Imaging Needs for Protons

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**Propositions**

- Imaging serves to ensure the correct fraction dose
  - ... and, in current practice, assumes geometry equals dosimetry.
    - *True for γ – Geometry does not affect dosimetry*
    - *False for p – Geometry strongly affects dosimetry*
  - Not all observables are image-based
  - DGRT: Dose-Guided RT

- p RT requires different implementations
  - ... thus, equipment has different effectiveness between γ and p

- p physics offers novel capabilities
  - ... in-vivo, chemical, control-feedback at the delivery level

- Identify p-specific requirements & deployments
- Identify p workflow requirements
Active Goals in RT

- Image-guided therapy for improved targeting
- Increase target to healthy tissue dose ratio
- Reduce treatment time and/or increase fraction size
- Reduce cost for patient, society, and caregiver

Requires

- Registration – Common reference of data
- Adaptive RT – Adjust delivery pattern
- Motion tracking – In-vivo
- Performance – Computations, Feedback & Control
- Connectivity – Data backbone & Logic

Claim: p can outperform \( \gamma \)
The $p$ is an instrument

- A narrow $p$ beam is a concise information package
  - $E_{in} - E_{out}$
  - $dE/dX(x,y,z)$
  - Bragg peak localization
  - $(x,y,z)$
  - Charged
  - Ionizing, count, control / ion
  - Nuclear interactions
  - $\gamma$
  - Highly redundant
  - Effective use of prior knowledge

- Immediate control feedback
  - Parameters into the system – $(E,Q,x,y)$ – are the ones observed
    - We also need ‘t’
    - Unlike IMRT where $D = f(\text{leaf position})$
  - High-speed controls
    - Limited, typically, by $E$ switching
In PBS: Same variables (Q, E, x, y) throughout in planning, control, and verification
• Fully electronic
Challenge – IGRT

p IGRT: Difference Range Map

Patient 2 Subtraction (before - after treatment)
Exam ID 8532 - 8795  T= 0 %

Blue region
Primary changes due to tumor Shrinkage

S Mori, PhD MGH 2006
Prior Knowledge

- Pre-treatment imaging resolves the set of target positions
- Selective range imaging can rapidly “probe” the patient

PBS time structure is fast

- Energy is slowest (0.5 s ?)
- $Q(x, y, E) \rightarrow Q(x, y, E, t)$
In vivo dosimetric verification of proton radiation therapy: Biomolecular understanding and application of hepatocyte-specific functional MRI

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Gd-EOB-DTPA

- Clinical available (Eovist = Primovist)
- 50 % actively taken up in healthy hepatocytes by Organic Anion Transporter Proteins (OATPs)

Influence of irradiation

- Irradiation induced release of proinflammatory cytokines (TNF-α, IL-1β, IL-6)
- Proinflammatory cytokines influence hepatocytic function
2.5 months after end of proton therapy
40 Gy in 5fx over 2 weeks

Eovist enhanced MRI post-pRT
Response during treatment?

Dose-correlated changes visible about 7-12 days after start of treatment!
A Detailed Comparison of proton vs. Carbon Ion Computed Tomography

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Ion Tomography

- Stopping Power ratio conversion from HU based on population average has a systematic range error (~2%)
- Proton tomography originally proposed by Andy Koehler (1968, Science)
  - Experiment: A Cormack & A Koehler (1976, PMB)
- Issues:
  - Proton: Scatter in patient
  - Carbon: Dose in patient
- Use prior information

Conventional: \[ \min ||Ax - b||^2 \text{ subject to } x_i > 0 \]

+ Prior CT: \[ \min ||Ax - b||^2 + \lambda ||x - p||^2 \text{ subject to } x_i > 0 \]

where \( A \) is the path to \( \Delta E \) functional, \( x \) reconstructed density, \( b \) energy loss, \( p \) prior CT converted to S
Ion Tomography

Normalized difference to ground truth

<table>
<thead>
<tr>
<th>Type</th>
<th>Resolution (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>230MeV Protons</td>
<td>1.04</td>
</tr>
<tr>
<td>230MeV Protons &amp; X-ray</td>
<td>0.38</td>
</tr>
<tr>
<td>330MeV Protons</td>
<td>0.84</td>
</tr>
<tr>
<td>430MeV/u C-12</td>
<td>1.12</td>
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</tbody>
</table>
In vivo proton beam range verification using resolvable prompt gamma lines

Joost Verburg, Kent Riley PhD, Joao Seco PhD

Harvard Medical School and Massachusetts General Hospital
Resolvable prompt gamma lines

• Most prompt gamma-rays near end-of-range result from a few nuclear level transitions
  - $^{16}\text{O}(p,p')^{16}\text{O}^*$ 6.13 MeV γ
  - $^{12}\text{C}(p,p')^{12}\text{C}^* + ^{16}\text{O}(p,\alpha)^{12}\text{C}^*$ 4.44 MeV γ
  - $^{16}\text{O}(p,p')^{16}\text{O}^*$ 2.74 MeV γ
  - $^{16}\text{O}(p,p\alpha)^{15}\text{N}^* + ^{16}\text{O}(p,p\alpha)^{15}\text{O}^*$ … 5.2 MeV γ

• Resolving discrete energies allows for novel range verifications methods
  - Incorporate known nuclear reaction cross sections
  - Improve accuracy in the presence of tissues with unknown compositions
Prototype detector

1. **LaBr₃(Ce) scintillator with high energy resolution**

2. **Active anti-coincidence shield**
   - Reduce Compton background
   - Reduce neutron-induced gamma background

3. **Data acquisition system**
   - Synchronized to cyclotron radiofrequency (9 ns period)
   - 200 ps sampling resolution
   - Digital pulse processing
Results: Time/energy histogram

9 mm proximal to end-of-range:
- 6.13 MeV
- 5.2 MeV
- 4.44 MeV
- 2.74 MeV

9 mm distal to end-of-range:

counts
Results: Range 16 cm
Patient Imaging Requirements

- Geometric setup and stability
  - Multi (1..n) planar X-ray

- Motion tracking
  - Surface tracking (RPM, VisionRT, …)
  - Fluoroscopy of diaphragm / internal markers
  - EM / RF

- Soft-tissue deformation / changes
  - CBCT

- Adaptive planning
  - (4D)CT

- Perform within the treatment session workflow
  - Optimization
  - Connectivity
Workflow

Imaging
• X-ray + CBCT
• CT

Procedures
• Scenarios
  • Outside / Inside room Immobilization / Imaging
  • Optimization
  • Flexibility
• Facility Layout
• Workflow
IGRT: Some in-room solutions

CT (on rails) – Off isocenter, space, time

HIT PPS solution

Gantry mounted X-ray systems
PAIR: Integrated imaging ring:

- X-ray / Panel Independent Motion
- Couch CS
- X-ray
- CBCT
- Fluoroscopy

medPhoton GmbH

radART
Paracelsus Medical University
Salzburg
Ultra-large Field of Views

Image auto-stitching

medPhoton GmbH
Fixed Beam Setup for Seated Patients

Products

1. P-ART Comprehensive System (all modules but adaptive therapy sw)
2. P-ART Imaging System (all modules, but the robot and the adaptive sw)
3. P-ART Adaptive Therapy System (the adaptive sw)

Product Modules

- P-Cure Moving Platform
- CT Scanner
- Camera
- Robotic Chair
- Adaptive Therapy Software
- Positioning Software

Real-Time imaging + ART can compensate for uncertainties in seated patients
Workflow Simulation

- Analyze
  - Patient flow - are there bottlenecks?
  - Queue locations and sizes – are they blocked or starved?
  - Resources - are they sufficient, do they starve important operations?
  - Failure modes - what are they and what causes them?
  - Check required capacity

- Optimize
  - A stitch in time saves nine – find all the little holes in the process
  - Try before you build
  - Create baseline for performance and improvement

- Discrete-Event Simulation
  - Model system state changes at precise points in simulated time
  - Many commercial packages – Simul8
**Workflow Scenarios**

- **In gantry**
  - 1..2 X-ray imaging
- **Dedicated per gantry**
- **Immobilization with either**
  - No imaging
  - CT
  - **Orthogonal Imaging**
- **In gantry**
  - 1..2 X-ray imaging
Current State – 100 days

Total (min)  553
Gantry (min)  501
Interval (min)  51

Total = End of Last – Start of First patient
Gantry = sum of all patient time in gantry
Request = waiting time in request
Workflow Connectivity

• The treatment session comprises several discrete tasks combinable in various workflow scenarios
  • Immobilization
  • Volumetric imaging for dose verification
  • Treatment plan adaptation
  • Setup verification
  • Beam-on monitoring

• Requires data model and connectivity for inter-task communication
  • DICOM Gen 2
  • IHE-RO Profiles
Sup 147: Second Generation RT Radiotherapy

- Existing radiotherapy IODs were designed as containers to communicate radiation therapy data.
- Radiation therapy practice and DICOM have evolved.
- In particular, workflow management is now a key aspect of DICOM’s domain of application.
  - Unified Worklist and Procedure Step
  - Temporal view to map the treatment sequences
Workflow Connectivity

- MGH uses a “Whiteboard” that manages the data hand-off between tasks
  - Did not find sufficient or efficient support in existing systems
- MGH / ICT are developing an Enterprise System Bus to
  - Capture and coordinate all data transactions between systems (tasks)
    - Build-up DICOM Gen 2 RT Course Record as a function of executed and pending tasks
  - InterSystems Ensemble and Cache for ESB
    - Service Oriented Architecture
      - RT systems are, typically, “stand-alone” applications
    - Business Rule Engine to manage task scheduling and execution
- mirth
  - DICOM interface and routing
Service Oriented Architecture

- Client App
- Workflow
- Event Processing
- BPL
- Messaging Transformation Security
- Cloud Computing
- DB
- PACS
- RT Course
- Intersystems

Massachusetts General Hospital Cancer Center
Harvard Medical School
Large Scale Computing Architecture

Web Application
Desktop Client Application
Test and Commissioning Scripts
User
Summary

- \( p \neq X \)
  - Same (perhaps) requirements
  - Different Implementation especially where geometry does not suffice for dosimetric feedback (CT vs CBCT)
- \( p \) physics offers enhanced feedback
  - Tissue interactions: Prompt \( \gamma \)
  - Immediate dosimetric feedback during delivery
    - Permits control and adaptation during delivery
- Workflow integration and variation
  - “Old” LINAC workflow model must be challenged
  - Do not, ad-hoc, re-use solutions – Look at requirements
- Data & High Performance Computation Backbone
  - Light-weight “point of service” applications
  - Need to capitalize on “modern” computing