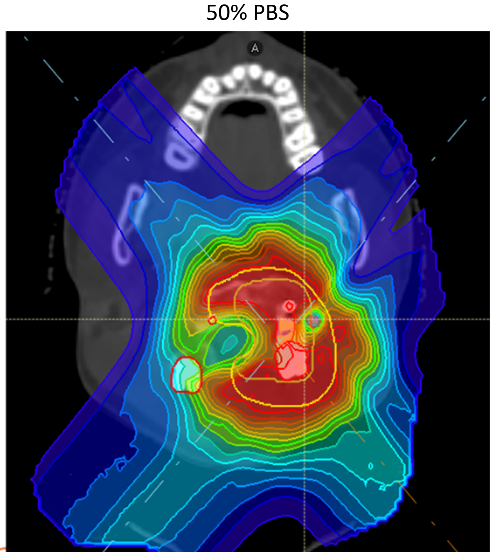
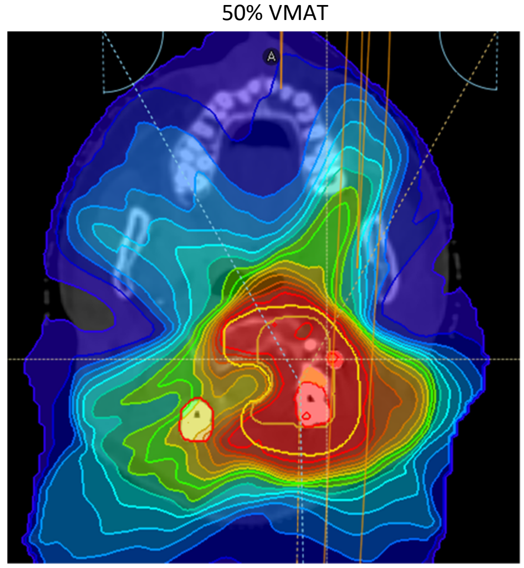
Chordoma C1-5 Spine

50% PBS



50% VMAT



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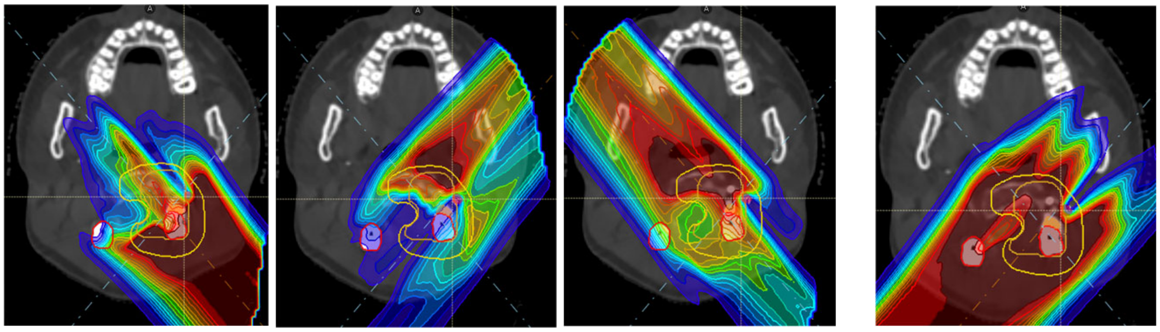
Chordoma C1-5 Spine



Did not treat thru platinum embolization coil + 1mm

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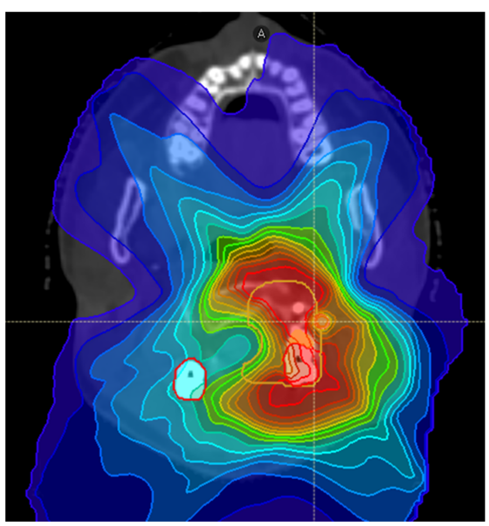
Chordoma C1-5 Spine

Composite 7380 cGy PBS/ VMAT50/50



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Clinical Case Studies (Prostate)

- **Case Study** *Pelvis (e.g., prostate/with a unilateral metallic hip prosthesis).*
- Strategy: Beam specific avoidance
- Strategy: Beam specific targets for range uncertainty.

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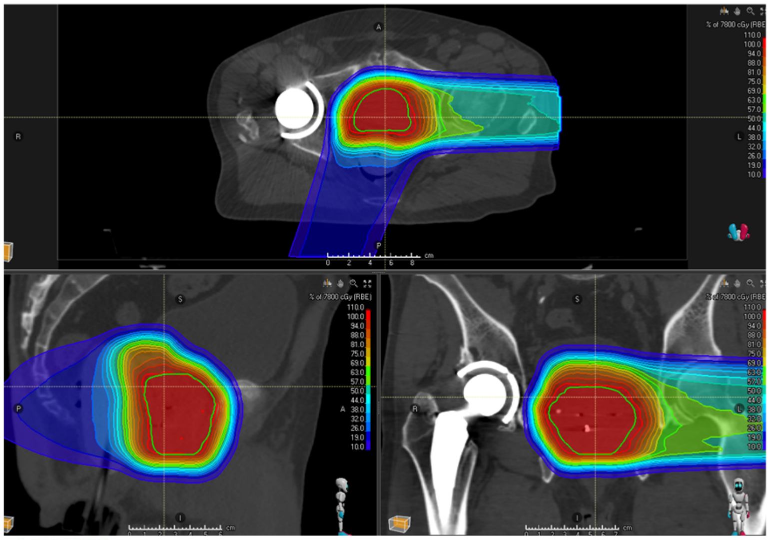
Prostate with unilateral hip implant



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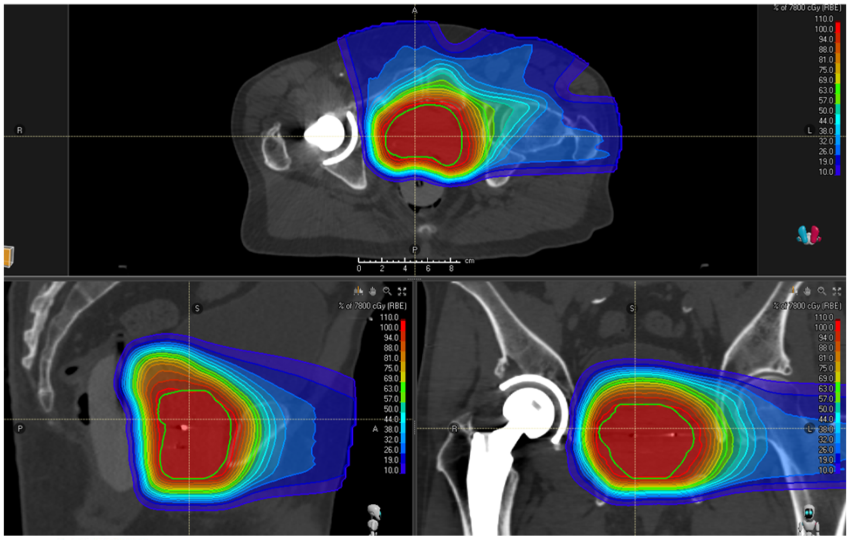
Prostate with unilateral hip implant



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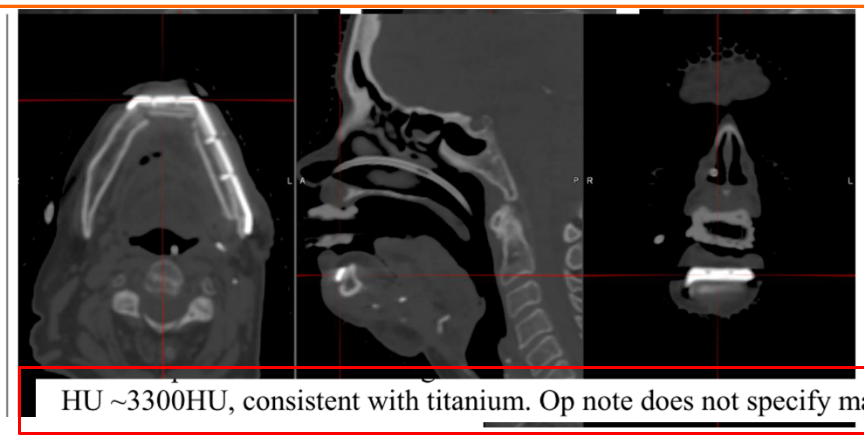
Case Studies: SCC Mandible



HU ~3300HU, consistent with titanium. Op note does not specify material

- Mandibular plate is enclosed within PTV SR and PTV HR
- Avoid beam angles directly along long axis of mandibular plates (shown right)

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SCC Mandible

1. Calculate plan on CT reconstructed with OMAR metal artifact reduction
2. Contour all metal structures
3. Contour remaining artifacts in soft tissue and override to the appropriate HU
4. Utilize Monte Carlo for PBS planning
5. Increase range uncertainty to 4% during robust optimization
6. OK to treat through thin plates and small dispersed material
7. For treatment planning w/PBS always utilize Monte Carlo
8. Consider using higher priorities on robust objectives
9. Robust evaluation should be utilized during physics review
10. Use multiple beams to average out range uncertainties
11. Keep large angles between beams; consider using non-coplanar beams
12. Use different angles for boost phases
13. Avoid long path lengths through metallic material, i.e. keep physical path lengths <1cm
14. Use BEV, w/'metal contours' to determine best treatment angles
15. Ensure all hardware included in export for site-setup for AdaptInsight

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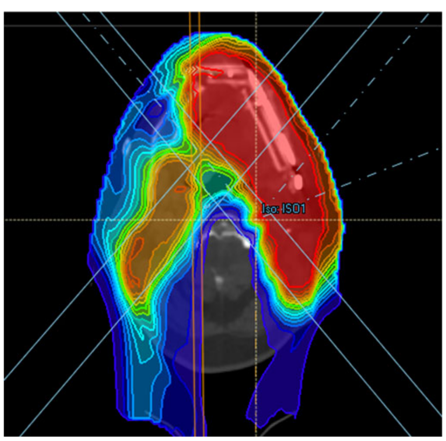
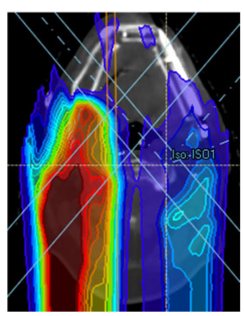
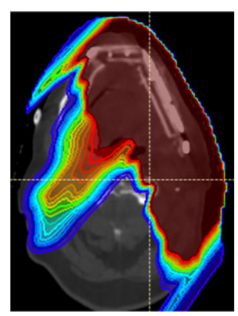
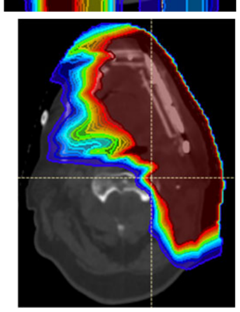
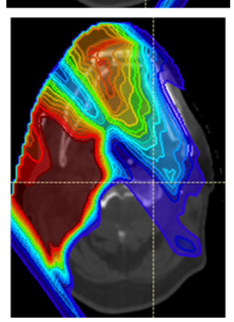
SCC Mandible











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Clinical Case Studies (thorax)

- **Case Study :** *Thorax (*sternotomy wire from CABG *).*
- Strategy: Multiple non-coplanar fields to mitigate uncertainties of treating thru high Z high density metal wire.
- *Wire: Stainless Steel (Z = 24-27):* High density.
  - Override wire to density~ 7.9 mass density
  - Use alternating fields/angles to feather or smear out any cold spots
  - Treated thru

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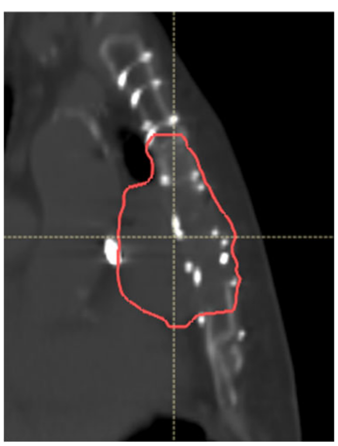
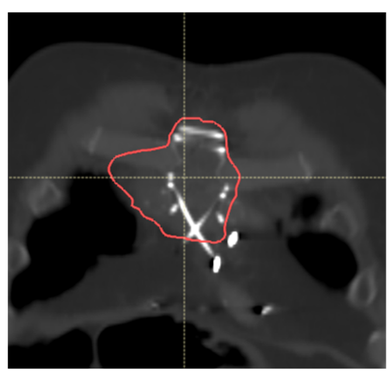
Case Study : *Thorax (*sternotomy wire from CABG *).*





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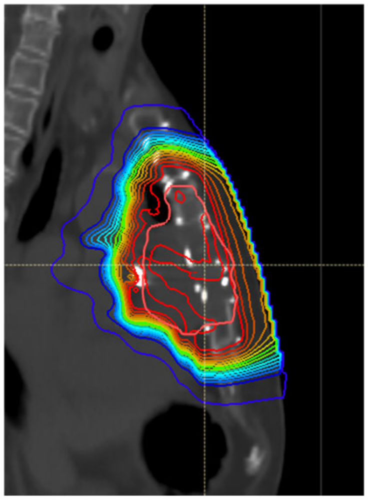
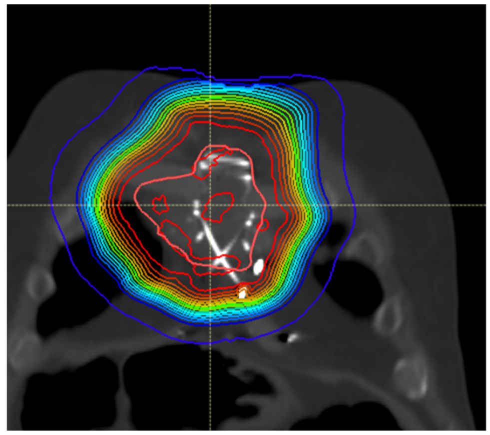
Case Study : *Thorax (e.g.,* sternotomy wire from CABG *).*





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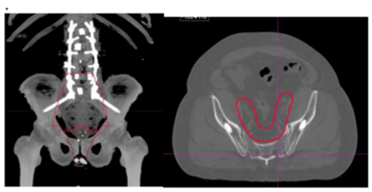
Pelvic Nodes with screws in field

Operative Report:
Patient has prior surgical fixation to Lumbar spine as seen on MIP images below. Fixation screws and hardware are typically Titanium.

Radiographic findings:
.



Recommendations:

Patient Specific recommendations:

Contour recommendations: Raystation will automatically utilize Ti stopping power for all HU > 4500 – <u>No need to override.</u>

1. Contour the Ti screws for use when aligning with X-rays.
2. Contour visible imaging artifacts outside the Ti screws, and assign these with their corresponding soft tissue and bone mass densities/HU values.

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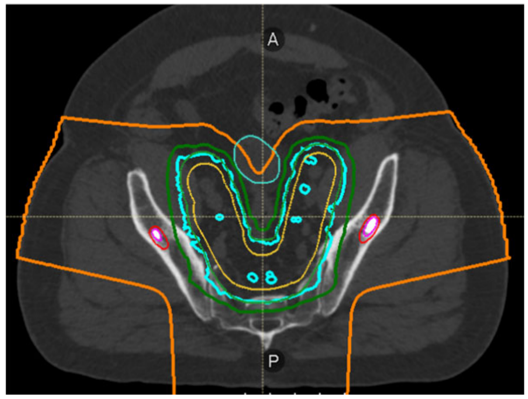
Pelvic Nodes with screws in field

1. Calculate plan on CT reconstructed with metal artifact reduction.
2. For treatment planning w/ PBS always utilize Monte Carlo.
3. Use slightly LAO and RAO beams to avoid Left and Right hip screws from being opposed to each other (and shadowing the target).
4. Use BEV, w/ 'metal contours' on to determine the best treatment angles.
5. Ensure all hardware included in export for site-setup for AdaptInsight.
6. Increase Robust optimization to 3mm and 4.5% for the Nodal volume plan only.



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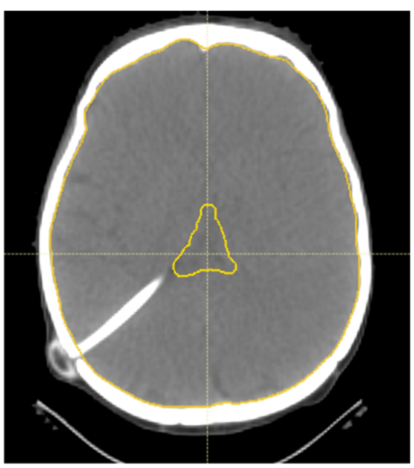
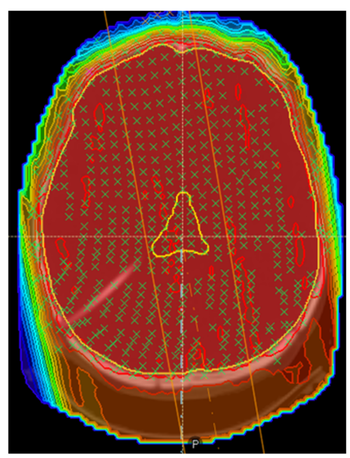
CSI with intracranial boost – External shunt port



External shunt ports with radiopaque drain tubes:

- For CSI phase use 10 degree oblique to avoid spots distal of shunt port in target
- Tested shunt tube with & w/o density override in robust eval
  - showed no difference
  - shunt tube plays no role in plan design
- Avoid shunt port for boost target



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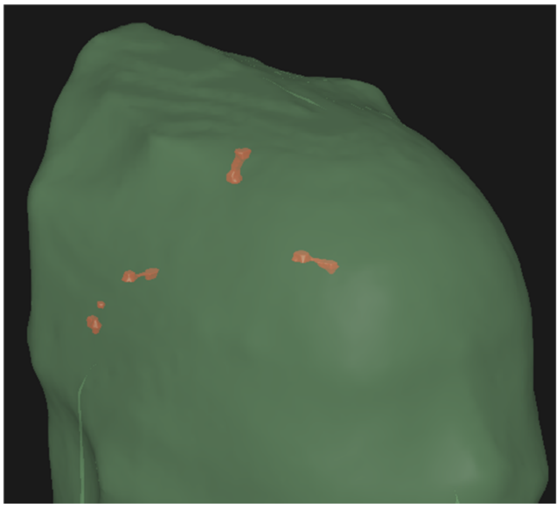
Small metal clips in skull



This may be most common scenario we encounter

Most commonly Ti

Seems to play no significant role in perturbing dose distribution

Historically we may have increased robust optimization settings for general range/setup uncertainty in presence of small clips

- 2mm to 3mm
- 3.5% to 4%

But if able to mostly avoid the clips and/or spread out beam angles to amount of metal in proximal BEV then no need to account for these

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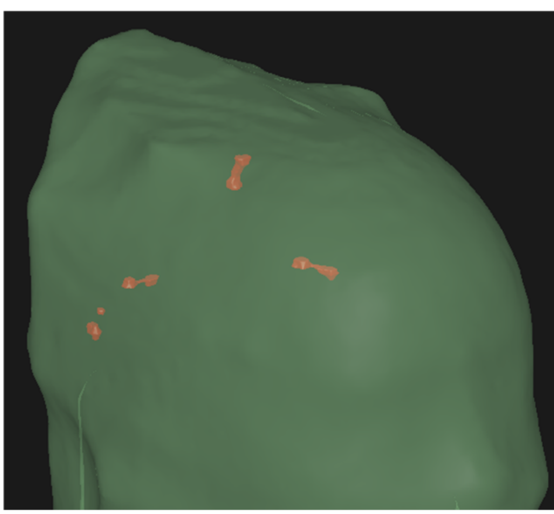
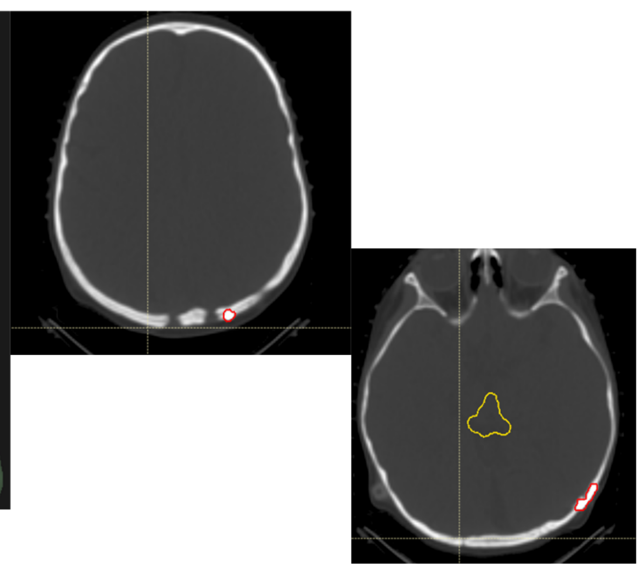
Small metal clips in skull





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Effect on patient

- Due to the dose perturbation, the local control of the tumor would be affected and cause excessive damage to the normal tissues and organs at risk surrounding the tumor, resulting in short- or long-term toxicity
- Although different metal implants have different effects on RT dose, the methods of reduce metal artifacts and dose calculation algorithms can decrease the impact to minimum, which result to a favorable clinical outcome

LIANG; Impact of metal implants on the dose & clinical outcome of radiotherapy; MOLECULAR AND CLINICAL ONCOLOGY 21: 66, 2024

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Related Clinical Outcomes

- Research at the Paul Scherrer Institute (PSI) indicated that patients with post-operative metal spinal implants treated with protons experience a lower overall 5yr survival than those without metal implants (~ 17%). It is unclear if this is due to the metal degrading proton radiation or if the implants simply indicate a more aggressive disease stage.
  - PBS beam measurements were reliable despite presence of metal

Newsletter of the Center for Proton Therapy :: Paul Scherrer Institut :: March 2016 :: #8; p3

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Conclusion & Best Practices Summary

- With a solid combination of the following a reliable PBS beam delivery in the presence of metal materials can be achieved:
- OMAR CT scan for planning
- Contouring overrides when applicable
- Educated beam selection (treat thru or avoid)
- Monte-Carlo computation
- robust optimization parameters

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Kevin Kirby, CMD, RT (R)(T)
Director of Clinical Dosimetry

Thank you for your time.

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