State-of-Art IMPT vs. IMRT

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Goals
- Review proton therapy technologies and IMPT
- Compare differences between IMRT and IMPT
- Discuss challenges in using IMPT in clinical practice

Why protons?
- Depth dose
- Bragg peak

Other Factors
- No. of beams
- Inverse planning
- Pencil beams
- PTV and size
- IGRT

Proton Therapy Centers in US

Growth of Proton Treatments

100,000th patient in 2012
Reasons to Establish a Proton Center

- Belief in Clinical Efficacy
- Program Differentiator
- Revenue Generation
- Institutional Prestige
- Defensive Maneuver

Physics

- Requires higher energy: 250 MeV p+ ~ 30cm
- Requires magnetic field for beam acceleration and beam steering

Cyclotron

Alternating Radio Frequency (RF) voltage accelerates protons when they go across the gap in each turn.
The Principle of Synchrotrons

Hitachi and Siemens Synchrotrons:
- Both designs use 7 MeV multi-turn injection for higher intensity: 1.2 x 10^11 protons per pulse (Hitachi)
- Both use RF driven extraction for tuning beam on and off quickly (< 200 μsec) and for gated respiration
- Both are strong focusing with similar magnet layout and beam optical

LLUMC Synchrotron:
- Uses slow extraction with 0.2 – 0.5 sec every 2.2 sec weak focusing
Beam Delivery System

- Gantry
  - Position beam in different angles (isocentric)
  - Mounting of imaging systems
  - Lasers
- Fixed beam port (horizontal/inclined)
- Nozzle
  - Delivery the protons
  - Dose monitoring system
  - Beam shaping devices
  - Protect patient from unwanted radiation
  - Imaging (optional)

Multi-room Systems

- Hitachi 270 MeV proton synchrotron
- IBA 220 MeV cyclotron
- Mitsubishi 235 MeV proton synchrotron
- Mitsubishi* 320 MeV/u synchrotron (20 cm – ¹²C)
- Optivus 250 MeV proton synchrotron
- ProTom 330 MeV/u proton synchrotron
- Siemens* 430 MeV/u synchrotron (30 cm – ¹²C)
- Varian 250 MeV superconducting cyclotron

* Proton and ¹²C

Single Room Systems

- IBA: ProteusOne

From 2D to 3D

What have been changed?
Revolution in Radiotherapy
From 2D RT to the Current State of the Art

- 1980s - 2D RT
- 1990s - 3DCRT → IMRT
- 2000s - IMRT → IGRT → Particle Therapy

2D RT

3D RT

IMRT

Patient Model for Planning Treatment

Fletcher’s Textbook of Radiotherapy

2D Isodose Calculation

Fletcher’s Textbook of Radiotherapy

2D Compensator

Fletcher’s Textbook of Radiotherapy

What Is Intensity Modulated Radiation Therapy (IMRT)

An approach to deliver conformal therapy with optimized non-uniform beam intensities:
- Use computer mathematical scoring to design non-uniform radiation fields,
- Use dynamic motion of Multileaf Collimator to “paint” dose where desired - Intensity Patterns.

9-Field Head & Neck IMRT Case

Int J Radiat Oncol Biol Phys 2001;51:865-7
Why is IMRT Possible Today?

- Computer power sufficient to calculate plans in reasonable amount of time
- Linear Accelerators are computer-controlled
- Automated methods of machine setup and setup verification are convenient and commonplace
- Multileaf collimators have good mechanical precision and reliability

From 2D to 3D to IMRT

- IMRT was the major treatment choice.
  - 3DCRT: conventional RT
  - FIF: manual field-in-field IMRT
  - IMRT: computer-optimized IMRT

New H&N Cases at MDACC (2007)

Technology Evolution in Proton Therapy

- From Scatter to Scanning
Passively Scattered Protons

2D Compensator

Constant Range Modulation Width and Distal Range Compensation

- Usually use range modulator wheels
- Distal range compensator (usually plastic or wax)
- Block/Aperture for collimation

Medulloblastoma (3 y old boy)

New survey from the National Association for Proton Therapy (NAPT) and the Pediatric Proton Foundation (PPF):
more children are being treated for cancer with proton therapy. 613 children were treated with proton beam therapy in 2011, an increase of 32 percent from 2010.


Lung Cancer

Red is higher dose and blue is lower dose.
Notice how much of heart and opposite lung is being irradiated w/ x-rays.
Pencil beam scanning nozzle
- Layer-by-layer scanning (changing energy is not easy)
- Spot scanning or raster scanning
- Max patient field (40x30) cm²

Constant Range Modulation Width and Distal Range Compensation
- Usually use range modulator wheels
- Distal range compensator (usually plastic or wax)
- Block/Aperture for collimation

Pencil Beam Scanning is Simpler
- Variable energy to treat tumor at different depth
- Dose conformality for both distal and proximal surfaces
- Sharp pencil beam to replace aperture

Why is PBS Possible Today?
- Better power supply for magnets (dipole; quadruple; fast scanning coils)
- More advanced accelerator technology
  - More efficient accelerator
  - Better beam optics (smaller spots)
  - Fast energy change and current modulation
  - Automatic beam tuning and control system
- Scanning nozzle (~ MLC)

Advantages for using Pencil Beam Scanning
- Fewer neutrons
- No physical compensator or aperture
- Sparing of healthy tissues proximal to the target
- Large treatment field
- Intensity and energy modulated proton therapy (IMPT)
  - Inverse planning
  - Dynamic dose painting (control points)

Step-and-shoot delivery of proton beam scanning
- Discrete spot scanning method
Proton Beam Delivery Mode

- Passive Scatter (PS)
  - Use scatter technique to create a large treatment field
  - Range modulation is required
- Uniform Scanning (US)
  - Pre-programmed PBS with beam aperture (more tolerant of motion)
- Pencil Beam Scanning (PBS)
  - Use magnetic field to scan the treatment field
  - High intensity modulation (better plans)
  - Energy (range) can be changed spot-by-spot

Raster Scan vs. Spot Scan

- Intensity modulation is much higher in spot scanning technique, which leads to better treatment plans
- Raster scanning may be more tolerant for organ motion

Evolution of Proton Therapy

Conventional PT → PBS (Pencil Beam Scanning) → IMPT (Intensity Modulated Proton Therapy)

IMRT vs. IMPT (big spot size)
PBS has better conformality and allows fewer fields.

- IMRT vs. IMPT
  - IMPT typically use fewer beams
    - 2-3 (IMPT) vs. 5-9 (IMRT)
  - Range uncertainties – PTV concept
  - CT image quality is important
  - Metal artifacts
  - Patient scatter
  - Normal tissue motion is important
  - IGRT
    - CBCT is lacking in proton therapy centers (today)

Image Guidance in New Systems

Image Guidance

- X-ray source to axis distance = 2 meters
- Detector to axis distance = 1 meter

Robotic Couch

Challenges
Inverse Planning Challenges

IMRT
- Beam angle
- Pencil beam position
- Pencil beam intensity

IMPT
- Beam angle
- Pencil beam position
- Pencil beam intensity
- Pencil beam energy
- Pencil beam spacing f(E)
- Robustness considerations

Straggling from Multiple Particle Paths

10 MeV electrons 10 histories
80 MeV protons 59 histories
150 MeV/n carbon ions 560 histories

MCNPX simulations

RBE Uncertainties

CT Number Uncertainties
Leading to errors in predicted proton range in patient

CT number to Proton Stopping Power

- Degeneracy problem
- HU (ρ₁, Z₁) = HU (ρ₂, Z₂)
- SPR(ρ₁, Z₁) ≠ SPR(ρ₂, Z₂)

Variations in Human Tissue Composition

Yang M.
SPR uncertainties have a significant impact on proton dose distributions. Commonly it’s not visible on proton plans.

Impact of 3.5% Range Uncertainty
- Uncertainty in SPR estimation
  - Estimated to be 3.5% (Moyers et al, 2001, 2009)

Beam-Specific PTV for Protons
- Relative Water Equivalent Depth Matrix

PTV is invalid for proton planning of mobile target
- Beam Angle Optimization
  - Setup error: 6mm
  - Internal motion error: 0mm (AVG CT)
  - Range error: 3.5% of total WET
  - Smearing: 1cm

Free breathing Treatment
- Gated treated on exhale
Materials and Methods

Experiment: 2D dose measurement

Snout Experiment:

2D dose measurement

Moving Platform (1D motion)

Stepping motor

Matrix monitored by an external sensor

Laser displacement sensor: Omron ZS-LDS2VT

Results (no gating)

Orthogonal – 3s

Proton Lateral Penumbra vs. Distal Falloff

95-50% ~ 10 mm 95-50% ~ 4 mm

Inter-fractional Variations

Planning contours mapped to 24 in-room CTs

Impact of Tumor Shrinkage on Proton Dose Distribution

Original Proton Plan

Dose recalculated on the new anatomy

Bucci/Dong et al. ASTRO Abstract, 2007

Patient Setup

Thoracic

H&N

Prostate
Setup Error and Positional Variation of Immobilization Device

Couch Edge Effect

IMPT Planning

Robustness of IMPT for Multi-beam IMPT?

SFO vs. MFO
- Single-Field Optimization
  - Treat the entire target from one beam
  - Less normal tissue sparing
  - Relatively more robust for range uncertainties
- Multi-Field Optimization
  - Simultaneous optimization of multiple beams for one or more targets
  - Better plan (on paper) and more tissue sparing
  - Sensitive to range uncertainties and organ motion

IMRT vs. IMPT Example

RapidArc™ 3F IMPT
Robustness Evaluation

SFO vs. MFO

3F SFO

3F MFO

Robustness Evaluation

3F MFO Plan

3mm and 2% Uncertainties

Robustness Evaluation

Prostate Region

3F MFO Plan

3mm and 2% Uncertainties

Robustness Evaluation

Nodes Region

3F MFO Plan

3mm and 2% Uncertainties

Robustness Evaluation

3mm and 2% Uncertainties

3F SFO Plan

3F MFO Plan

Robustness Evaluation

Target Coverage and Hotspots

3F MFO Plan

3mm and 2% Uncertainties
Robustness Evaluation

Summary

Challenges
- Development and optimal use of IMPT
- Measurement dosimetry
- In vivo range verification
- Robustness plan evaluation
- Robust plan optimization
- Motion management strategies
- Dose-guided setup and adaptive RT
- Workflow optimization and efficiency
  - Auto-segmentation
  - Workflow assessment and optimization
  - Setup outside of treatment room

Opportunities
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Future Proton Therapy Machines will be Different from Today!

What is IMRT?
I'M Really Tired

What is IMPT?
I'M Painfully Tired