Dielectric Wall Accelerator and Intensity Modulated Proton Therapy

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I am a founder and Chairman of TomoTherapy Inc. (Madison, WI) which is participating in the commercial development of helical tomotherapy.
Acknowledgements

• George Caporaso
• Steve Sampayan
• Yu-Jiuan Chen
• Ryan Flynn
• Evan Sengbusch

• Angelica Pérez-Andújar
• David Westerly
• Thomas Bortfeld
• Tony Lomax
• Gustavo Olivera
Conventional Proton Treatment

- Adenocytic carcinoma of the lacrimal gland
- CTV 56 CGE and GTV 72 CGE
- Minimize dose to temporal lobes

(Bussiere and Adams, 2003)
Conventional Proton Treatment

- Paranasal sinus tumor
- CTV dose 54 CGE and GTV dose 76 CGE
- Minimize the dose to the temporal lobes, brainstem, orbits, optic nerves and optic chiasm

(Bussiere and Adams, 2003)
Conventional Proton Treatment

- Hepatoma
- 42 CGE
- Minimize the dose to the normal liver.

(Bussiere and Adams, 2003)
Conventional Proton Treatment

- Skull base chordoma
- CTV dose 50 CGE and GTV 80 CGE
- Minimize dose to the brainstem.

(Bussiere and Adams, 2003)
Photon IMRT Vs Conventional Protons

Conventional Protons Are Delivered With Only A Few Fields

Greater high dose conformity with IMRT…

| Proton Pinnacle IMRT | Tomo (Isodose Lines: 15, 30, and 60 Gy) |

…but less integral dose with protons.
Conventional Proton Therapy

- Scattered beam systems with fixed distance range shifting systems (e.g. “propeller wobblers” or “ridge filters”) create copious neutrons.
- Unnecessary dose proximal to the tumor because of fixed distance range systems.
Passive Scattering and Proximal Dose

- Passive scattering leads to unnecessary dose to the proximal side of the target volume.
- More sophisticated range shifting and magnetic scanning can eliminate this proximal dose by preventing Bragg peaks (beam spots) from falling outside the target.
Conventional Protons < IMRT < IMPT

From Tony Lomax
Example of IMPT

From Thomas Bortfeld
Typical Proton Treatment Paradigm

Shizuoka Proton Center, Japan

- Large Facility
- Cost ≈ $120M
- Neutrons Flux

3 story gantry vault

40 ft

4 Bending Magnets
Barriers to Entry

• Facility and Equipment
  – Large and expensive

• Spot Scanning and Intensity Modulated Proton Therapy (IMPT) are Desirable
  – Retrofitting is Difficult

• Neutron Production
  – Unwanted dose to patients
  – Massive concrete to protect staff
  – Activation of beam components
Dielectric Wall Accelerator* (DWA)

- Laser
- Proton Source
- Focusing
- High Gradient Insulator
- SiC Optical Switches
- Monitor
- Stack of Blumleins

*Lawrence Livermore National Laboratory, Livermore CA
Dielectric Wall Accelerator (DWA)

Conventional Insulator

High Gradient Insulator

Emitted electrons repeatedly bombard surface

field emitted electrons

Emitted electrons repelled from surface

floating conductors

From George Caporaso, Lawrence Livermore
Breakdown Voltage Increases as the Pulsewidth Decreases

From George Caporaso, Lawrence Livermore
Matching Phase Velocities

Proton Source

High Gradient Insulator (100 MV/m)

- The phase of the first Blumlein firing has to match the proton source
- The phase velocity of Blumlein firings have to match the proton velocity throughout the accelerator
Operation of a Basic Blumlein

Closing switch

Output voltage

Matched load

Beam

Output Voltage

Time

$V_o$
With the absorption of light the optical switch rapidly transitions from electrically open to closed.
Blumlien Switching Used to Accelerate Protons
Focusing to Change the Beam Spot Size
DWA Can Eliminate Deuteron Contamination
Beam Capture into the DWA
Proton injector

- F.A.S.T. pulsewidth of 3 ns = crossing time of injected protons
  => 300 keV initial energy
- Acceleration provided by induction modules
  - 5 induction cells simultaneously triggered
  - 300 kV @ 30+ ns
  - SF₆ insulation
  - Powered by cable Blumleins
- F.A.S.T. specifications
  - 7 Kapton Blumleins
  - Cree switches
  - 532 nm light
Compact Proton Injector @ 300 keV
Interior Detail

- anode
- cathode
- gate electrode
- accelerator grid grids
- e-repeller
- source
- Blumlein stack
- HGI
Hydrated Ti Electrode Proton Source
Benchtop Test Assembly

One section of DWA

2 meters = 200MeV
Test Assembly

- Vacuum pump
- 5-Induction cells
- Thomson spectrometer
- Spectrometer & camera
Thomson Ion Spectrometer

Principle of the Thomson spectrometer

- Vertical electric field gives rise to vertical deflection inversely proportional to energy
- Vertical magnetic field gives rise to horizontal deflection varying inversely with the square root of the particle energy
Documenting Acceleration

H⁺, H₂⁺ or D⁺, C⁺⁺

Accel. phase

Decel. phase

Energy →

Injector Voltage 8352ion85.scp

Time (ns)

70 75 80 85 90
Comparison of Proton Accelerators

The DWA is the only accelerator technology for which the energy, intensity and beam spot size can be varied pulse to pulse.

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<thead>
<tr>
<th></th>
<th>Energy</th>
<th>Intensity</th>
<th>Spot Size</th>
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<tbody>
<tr>
<td>Cyclotron</td>
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<td>X</td>
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<tr>
<td>Synchrotron</td>
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<tr>
<td>DWA</td>
<td>✓✓</td>
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Distal Edge Tracking (DET)

- Use energy modulation to have the Bragg peak follow the distal edge of the tumor.
- Provide intensity modulation to control the dose homogeneity in the target and avoid normal tissues.
- Needs sufficient treatment directions to enable it, e.g., arc therapy.
- Oelfke and Bortfeld * have shown that DET provides the lowest normal tissue dose for a given target dose.
- Fastest delivery.

X-Ray IMRT Vs DET

Voxel at the Tumor Boundary

Tumor

X-Ray

Sensitive Structure

Proton DET
Spot Scanning and DET

For DET both intensity modulation and multiple directions or rotation therapy is required to obtain uniform dose distributions.

From Ryan Flynn
Arc Therapy for Protons

360 deg Intensity Modulated Arc Therapy (i.e. Tomotherapy)

135 deg Intensity Modulated Arc Therapy

From Ryan Flynn
Off-Axis Disk Target Volume

From Ryan Flynn
Off-Axis Ring Target Volume

From Ryan Flynn
Head and Neck Structure Sets

Four levels of Dose on PTVs

- 70 Gy
- 63 Gy
- 60 Gy
- 56 Gy

Sensitive Structures

- Parotids
- Spine
- Lungs
- Brainstem
- Mandible
- Brain
- Opt chiasm
- Eyes
- Optical Nerves
- Glottis
- Esophagus
- Inner ears

From Gustavo Olivera, TomoTherapy Inc
Breast Case

12 directions spread through 180 deg.

From Evan Sengbusch, UW-Madison
Craniospinal Case

Tomo Photon

Tomo IMPT

No Dose
Craniospinal Case

DVH: Full line: Photons  Dash line: IMPT
Dose Contrast Resolution

Boost (+) and Avoidance (-) Dose

From Ryan Flynn
Design for a Conventional Vault

We feel it is important to build a CT scanner into our unit.
What Energy is Required for Arc Delivery

From Evan Sengbusch, UW
200 MeV is Sufficient for 90 to 95% of Patients

From Evan Sengbusch, UW
Fluence Increases Rapidly with Proton Energy

Neutrons Go Mainly in the Forward Direction

From Angelica Pérez-Andújar and Paul Deluca, UW
Neutrons

- Conventional proton radiotherapy produces copious quantities of neutrons due to slowing down the protons to produce the desired range.
- Our machine will produce the desired proton energy in the linac – no slowing down required.
- Neutrons are still produced in the patient.
- Minimizing the proton energy needed will reduce neutron production.
- Forward directed neutrons can be attenuated in the machine like tomotherapy does with the beam stop and this also serves as a counterweight.
Timeline

- First Article DWA
- Acceleration of Protons from Source
- Subscale DWA Q1 2009.
- Clinically useful energy Q1 2010
- Pilot release late 2011.
- Regulatory approval and commercial release 2012.
- Continue to work on heavier ions
Conclusions

- Not all proton radiotherapy is the same.
- Need for intensity modulated proton therapy.
- Rotation therapy is best.
- CT-guidance is necessary for proton radiotherapy, especially DET.
- Compact proton linac being developed with Lawrence Livermore National Laboratory.
- Fit within a conventional vault footprint.
- Low neutron dose and lower facility cost.
- Target commercialization in 2012.
Questions