Basic Radiation Physics of Protons

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OVERVIEW

- **Interactions of individual particles with single atoms**
  - photons and electrons
  - protons

- **Interactions of a proton beam in bulk matter**
  - in a water bucket
    - photons (briefly)
    - protons
  - in simple inhomogeneities
  - in complex inhomogeneities (e.g. the patient)
    - distal edge degradation
  - in a moving medium
    - interaction between delivery dynamics and target motion
INTERACTIONS OF PHOTONS AND ELECTRONS
PHOTON INTERACTIONS

• Photoelectric effect

• Compton scattering

dominates in the radiotherapeutic energy range

• Pair production
**PHOTON INTERACTIONS**

- **Compton scattering**

  In the energy range of interest:
  - both the scattered photon and the ejected electron tend to go off in the near-forward direction (within $\sim10^\circ$)
  - the scattered photon and the ejected electron partition the incident photon’s energy arbitrarily

  the atom is ionized, potentially leading to biological damage

  the photon is scattered and may suffer a further interaction – if so, almost certainly a Compton scattering interaction

  dominates in the radiotherapeutic energy range

  what about the electron?

Illustration from M. Goitein “Radiation Oncology: A Physicist’s-Eye View” © Springer, 2007
ELECTRON INTERACTIONS

• **Excitation (Coulomb effect)**

  ![Diagram of electron excitation](image)

  An atomic electron is knocked out of the atom, thereby ionizing it – potentially leading to biological damage of the struck cell.

• **Ionization (Coulomb effect)**

  ![Diagram of electron ionization](image)

  Meanwhile, both electrons will go off and almost certainly induce further ionizations → biological damage to further cells.

• **Coulomb scattering by the atomic nucleus**

  ![Diagram of electron scattering](image)

  The incident electron may be scattered by the positively charged nucleus – the main effect of which is to alter its direction.

• **Bremsstrahlung**

  ![Diagram of bremsstrahlung](image)

Illustrations from M. Goitein “Radiation Oncology: A Physicist’s-Eye View” © Springer, 2007
RELATIVE LIKELIHOODS OF INTERACTIONS
(in the energy ranges of interest)

• **Photons**
  
  Being neutral, photons interact with atoms only weakly – via the interactions of their electrical/magnetic fields with atomic constituents. The mean free path of a photon in the energy range of interest is very approximately 20cm (i.e. a few percent chance of a single interaction per centimeter of travel).

• **Electrons**
  
  Being charged, electrons interact with the charged constituents of atoms (orbiting electrons and the nucleus) very readily. A few-MeV electron will, together with secondary electrons that it sets loose, ionize some tens to hundreds of thousands of atoms per centimeter of travel.
HOW DOES RADIATION DEPOSIT ENERGY IN TISSUES?

X-ray

atom within a cell

electron

nucleus
HOW DOES RADIATION DEPOSIT ENERGY IN TISSUES?

X-ray

atom within a cell

nucleus

electron

scattered X-ray
HOW DOES RADIATION DEPOSIT ENERGY IN TISSUES?

X-ray

atom within a cell

scattered X-ray

nucleus

X-ray energy is lost and is deposited locally
DEPOSITED ENERGY = DOSE

- The interactions of radiations with atoms result in the transfer of energy from the particles to the medium

- The energy loss per unit mass is called the dose
  
  \[ \frac{1 \text{ Joule}}{\text{kilogram}} = 1 \text{ gray (Gy)} \]

- The energy loss has two consequences:
  
  - it heats up the medium (via vibration and rotation of molecules)
  - it damages the molecules of the medium (primarily via ionization of atoms)

> 96% of energy appears as heat
HOW DOES RADIATION DAMAGE BIOLOGICAL TISSUES?

1) ionize atoms
2) vibrate/rotate
→ heat
HOW DOES RADIATION DAMAGE BIOLOGICAL TISSUES?

**Physics**

1) ionize atoms
2) vibrate/rotate
→ heat

**Chemistry**

\[ \text{H}_2\text{O} \rightarrow \text{H}_2\text{O}^+ + e^- \]

\[ \text{H}_2\text{O}^+ + e^- \rightarrow \text{H}^+ + \text{OH}^- \]

i.e. formation of highly reactive free radicals within cells
HOW DOES RADIATION DAMAGE BIOLOGICAL TISSUES?

**Physics**
- 1) ionize atoms
- 2) vibrate/rotate → heat

**Chemistry**
- i.e. formation of highly reactive free radicals within cells
- $H_2O^+ + e^- \rightarrow H^+ + OH^-$
- $H_2O^+ + e^- \rightarrow H^+ + OH^-$

**Biology**
- DNA damage repaired
- DNA causes single-or double-strand DNA break
- DNA damage
- cell “death”
- tumour / whole organ damage

Dose is merely a surrogate for what we care about – namely, biological effect.
• Ionization (Coulomb effect)

An atomic electron is knocked out of the atom, thereby ionizing it – potentially leading to biological damage of the cell. Meanwhile, the incident proton will go off and induce further ionizations.

The difference from electrons is that, due to the proton’s much greater mass, it loses very little energy, and is very little deflected.

• Coulomb interactions with the atomic nucleus

The incident proton may be scattered by the positively charged nucleus – thereby altering its direction, but with little energy loss.

• Nuclear interactions with the atomic nucleus

The incident proton may interact (via the strong interaction force) with the nucleus and break it up into fragments. Fractional energy:

<table>
<thead>
<tr>
<th>Particle</th>
<th>Energy Fraction</th>
</tr>
</thead>
<tbody>
<tr>
<td>Protons</td>
<td>60%</td>
</tr>
<tr>
<td>Neutrons</td>
<td>20%</td>
</tr>
<tr>
<td>α Particles</td>
<td>3%</td>
</tr>
<tr>
<td>Deuterons</td>
<td>1.6%</td>
</tr>
<tr>
<td>Others</td>
<td>2%</td>
</tr>
</tbody>
</table>

Illustrations from M. Goitein “Radiation Oncology: A Physicist’s-Eye View” © Springer, 2007
BULK MATTER
BULK MATTER:
Dose Distribution in a Water Bucket
Q: What is the most likely thing to happen when a photon is directed towards a bucket of water?

A: Absolutely nothing!
Q: What is the most likely thing to happen when a photon is directed towards a bucket of water?

A: Absolutely nothing!

reminder:
Meanwhile, the incident electron will go off and almost certainly induce further ionizations.
PHOTONS in bulk matter
near-exponential fall-off (typical of uncorrelated catastrophic events)

"skin sparing" (due to build-up of electronic equilibrium)

~8 mm tail due to secondary X-rays

~8 mm penumbra due to transport of secondary electrons

~60 Gy

70 Gy

~80 Gy

Dose (%) vs Depth (cm)

Dose (%) vs Distance (cm)
PROTONS in bulk matter

cross-field (lateral) profile

depth dose
PROTONS in bulk matter

- Proton deflected by scattering off atomic nuclei
- Electron set loose by scattering of proton off atomic electron
PROTONS in bulk matter

- Proton deflected by scattering off atomic nuclei
- Electron set loose by scattering of proton off atomic electron
- Numerous additional electrons set loose - creating a local dose “splash”

100’s of thousands of “splashes”, giving rise to the Bragg peak (named after Sir William Henry Bragg – not his son, Sir William Lawrence Bragg)
CONSTRUCTION OF THE BRAGG PEAK
principal effect: Coulomb interactions of protons with atomic electrons

Illustration from M. Goitein “Radiation Oncology: A Physicist’s-Eye View” © Springer, 2007
CONSTRUCTION OF THE BRAGG PEAK: 3 components

1. Coulomb interactions of protons with atomic electrons

2. Near-Gaussian blurring of the Bragg peak due to energy loss fluctuations and beam energy spread

3. Nuclear interactions with atomic nuclei – including build-up of interaction products
1 Ionizations produced primarily by electrons set loose by Coulomb interactions of protons with orbiting electrons of the atoms in the medium
   Bethe-Bloch formula

2 Near-Gaussian blurring of the Bragg peak
   statistical fluctuations in the interactions
   \( \sigma \) typically \( \sim 1\% \) of the proton range
   energy distribution of protons
   \( \sigma \) also typically \( \sim 1\% \) of the proton range
   \( \sigma \) typically \( \sim 1.5\% \) overall

3 Nuclear interactions of the protons with the nuclei of atoms in the medium
   typically \( \sim 1\%/cm \)

Importance of the Ingredients of the Proton Depth-Dose Distribution
Fluence and dose as a function of depth for proton beams of a given range and different energy spreads, illustrating $r_0 = d_{80}$.

N.B. range is stable at the 50% level while dose is stable at the 80% level.

The 80% dose level is important!

d_{80-20} typically about 2.5% times range

i.e. ~ 4 mm at 15 cm depth

Figure courtesy of Bernie Gottschalk
RANGE SHIFTING:
by altering residual range or beam energy

When residual penetration changed by adding material upstream

When primary beam energy changed

$\text{range} \propto E^{1.8}$
$\Delta R \approx 1.1\% \cdot R$

The penetration of protons in the patient can be very accurately adjusted using either one of these methods.
AREAL DENSITY (brief interlude)

- It is common to express the thickness of a piece of material, not in terms of its physical thickness, $l$, but in terms of what is called its areal density, given by $\rho \cdot l$ where $\rho$ is the density of the material.

- If $l$ is expressed in cm, and $\rho$ in units of gm.cm$^{-3}$, then areal density has the units of gm.cm$^{-2}$.
SPREAD-OUT BRAGG PEAK (SOBP)

~10 MeV photons

Target volume
LATERAL DOSE DISTRIBUTION

Dominated by multiple Coulomb scattering
PROTON SCATTERING IN A THIN SCATTERER

\[ \sqrt{\theta_0^2} \approx \frac{z \cdot 21.2 \, MeV \sqrt{l}}{pc\beta \sqrt{X_0}} \]

where \( X_0 \) is the radiation length of the scattering medium and varies approximately as:

\[ \frac{A}{Z(Z+1)} \]

Illustration from M. Goitein “Radiation Oncology: A Physicist’s-Eye View” © Springer, 2007
PROTON SCATTERING IN A THICK SCATTERER

\[ \sigma \approx 2\% \text{ of range} \]
\[ \text{fwhm} = 2.35 \sigma \]
\[ \approx 4.7\% \text{ of range} \]
i.e. \( \approx 7\text{mm} \) at 15 cm depth

Minimum penumbra (80-20%) due to scattering within the patient:

- **Uniform beam**
  - **Penumbra** \( \geq 1.68 \sigma \)
  - i.e. \( \geq 5\text{ mm} \) at 15 cm depth

- **Intensity modulated beam**
  - (using edge enhancement)
  - **Penumbra** \( \geq 1.12 \sigma \)
  - i.e. \( \geq 3.3\text{ mm} \) at 15 cm depth

Figure courtesy of B. Gottschalk
PROTON SCATTERING IN A THICK SCATTERER:
very narrow pencil beams $\rightarrow$ depressed Bragg peak

Hong et al. Phys Med Biol 41: 1305, 1996

but, this does not mean that a broad beam made up of many pencil beams has a degraded Bragg peak:

“low” dose is augmented by neighbors
BROAD BEAM OF PROTONS

\[
d_{80-20} \approx 1.68 \sigma \approx 3.3\% \text{ of range}
\]

i.e. \(\sim 5\) mm at 15 cm depth (\(\sim 6\) mm in practice)

Image courtesy of Radhe Mohan
SUMMARY

1 plateau protons – excitation/ionization; & nuclear interactions
2 excitation/ionization (Bragg peaks); & nuclear interactions
3 range straggling and energy spread
4 multiple Coulomb scattering off nuclei
5 wide angle Coulomb scattering off nuclei
6 protons and neutrons from nuclear interactions
7 neutrons from nuclear interactions
INHOMOGENEITIES

- proton beam
  - infinite slab
- proton beam
  - semi-infinite slab
- proton beam
  - sliver

patient:
INFINITE SLAB

Andy Koehler’s “proof”

Lamb chop in H₂O tank

Michael Goitein, PSI teaching course January, 2010
Semi-Infinite Slab

Goitein and Sisterton
IN THE PATIENT

Urie et al. Phys Med Biol 1986; 31: 1
THE PATIENT: RANGE DEGRADATION

Irradiation of a water-filled human skull

Urie et al. Phys Med Biol 1986; 31: 1
distal edge degradation
and in the Lung...

Images courtesy of Uwe Titt, MDACC

protons

average density = 0.2 gm/cm³

density = 1.0 gm/cm³

3x3x3 mm³
WHAT CAN ONE DO ABOUT DISTAL DOSE DEGRADATION?

- Be aware of it!
- When possible, avoid beam directions which pass through regions of complex inhomogeneity especially when pointed at a critical OAR just beyond the target volume
- Allow an adequate safety margin distal to the target volume
- Perform uncertainty analysis to assess uncertainty in dose and hence the size of safety margin needed
- Improve calculational method to further reduce uncertainty use fine image and calculational grids (≤ 1mm) Monte carlo
- Possibly “fill in” dose with another beam
BEAM DELIVERY
SCATTERED BEAM GENERATION

Illustration from M. Goitein “Radiation Oncology: A Physicist’s-Eye View” © Springer, 2007
Scanned beams are needed for IMPT

Pretty much the only way to implement IMRT with protons (IMPT) is to deliver the protons by scanning a pencil beam of protons throughout the target volume.

Scanned beams are the wave of the future.
SHARP PEMUMBRAS ARE NEEDED CLINICALLY!

Inadequate attention in current commercial systems is being given to achieving good edge sharpness (i.e. to getting a sharp penumbra)

- **Scattering systems**
  
  double scattering degrades the penumbra because it increases the effective source size
  
  the aperture needs to be close to patient but not too close because of edge scattering

- **Scanning systems**
  
  a narrow pencil beam (fwhm < 10mm $\rightarrow \sigma < 4$ mm)
  
  is essential for close work at medium and small depths
  
  scattering in the patient dominates edge sharpness – but only for deep-seated targets
THE FLY IN THE IMPT OINTMENT: motion

Cell has received ~5 times intended dose

Cell has received ~0 times intended dose
Intestinal Crypt Regeneration in Mice in PSI’s Scanned Proton Beam (contd.)

Scatter in results interpreted as due to ±14% (SD) dose mottle as a consequence of about 1 to 2 mm motion of the intestine during scan.
and the simplest solution presently is:

1. reduce motion as much as possible – e.g. by
   patient immobilization
   respiration gating / breath hold
   abdominal compression, etc.

2. apply the treatment multiple times (repaint) thereby averaging out the dose mottle
   the more repaintings, the lesser the dose mottle ($\frac{\Delta D}{D} \propto \frac{1}{\sqrt{n}}$)
   about 10 repaintings (reducing dose mottle by about a factor of 3) seems a reasonable goal

The timing of the repainting is critical. The period of respiration, $t_{\rho}$, (~4s) sets the scale.

- ideally, the entire dose delivery would occur in much less than $t_{\rho}$, – but this is impractical.
- alternatively, the each repainting should take place on the order of, or more than, $t_{\rho}$ – i.e. roughly every few seconds and each repainting should be given either randomly in time, or at progressive phases of the respiratory cycle.
DOSE HOMOGENEITY vs. # REPAINTINGS

Motion: periodic with amplitude of 13.5 mm and period of 3.3 seconds

Scanned beam: fwhm = 6.5 mm

Scan vs. motion not “de-synchronized” in this simulation


And thesis: http://elib.tu-darmstadt.de/diss/000407/
The commercial realization of beam scanning (and, hence, IMPT) is immature and the currently implemented solutions appear to be inadequate for general clinical use.
RECENT TEXTS

  File named “pbs.pdf” can be extracted from BGdocs.zip
  See, also, PowerPoint lectures in BGtalks.zip

• ICRU report 78 “Prescribing, Recording and Reporting Proton Beam Therapy” Oxford U. Press. Journal of the ICRU 7(2); 2007

• T.F. Delaney and H.M. Kooy (eds) “Proton and Charged Particle Radiotherapy” Lippincott Williams and Wilkins, 2008

• M. Goitein “Radiation Oncology: A Physicist’s-Eye View” Springer, 2008
the end