Clinical Implementation of Pencil Beam Scanning (PBS) Proton Therapy

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Penn Radiation Oncology Penn Medicine

AAPM Education Session
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Learning Objects

- **Learn about essential steps for preparing and commissioning a PBS system (~Dr. Dong)**
- **Understand dose calculation algorithms and their current limitations (Dr. Zhu)**
- **Understand characteristics of PBS and IMPT (~ Dr. Pankuch)**
- **Suggest training needs & transition issues, differences in vendor implementations; share experience (Panel discussion)**

Preparing for PBS Commissioning and QA

Lei Dong, Ph.D.

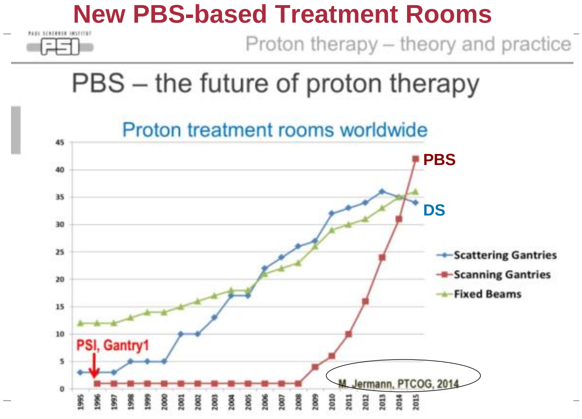
University of Pennsylvania

Disclaimer: Varian Proton Advisory Board Member
IBA customer

Scope and Goals

- To learn about common tasks for commissioning a PBS based treatment room
- To discuss time management to deal with commissioning
- To discuss risk-based vs. the best practice based approaches

New PBS-based Treatment Rooms



General Definition of Clinical Commissioning

- Preparation to treat the first patient
  - Workflow
    - Procedures, treatment protocol development, documentation
  - Equipment purchase & commissioning
    - Vendor selections (immobilization to chamber selection)
  - TPS commissioning
  - Quality assurance procedures
  - Training

Two-Face (Phase) Process

- **Prior to room handover (90%)**
  - Any preparation that does not need beam time
  - Negotiate beam time for commissioning
- **After room handover (10%)**
  - Beam calibration
  - External peer review
  - Beam data acquisition
  - TPS validation measurements
  - End-to-end tests
  - QA setup
  - User training

Simulation and Planning Workflow

Simulation
- Immobilization
- Special cases
  - Motion management
  - Supine vs Prone
  - Metal artifacts
  - MR sim
  - Documentation

Contouring
- Onsite contouring
- Density override policy
- Remote Access
- Image Fusion
- Communication with physicians
  - Prescription
  - Organ at risk

Planning
- IMRT comparison
- IMPT
  - Robustness evaluation
- Retreatment planning & composite dose plan
- Internal guideline

On-treatment Review
- Repeat CT imaging
- Adaptive RT

Develop Workflow Diagram

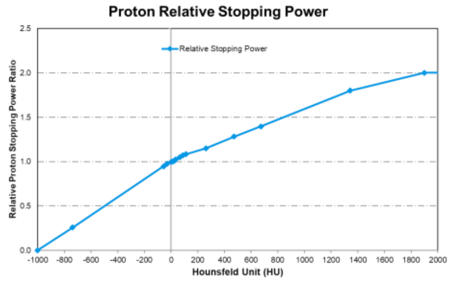
Site-Specific Guidelines (PBS vs. IMRT)

(Clinical Protocol Development)

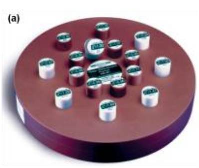
- **Clinical indicators**
  - What types of patients are suitable for proton therapy? Who are not?
  - Why physicists should care about this: plan check!
- **Simulation procedure**
  - Immobilization
  - Imaging requests
- **Treatment planning**
  - Prescription and normal tissue tolerances
  - Body contour (including treatment couch)
  - Density override policy
  - Planning techniques (class solution, beam angle selection)
  - SFO or MFO guideline
  - Plan report etc.

Commissioning a CT Scanner

HU to Stopping Power Ratio



Phantom Composition is Different from Human Tissue!



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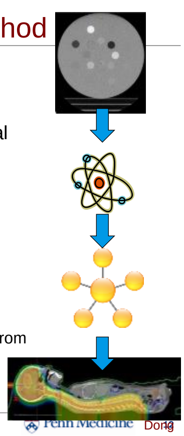
Stoichiometric Calibration Method



✓Parametric based CT calibration:

- CT#: fitting specific parameters from tissue substitutes with known chemical composition and electron density.
- SPR: calculated based on the Bethe-Bloch equation
- Extrapolation with Human tissue compositions information
  - Based on the population average values from ICRP 23, ICRU 44, etc.

Schneider, U., E. Pedroni, and A. Lomax, Physics in Medicine and Biology, 1996. 41(1): p. 111-124.

Additional Considerations

- **Patient Size Issue**
  - **Acquire phantom calibration in both head phantom and body phantom, and create an average table**
- **Peer Review**
  - **Similar CT models at other proton therapy centers**
- **Special material table**
  - Known materials and their SPRs
  - Dealing with metal artifacts
- **Documentation of CT recon parameters**
- **Metal artifact reduction algorithm**
  - Impact to normal tissue HU numbers?

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The First Week!

- **Evaluate measurement equipment**
- **Assess key commissioning measurements**
  - electrometer and ion chamber evaluation (leakage, linearity, end-effect, ion collection efficiency, etc.)
  - dose calibration
    - Challenging issues with high dose rate pencil beam
  - water tank and scanning hardware and software tests
  - detector tests for measuring beam profiles
  - gantry angle dependence (to ensure that measurement can be done, and measurements at one gantry angle would be adequate)
  - availability of accessories and other functions of the treatment unit

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PBS Dose Calibration

IAEA TRS 398

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Dose calibration

- **Establish the relationship between dose at reference conditions to charge collected in the monitor chamber in the nozzle**
  - Dose / MU
- **Steps**
  - Purchase ion chambers meeting TRS 398 specs
  - Send ion chamber + electrometer to ADCL for calibration
  - Make measurements under calibration condition
    - How to select calibration condition?
  - Measure Pion and Ppol
  - Measure absolute dose

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Chamber Selection

- **IAEA TRS 398**
  - Table 10

$$D_{w,Q} = M_Q N_{D,w,Q_o} k_{Q,Q_o}$$

Ionization chamber type [a]	Beam quality R_{res} (g cm^{-2})															
	0.25	0.5	1	1.5	2	2.5	3	3.5	4	4.5	5	7.5	10	15	20	30
PTW 30002/30011 Farmer	-	1.036	1.035	1.034	1.034	1.034	1.034	1.033	1.033	1.033	1.033	1.033	1.033	1.033	1.032	1.032
PTW 30004/30012 Farmer	-	1.044	1.042	1.041	1.041	1.041	1.041	1.041	1.041	1.041	1.040	1.040	1.040	1.040	1.040	1.039
PTW 30006/30013 Farmer	-	1.033	1.032	1.031	1.031	1.031	1.030	1.030	1.030	1.030	1.030	1.030	1.030	1.029	1.029	1.029
PTW 31002 flexible	-	1.032	1.030	1.029	1.029	1.029	1.029	1.029	1.029	1.029	1.029	1.028	1.028	1.028	1.028	1.027
PTW 31003 flexible	-	1.032	1.030	1.029	1.029	1.029	1.029	1.029	1.029	1.029	1.029	1.028	1.028	1.028	1.028	1.027
PTW 31006 PinPoint	-	1.027	1.025	1.025	1.024	1.024	1.024	1.024	1.024	1.024	1.024	1.024	1.023	1.023	1.023	1.022
PTW 31014 PinPoint	-	1.028	1.026	1.025	1.025	1.025	1.025	1.025	1.025	1.025	1.024	1.024	1.024	1.024	1.024	1.023
SNC 100700-0 Farmer	-	1.033	1.031	1.030	1.030	1.030	1.030	1.030	1.030	1.030	1.030	1.029	1.029	1.029	1.029	1.028
SNC 100700-1 Farmer	-	1.044	1.042	1.042	1.042	1.041	1.041	1.041	1.041	1.041	1.041	1.041	1.041	1.040	1.040	1.040
Victoreen Radocon III 550	-	1.031	1.030	1.029	1.029	1.028	1.028	1.028	1.028	1.028	1.028	1.028	1.028	1.027	1.027	1.027
Victoreen Radocon II 555	-	1.014	1.012	1.012	1.011	1.011	1.011	1.011	1.011	1.011	1.011	1.011	1.010	1.010	1.010	1.010
Victoreen 30-348	-	1.023	1.022	1.021	1.021	1.021	1.020	1.020	1.020	1.020	1.020	1.020	1.020	1.020	1.019	1.019
Victoreen 30-351	-	1.026	1.024	1.023	1.023	1.023	1.023	1.023	1.023	1.022	1.022	1.022	1.022	1.022	1.022	1.021
Victoreen 30-349	-	1.030	1.028	1.027	1.027	1.027	1.027	1.027	1.027	1.026	1.026	1.026	1.026	1.026	1.026	1.025
Victoreen 30-361	-	1.023	1.021	1.020	1.020	1.020	1.020	1.020	1.020	1.020	1.020	1.019	1.019	1.019	1.019	1.018
Scdx-Wellhöfer CC01		1.042	1.040	1.040	1.040	1.039	1.039	1.039	1.039	1.039	1.039	1.039	1.039	1.038	1.038	1.038
Scdx-Wellhöfer CC04/IC04		1.037	1.035	1.035	1.034	1.034	1.034	1.034	1.034	1.034	1.034	1.034	1.033	1.033	1.033	1.032
Scdx-Wellhöfer CC08/IC05/IC06	-	1.041	1.039	1.039	1.039	1.038	1.038	1.038	1.038	1.038	1.038	1.038	1.038	1.037	1.037	1.037
Scdx-Wellhöfer CC13/IC10/IC15	-	1.041	1.039	1.039	1.039	1.038	1.038	1.038	1.038	1.038	1.038	1.038	1.038	1.037	1.037	1.037
Scdx-Wellhöfer CC25/IC25	-	1.041	1.039	1.039	1.039	1.038	1.038	1.038	1.038	1.038	1.038	1.038	1.038	1.037	1.037	1.037
Scdx-Wellhöfer FC23-C/IC28	-															
Farmer shortened		1.042	1.040	1.039	1.039	1.039	1.039	1.039	1.038	1.038	1.038	1.038	1.038	1.038	1.038	1.037
Scdx-Wellhöfer FC65-P/IC69 Farmer	-	1.037	1.036	1.035	1.035	1.035	1.035	1.034	1.034	1.034	1.034	1.034	1.034	1.034	1.033	1.033
Scdx-Wellhöfer FC65-G/IC70 Farmer	-	1.044	1.042	1.041	1.041	1.041	1.041	1.041	1.041	1.041	1.040	1.040	1.040	1.040	1.040	1.039
Plane-parallel chambers																
Attix RMI 449	0.995	0.992	0.990	0.989	0.989	0.989	0.989	0.989	0.989	0.989	0.989	0.988	0.988	0.988	0.988	0.987
Capintec PS-033	1.029	1.026	1.024	1.024	1.023	1.023	1.023	1.023	1.023	1.023	1.023	1.022	1.022	1.022	1.022	1.021
Exradin P11	1.000	0.997	0.995	0.994	0.994	0.994	0.994	0.994	0.994	0.994	0.993	0.993	0.993	0.993	0.993	0.992
Holt (Memorial)	1.014	1.010	1.009	1.008	1.008	1.008	1.008	1.008	1.007	1.007	1.007	1.007	1.007	1.007	1.007	1.006
NACP / Calcam	0.994	0.991	0.989	0.989	0.988	0.988	0.988	0.988	0.988	0.988	0.988	0.987	0.987	0.987	0.987	0.986
Markus	1.009	1.005	1.004	1.003	1.003	1.003	1.003	1.003	1.002	1.002	1.002	1.002	1.002	1.002	1.002	1.001
Roos	1.008	1.004	1.003	1.002	1.002	1.002	1.002	1.002	1.001	1.001	1.001	1.001	1.001	1.001	1.001	1.000

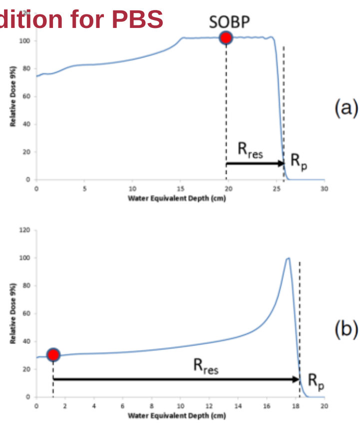
[a] Some of the chambers listed in this table fail to meet some of the minimum requirements described in Section 4.2.1. However, they have been included in this table because of their current clinical use

Calibration Condition for PBS

(a) Calibration at Mid SOBP (good for machines with built-in SOBP capabilities)

(b) Calibration at entrance region

For single energy planar irradiation (PBS)



TRS 398

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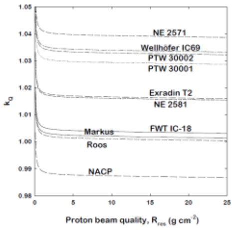
- Chamber perturbation correction factor
- Combines many corrections into one factor that is looked up in TRS 398 based on beam quality (Rres)
- Very stable number with Rres > 5cm (ie, 8cm+ SOBP)



$$k_{Q,Q_o} = \frac{(s_{w,air})_Q}{(s_{w,air})_{Q_o}} \frac{(W_{air})_Q}{(W_{air})_{Q_o}} \frac{p_Q}{p_{Q_o}}$$

TRS 398

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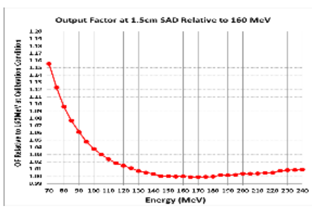
Calibrating the PBS system at Scripps

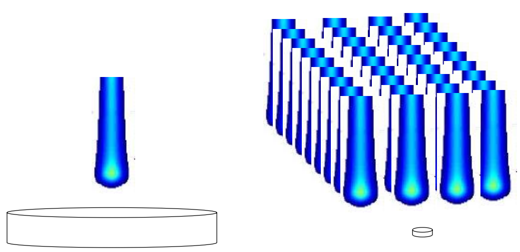
- **Goal: establish the dose-MU relationship**
  - IAEA TRS 398 protocol
    - Plateau region
      - **Less uncertainties Dwq**
      - **160 MeV**
      - **Uniform spot pattern**
  - **Energy dependent factor**
  - Normalized IDD Curves
- **Verify at SOBP**
  - After TPS commissioning



1.5cm depth

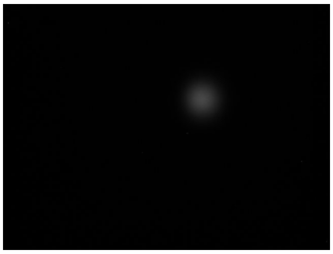
PBS Calibration Pattern

Large Chamber + Pencil Beam vs. Small chamber + Large Field



PBS Calibration Pattern

Scripps: 70-250 MeV Beam
Calibration Energy: 160 MeV
Depth: 1.5cm SAD



Correction for recombination:
Pulsed scanned – 1.0062
*Pulsed – 1.0048
Continuous – 1.0017

"Avg Dose Rate"
60k MU/min

Instantaneous DR
~ 10Gy/s

Pion

- **Corrects for recombination of ions in chamber. In other words, ions that are created but not collected.**
- **Two voltage technique with V1 and V2 differing by at least factor of 2.**
- **Our beam is pulsed scanned (pulsed for the chamber-eye-view)**
- **Generally this correction is less than 1%, but it is recommended to be less than 3%.**

Simplified version:

$$k_s - 1 = \frac{M_1/M_2 - 1}{V_1/V_2 - 1}$$

Long form for pulsed or pulsed scanned:

$$k_s = a_o + a_1\left(\frac{M_1}{M_2}\right) + a_2\left(\frac{M_1}{M_2}\right)^2$$

TABLE 4.VII. QUADRATIC FIT COEFFICIENTS, FOR THE CALCULATION OF k_s BY THE "TWO-VOLTAGE" TECHNIQUE IN PULSED AND PULSED-SCANNED RADIATION, AS A FUNCTION OF THE VOLTAGE RATIO V_1/V_2 [78]

	Pulsed			Pulsed scanned		
V_1/V_2	a_0	a_1	a_2	a_0	a_1	a_2
2.0	2.337	-3.636	2.299	4.711	-8.242	4.533
2.5	1.474	-1.587	1.114	2.719	-3.977	2.261
3.0	1.198	-0.875	0.677	2.001	-2.402	1.404
3.5	1.080	-0.542	0.463	1.665	-1.647	0.984
4.0	1.022	-0.363	0.341	1.468	-1.200	0.734
5.0	0.975	-0.188	0.214	1.279	-0.750	0.474

2
4

Peer Review

- **External review by a physicist**
  - Bring independent chamber and electrometer
- **IROC TLD measurements (at center of SOBP)**
  - TR4: 1.00
  - TR3: 0.99
  - TR2: 1.00

ACR-AAPM TECHNICAL STANDARD FOR THE PERFORMANCE OF PROTON BEAM RADIATION THERAPY

TPS Commissioning Measurements

- **See Dr. Zhu's presentation**

Creating Machine QA Baselines

- **Timing to create monthly and daily QA baselines**
  - During commissioning when TPS is finalized
- **Machine QA design**
  - Verify the machine is in the same condition as your TPS predicts
  - Risk-based

More about Risk-based Approach

- New ISO 9001:2015 promotes risk-based thinking in a quality management system due to **the need for balancing operational efficiency and comprehensive quality management**
  - Can we become **smarter** in our efforts while maintaining quality?
  - Risk-based ≠ Taking risks (without thinking consequences)
  - Act based on **"calculated" risks**
- **Knowledge is needed to estimate risks**

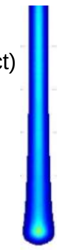
Machine QA Philosophy

- **Deciding what not to do are perhaps more important**
- **PBS (Spot Scanning vs. Raster Scanning)**
  - Spot intensity (dose/MU)
  - Spot position
  - Spot energy
  - Spot shape/size

  - ~~Dose Rate Stability?~~
  - Gantry dependence
  - Off-axis accuracy
  - Imaging-beam coincidence
  - Robotic couch

Assessing Risks Requires Knowledge

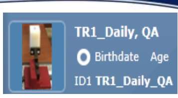
- **Relative risks for pencil beam delivery**
  - Spot Position (high risk)
  - Spot Intensity/dose (high risk/impact)
  - Spot Shape (intermediate risk)
  - Spot Energy (low risk)

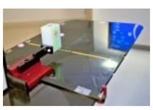


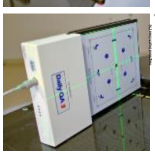
Scripps A World of Healing

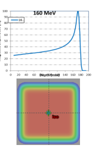
Daily QA

- End-to-end test run by therapists in the morning
- QA Phantom
- Imaging the block to verify:
  - Laser
  - couch position
- Dose pattern
  - Uniform spot pattern
  - 4 electron chambers to measure energy (~1mm resolution)
  - Central chamber for output
  - It can detect beam shape changes to some degrees









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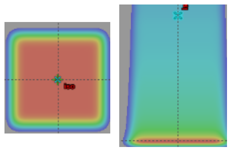
Monthly QA

Output measurement

- Repeat at machine calibration condition
  - Parallel plate chamber
  - Depth: 1.5 cm
  - Single layer
  - 160 MeV
  - Spot spacing 2.5mm
  - Electrometer bias -400v



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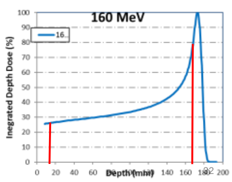
Monthly QA

Energy Check

- Two-depth Technique
  - Ratio of ion chamber readings
  - Base: 1.5cm build-up
  - Deeper depth: 16.5cm build-up
- Alternative
  - IBA Zebra™ (180 parallel plate chambers with 2mm resolution)



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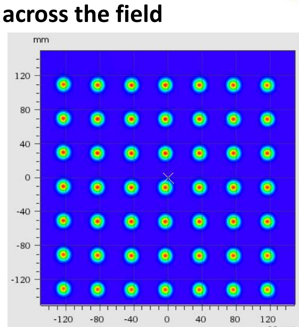
Monthly QA

Spot Position Accuracy across the field

- Coarse Pattern
  - Geometric distortion
  - FWHM in all positions
    - Shape of spots



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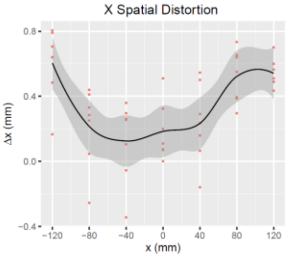
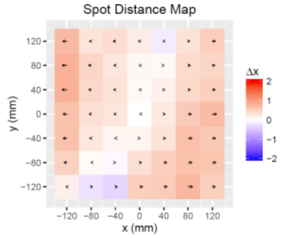
Monthly QA – Spot Off-Axis Position





Luis Perles
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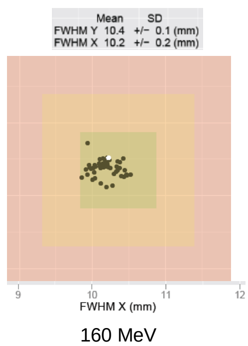
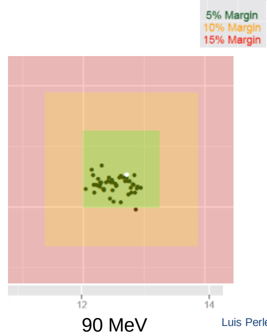
Monthly QA – Spot Size





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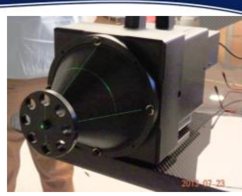
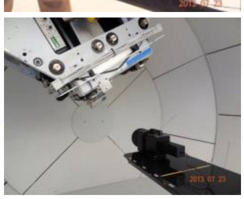
Monthly QA

- Center Spot Accuracy and agreement with imaging (kV or CBCT) and lasers



Logos Systems



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Annual QA – Repeat Commissioning

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- What if the QA baseline was wrong or changed?
- Repeat selected commissioning measurements
  - Measure IDD in water tank for selected energies
  - Measure spot shape and size for selected energies
  - Measure the relative energy dependence factor
  - Confirm range shifter thickness, integrity, and snout position accuracies

Summary: Establishing Machine QA Program

- Design tests to track changes from the TPS commissioning conditions (Risk-based; continuous improvement)
- Define Tolerances for each test
- Define Actions if out of tolerance
  - Treat options
  - Alternative validations
  - Additional tests for trouble-shooting
  - Standard Operating Protocol (SOP)
    - Contact List
    - Decision making

References:
- TG-224 (work-in-progress)
- Previous PTCOG presentations
- Books (books, AAPM summer school proceeding etc.)
- Standard Practice Guidelines (AAPM TG-40; TG-179, TG-142, IAEA TecDoc 1040 etc.

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Summary of Clinical Commissioning

- **Clinical commissioning is a multi-task project**
  - Start with self-education
  - Distribute work into smaller tasks
  - Planning and task management skills are important
  - Team work
- **Intense commissioning tasks involving physics/dosimetry:**
  - Dose calibration
  - TPS commissioning
  - QA procedures
  - Workflow
  - Planning comparison
  - Procedures and documentation

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