Rationale for Proton Therapy

Need for Improved Local Control in Cancer Treatment (selected sites) (all numbers are estimates)

<table>
<thead>
<tr>
<th>Tumor Site</th>
<th>Deaths/year</th>
<th>Deaths due to Local Failure</th>
</tr>
</thead>
<tbody>
<tr>
<td>Head/Neck</td>
<td>22,000</td>
<td>13,200 (60%)</td>
</tr>
<tr>
<td>Gastrointestinal</td>
<td>135,000</td>
<td>54,000 (40%)</td>
</tr>
<tr>
<td>Gynecologic</td>
<td>28,000</td>
<td>14,000 (50%)</td>
</tr>
<tr>
<td>Genitourinary</td>
<td>55,000</td>
<td>27,500 (50%)</td>
</tr>
<tr>
<td>Lung</td>
<td>160,000</td>
<td>40,000 (25%)</td>
</tr>
<tr>
<td>Breast</td>
<td>41,000</td>
<td>4,920 (12%)</td>
</tr>
<tr>
<td>Lymphoma</td>
<td>20,000</td>
<td>2,400 (12%)</td>
</tr>
<tr>
<td>Skin, Bone, Soft Tissue</td>
<td>15,000</td>
<td>5,000 (33%)</td>
</tr>
<tr>
<td>Brain</td>
<td>12,000</td>
<td>10,800 (90%)</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>488,000</strong></td>
<td><strong>171,820 (35%)</strong></td>
</tr>
</tbody>
</table>

Over 1,350,000 new cancer patients per year in the US
Dosimetric advantages of proton beams

- Protons Stop!
- Photons don’t stop.
- Proton dose at depth (target) is greater than dose at surface.
- Photon dose at depth (target) is less than dose at d_{max}.

Advantages of Proton Therapy

Highly localized dose distributions →
- Increased local control of tumors
- Decreased treatment-related side effects
- Improved Quality of Life

Proton Physics

Protons lose energy by:
- ionizations
- multiple Coulomb scattering
- non-elastic nuclear reactions.
Electromagnetic energy loss of protons

1. The incident beam has a narrow energy spread ($\Delta E/E \approx 0.2\%$)
2. Bragg peak is "broadened" by range straggling (statistical differences in energy losses in individual proton paths).

Mass Electronic Stopping Power is the mean energy lost by protons in electronic collisions in traversing the distance $dx$ in a material of density $\rho$.

$$\frac{S}{\rho} = \frac{1}{\rho} [\frac{dE}{dx}] \propto \frac{1}{v^2}$$

Where $v =$ proton velocity

This is the main interaction that causes formation of Bragg peak.

Nuclear interactions of protons

- A certain fraction of protons undergo nuclear interactions, mainly on $^{16}$O ($\sim 1\%$/cm)
- Nuclear interactions lead to secondary particles and thus to local and non-local dose deposition, including neutrons.

Effect on lateral dose distribution

Pedroni et al. PMB, 50, 541-561, 2005

Effect on Depth Dose

Normalized (at peak) Bragg Curves for Various Proton Incident Energies

Range Straggling will cause the Bragg peak to widen with depth of penetration

230 MeV protons

Total Absorbed Dose

Primary Dose

'Secondary' Dose

Normalized (at entrance) Bragg Curves for Various Proton Incident Energies

Depth in Water (cm)

Relative Dose [%]
Dose depositions in water from 160 MeV protons. Beam slit delimiters with width $W$ cm. Uniform particle distributions.

<table>
<thead>
<tr>
<th>Depth (cm)</th>
<th>Dose (MeV/cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>5</td>
<td>0</td>
</tr>
<tr>
<td>10</td>
<td>0</td>
</tr>
<tr>
<td>15</td>
<td>0</td>
</tr>
<tr>
<td>20</td>
<td>0</td>
</tr>
<tr>
<td>25</td>
<td>0</td>
</tr>
<tr>
<td>30</td>
<td>0</td>
</tr>
</tbody>
</table>

For small fields, loss of in-scattering (charged particle equilibrium) results in deterioration of Bragg peak and non uniformity of SOBP.

Multiple Coulomb Scattering (MCS) leads to broadening of lateral penumbra as beam penetrates in depth.

- Protons undergo multiple deflections through elastic coulomb interactions with atomic nuclei
- Beam broadening can be approximated by a Gaussian distribution

Lateral penumbra:
- Dominated by Multiple Coulomb Scattering
- $d_{80:20} = 1.68 \sigma = 3.3\%$ of range $\Rightarrow \approx 5$ mm at 15 cm depth
- Wide angle scattering and nuclear interaction products add
- Total penumbra $\approx 6$-$7$ mm at 15 cm depth

Lateral dose fall-off: Protons vs. Photons
Large air gaps will degrade the lateral penumbra.

Proton Therapy
Beam Delivery Technology

Physics of the Passive Scattering Mode of Proton Beam Delivery

Passive Scattering Nozzle with Range Modulation Wheel

Hitachi Passive Scattering Nozzle
How a Spread Out Bragg Peak (SOBP) is formed.

- Modulation wheel rotates in the beam.
- Pull-back (energy shift) determined by height of step.
- Weight determined by width of step.
- Multiple SOBPs can be obtained by gating beam.

Deficiencies of Proton Passive Scattering Techniques

- Excess normal tissue dose.
- Increases effective source size which increases lateral penumbra.
- Requires custom aperture and compensator
- Inefficient - high proton loss produces activation and neutron production.

Prostate Patient Treatment Plan

- Measurements in water phantom using EBT film, patient aperture, and range compensator

QA of Prostate Treatment using patient treatment parameters/appliances and EBT film in water phantom.

- Treatment plan on CT geometry converted to dose distribution in water phantom.

The Pencil Beam Scanning Mode of Proton Beam Delivery

- ACTIVE SCANNING
  - Dynamically varying sweeping magnets (in and out of plane)
  - No compensator, and generally no collimator needed
  - No wasted protons

- Variable SOBP
  - Protons produced of the lateral beam profile
**Pencil Beam Scanning Nozzle**

**Performance**
- Range: 4 – 36 g/cm²
- Adjustability: 0.1 g/cm²
- Max. field size: 30 x 30 cm
- Beam size in air: 5 – 10 mm \( \sigma \)
- SAD: > 2.5 m
- Dose compliance: +/- 3% (2 \( \sigma \))
- Irradiation time: < 1.5 min to deliver 2 Gy to 1 liter at any depth.

**A major problem with spot scanning:**
The target can move during treatment leading to dose errors!

**Remedies:**
- Rescanning (spot, layer, volume)
  \[ \Delta D/D \propto \frac{1}{\sqrt{n}}, \text{ where } n = \text{number of scans} \]
- Beam Gating
- Real time tracking with markers

**Orthogonal IC array measurements performed at different water depths using a computer controlled water column and compared with calculations.**

**Pedroni, PSI, Switzerland**

**PTCOG 46 Educational Workshop**

**Ionization Chamber Array**

**Water column with 26 small ionization chambers of 0.1 cm\(^3\)**

**Martin Bues**

**Beam Mirror**

**CCD Camera**

**Scintillating Plate**

**Scintillating Plate, Mirror and CCD Camera used for pencil beam scanning QA.**

**Spot Pattern Test**

**Uniform Field Scanning Test**

**WER**

**6.65 CM**

**WE**

**7.82 CM**

**W= 6.65 cm**

**W= 7.82 cm**

**1. Proton Accelerators**

**2. Isocentric Gantries**

**3. Typical Facility**
Accelerators used in proton therapy facilities

- **Hitachi 250 MeV synchrotron**
  - Total weight: 63 tons
  - 8 m dia.
  - 250 MeV; 90 tons; 3.2 m dia.

- **Varian/ACCEL Superconducting Cyclotron**
  - 250 MeV; 90 tons; 3.2 m dia.

- **IBA 230 MeV Cyclotron**
  - 220 tons
  - 250 MeV; 20 tons; 1.7 m dia.

- **Still River Superconducting Synchrocyclotron**
  - 250 MeV; 20 tons; 1.7 m dia.

- **ProTom International Inc.**
  - **A Scanning-Optimized Synchrotron**
  - Total weight = 15 tons; 4.9 m diameter
  - 330 MeV → Proton tomography
  - 0.1 to 10 sec extraction
  - Variable intensity
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- **M. D. Anderson Gantry**
  - 190 tons
  - Hitachi

- **Siemens Heidelberg**
  - 600 tons
  - Proton
  - Carbon

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  - 600 tons
  - Proton
  - Carbon
Still River
Proton Therapy System
- Accelerator mounted on Gantry
- Entire system contained in one room
- Multiple independent rooms can be installed

Typical Proton Therapy Facility

1. Accelerator
2. Beam transport line
3. Gantry room
4. Gantry room
5. Fixed beam room
6. Patient support area

A Proton + Light Ion Facility built in two phases

PHASE I
Protons only

PHASE II
Add Light ions

Robotic Applications
Proton acceleration is achieved by focusing a high-power laser on a thin target. The short (10^{-16} \text{ sec}) laser pulse width produces a high peak power intensity that causes massive ionization in the target, expelling a large number of relativistic electrons. The sudden loss of electrons gives the target a high positive charge and this transient positive field accelerates protons to high energies.

Laser accelerated proton therapy has a time frame of 5 – 10 years.
Dielectric Wall Proton Accelerator (DWA)

Conventional accelerator cavities have an accelerating field only in the gaps which occupy only a small fraction of their length. In a DWA, the beam pipe is replaced by an insulating wall so that protons can be accelerated uniformly over the entire length of the accelerator yielding a much higher accelerating gradient.

The goal is to have a full scale prototype in ~ 4-5 years, which will be installed at UC Davis CC. Thomotherapy is the private sector partner.

Thank You!