Cancer Radiotherapy with particle beams

Dr. Cornelia Hoehr
Cancer Radiotherapy with particle beams

- Cancer treatment
- Ionizing radiation
- Different Radiotherapy options
- Radiotherapy @ TRIUMF
- State-of the art Radiotherapy

Dr. Cornelia Hoehr
TRIUMF - nuclear physics lab.

Expertise in:

- Accelerator technology
- Accelerator operation
- Detectors
- Targets for isotope production
- Interaction of particles

Applicable to nuclear medicine
Cancer

Cancer occurrence
- Lung cancer, 15%
- Breast cancer, 26%
- Prostate cancer, 25%
- Colorectal cancer, 10%
- Skin melanoma, 5%
- Oral and pharyngeal cancer, 3%
- Leukemia, 3%
- Pancreatic cancer, 3%
- Other, 20%

Cancer mortality
- Lung cancer, 31%
- Breast cancer, 15%
- Colorectal cancer, 10%
- Pancreatic cancer, 8%
- Liver & intrahepatic bile duct, 4%
- Leukemia, 4%
- Esophageal cancer, 4%
- Bladder cancer, 3%
- Non-Hodgkin lymphoma, 3%
- Kidney cancer, 3%
- Other, 24%

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If you were to develop cancer:

- **Surgery** – to remove the tumor
- **Chemotherapy** – to kill the tumor with drugs (fast-dividing cells)
- **Radiotherapy** – to kill the tumor with radiation
  - * External beam therapy – photons, neutrons, protons
  - * Internal therapy – brachytherapy (radioactive isotopes)

**Success:** Tumor control vs. complications
Destroy/remove tumor without damaging healthy or normal tissue nearby
Some numbers:
- 0.4%: develop cancer per year in US
- 25%: probability to die of cancer in industrialized countries
- 45%: of cancer patients can be cured
- 50%: of those 45% are treated with radiation therapy, alone or in combination
- 65%: diagnosed with localized tumor
- 70%: of patients receive radiotherapy
- 80%: of radiotherapy is with photon beams

Ionizing Radiation

- Charged particles interact strongly and ionize directly.
- Neutral particles interact less, ionize indirectly and penetrate farther.
DNA break

• DNA (Deoxyribonucleic acid): genetic instructions for development and functioning
• Cell needs information from DNA for survival

• Single helix break easy to repair
• Double helix break more difficult to repair
• Cell can not survive

• Radiotherapy: as many double helix breaks in cancer cells as possible with as few double breaks as possible in healthy cells
LET – Linear Energy Transfer

Linear Energy Transfer (LET): Energy transferred (ionization, secondary electrons) per unit distance.

High LET – ions, neutrons, direct damage

Low LET – photons, electrons, protons, indirect damage via free radical formation
Relative Biological Effectiveness

Definition of Relative Biological Effectiveness:
RBE = \frac{D_x}{D_i}

Data for CHO-K1 cell line irradiated by photons (blue curve) and carbon ions (red curve).
Choice of Treatment

Choice of Treatment

Choice of Treatment

Choice of Treatment

- Radiosensitivity of cancer cell
- Repair ability of healthy tissue
- Size of tumor
- Fractions

Electron Volt

Energy unit

1 eV = 1.602*10^{-19} J

Amount of kinetic energy gained by an electron accelerated through 1 V electrical potential (E=qU)
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Amount of kinetic energy gained by an electron accelerated through 1 V electrical potential (E=qU)
External: Photon treatment

- Cost-efficient, easy set-up, very common
- Many techniques to minimize dose to healthy tissue (multiple beams, wedges, intensity modulation…)
- Dose does not stop after tumor
- Low LET

![Graph showing dose depth profile for X-rays (20 MeV) and X-rays (4 MeV).]
From the Greek word *brachys*, meaning "short-distance", most isotopes used are gamma emitters

**Advantages**
- Very localized
- Can have shorter treatment times
- Moves with tumor
- Can be permanent or temporary

**Disadvantage**
- High dose to medical personnel
- Dose not homogeneous (in some cases 40% of dose can be deposited in 15% of tumor)
- Tumor-size dependent
External: Electron-beam treatment

- Mostly used for tumors close to skin
- Low LET
External/internal: Neutron treatment

- Boron neutron-capture therapy (BNCT)

- BNCT (thermal <0.1 eV)
- Only experimental (treatment for hours)
- Tracer development still in beginning

Fig. 1. Nuclear reaction utilized in BNCT. A $^{10}$B nucleus absorbs a thermal neutron and promptly emits a back to back $^7$Li ion and a $^4$He (alpha) particle. The combined range of 12–13 μm is similar to mammalian cell dimensions.
External: Ion-beam therapy

Advantage
• Less dose to surrounding tissue (Bragg peak)
• Very homogeneous tumor dose
• High control over position of Bragg peak (low to high LET)

Disadvantage
• Need higher-energy accelerator
• 250MeV for 30cm in human tissue
• Expensive
Advantage
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X Rays vs. Protons

Highest dose - red
Lowest dose - yellow

X rays
Protons
External: Pion-beam treatment

- Pion - subatomic particle, meson
- In nuclei, glue to hold protons and neutrons
- Some are charged
- Have Bragg peak, little damage to surrounding tissue, high LET in Bragg peak
- Lots of damage at Bragg peak (‘pion star’)
• Study from 1980 – 1994 (over 300 patients), one of only three in the world
• Brain tumors (glioblastoma) and prostate cancer

• Result of study: no advantage over conventional photon therapy

Proton Therapy at TRIUMF

BEAMLINE 2A
450-500 MEV
(ISAC)

BEAMLINE 2C
65-120 MEV

BEAMLINE 1B
0-5 nA

BEAMLINE 1A, 180-500 MeV 200 μA

PROTON IRRADIATION TEST AREAS

NEUTRON IRRADIATION

NEUTRON TEST AREA
Ocular Melanoma

Frequency: 5 - 6 cases/year per million population

Treatment protocols: Radioactive plaque therapy
Charged-particle radiotherapy
Enucleation

Uveal Melanoma before proton beam treatment
Uveal Melanoma after proton beam treatment
Beamline
Beamline

Profile Monitor

Collimator/Scatterer

Range Shifter

Modulator Wheel

Diag. Ion Chamber
Modulators: 5 mm to 27 mm in 1 mm increments (depth control)
Brass collimators (lateral control)
Markus data, comparison of raw Bragg peak, 15 mm and 23 mm cal wheels SOBP, 2.0 cm coll.

Mono-energetic proton – Bragg peak at the end of its range

Modulate energy – Spread Out Bragg Peak (SOBP)

Maximum dose to tumor – minimize dose to nearby sensitive structures
Patient Set-up

Treatment Chair

6 motorized motions

X, Y, Z, K, θ, Φ
Patient Set-up

First set-up  Second set-up  Treatment plan

Treatment: four days in a row, around 90 seconds each
Patient Set-up

First set-up  Second set-up  Treatment plan

Statistics: 147 patients, average 10/year, ages 14-80, median 57
Tumor control >95%, survival rate (>5 years) 80%

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Collaboration

Eye Care Centre

Dr. Ewart Blackmore
Heavy Ions

Biologically effective doses for photons, protons and carbon ions

HIT website
Fig. 4. Display of the penetration of fragmentation tails of 195 MeV, 281 MeV and 392 MeV $^{12}$C beams. This contrasts with no tail for proton beams of energies of 103 MeV, 147 MeV and 204 MeV.
• Active raster scan via magnets
• Depth between 20 mm and 30 cm
• Protons and heavy ions
• Three beam lines
• Two ion sources

HIT website
Heavy-Ion Gantry

First heavy-ion gantry

• 25 m long
• 13 m diameter
• Total weight 670 tons
• Movable 600 tons

HIT website
Proton and heavy ion therapy centers

Thank you