4D Monte Carlo for IMRT and Proton beams

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Radiotherapy is a therapeutic modality used in the treatment of cancer, with ionising radiation such as protons and photons.

AIMS OF RADIOTHERAPY IS TO IRRADIATE THE TUMOUR (PTV) WHILE SPARING THE ORGANS AT RISK (OAR).
Monte Carlo methods refers to any procedures which involve sampling from random numbers:

Random Numbers $\rightarrow$ Probability Density Function

At each step in the simulation, the size of which is chosen randomly from probability distributions defined by laws of physics (cross-section data), events occur which result in the change in the direction of the particle, deposition of energy, production of secondary particles, etc..
Time Development of MC Computation

1.1 \times 10^4 \text{ particles}

6.6 \times 10^4 \text{ particles}

1.7 \times 10^5 \text{ particles}

1.2 \times 10^6 \text{ particles}
Time Development of MC Computation

- 3.2 \times 10^6 \text{ particles}
- 8.2 \times 10^6 \text{ particles}
- 3.8 \times 10^7 \text{ particles}
- 6.8 \times 10^7 \text{ particles}
What is moving in radiation therapy?

- Dynamic beam delivery systems
- Dynamic patient anatomy
- Dynamic beam and dynamic patient

Why are we using Monte Carlo?

- Empirical or semi-empirical calculations are only approximations
- There is a potential for an improvement in clinical outcome if accuracy in dose is improved
Radiation Treatment Involving Moving Targets

- **Dynamic beam delivery systems**
  - Monte Carlo (MC) implementation  

- **Dynamic patient anatomy**
  - Obtaining 4D information  
  - 4D treatment planning  
  - 4D dose calculation (MC)  

- **Dynamic beam and dynamic patient**
  - 4D² dose calculation (MC)
Dynamic Systems in Radiation Therapy
- Beam Delivery -

Types of variations:
IMRT: moving leaves
Tomotherapy: rotating beam
Protons: rotating absorber
IMPT: changing magnetic field

1 Xia and Verhey Medical Dosimetry, 26: 169-177, 2001
2 Mackie et al. Seminars in Radiation Oncology, 9: 108-117, 1999
3 Koehler et al. Nuclear Instruments and Methods, 131: 437-440, 1975
4 Lomax Physics in Medicine and Biology, 44: 185-205, 1999
Protons
Photons
Proton Therapy

Water Phantom

Snout retraction area

Jaws (X and Y) (& Range Verifier)

Magnet 2

Range Modulator Wheels

IC1

First Scatterers

Magnet 1

Second Scatterers

IC2 and IC3

Snout
4D Monte Carlo: Scanning Magnet
4D Monte Carlo: Range Modulator Wheel
Photon Therapy

Primary electron beam

Target ($SLABS$)

Primary collimator ($CONS3R$)

Flattening filter ($FLATFILT$)

Monitor ion chamber ($CHAMBER$)

Back Scatter Plate ($PYRAMIDS$)

$Y$ MLCs ($MLCQ$)

$Y$ JAWS ($MLCQ$)

$X$ JAWS ($JAWS$)
Proton beam therapy is highly conformal but ...
... but 4D IMRT improves dose coverage of tumor volume
Dynamic Systems in Radiation Therapy
- Breathing Patient -

- posterior view
- posterior cut
Characterize Tumor Motion

Strategies:

treatment planning for lung cancer with respect to breathing\(^1\)

4D Proton dose calculations

4 field oblique box plan

99% prescription dose (red), 95% (green), 90% (blue), ..., 10% (brown)
INTRA-THORACIC TUMOUR MOTION

• on average 6.1mm laterally and 2.7mm AP; greatest (up to 2cm; average 1cm) for lesions adjacent to the heart or aorta or near the diaphragm

• tumor-bearing lung regions show lower mobility; high variability; safety margins of 3.4, 4.5, and 7.2mm for upper, middle and lower lung region

• cranio-caudal motion of, on average, 7.4mm

• maximum movement of about 1.2cm

3 Gierga et al. International Journal of Radiation Oncology, Biology, Physics, 58: 1584-1595, 2004
5 Hanley et al. International Journal of Radiation Oncology, Biology, Physics, 45: 603-611, 1999
Time-resolved anatomy using 4D CT

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temporal description of anatomy

⇒ all lung/liver patients at MGH get 4D CT
Movement based on 4D CT

“voxel xyz”

Unique Voxel Descriptor (index) independent of a coordinate system

Volume Displacement Map obtained by deformable image registration

Respiratory Motion

Software: CISG Kings College London
[T.Hartkens, BVM 2002, Springer-Verlag, March 2002]
Volume Displacement Information

Software: CISG (Computational Imaging Science Group) Kings College London\textsuperscript{1,2}

Arrows: moving areas (voxel centers)

\textsuperscript{1} Hartkens et al. Springer-Verlag, March 2002, ISBN: 3-540-43225-6, 2002
Keall et al. Physics in Medicine and Biology, 49: 3639-3648, 2004
Four-dimensional Monte Carlo dose calculations\textsuperscript{1}

**Goal**: time-dependent geometry during calculations:

- avoids cumbersome adding techniques for runs
- allows the study of 4D effects in any arbitrary time scale, e.g. to study dose rate effects
- allows to study continuously moving objects (e.g. MLC motion in sliding window technique)
- temporal sequence of events is taken into account
- temporal step size in between two stages does not affect the speed of the calculation

\textsuperscript{1} Paganetti et al. International Journal of Radiation Oncology, Biology, Physics, 60: 942-950, 2004
4D Dose Deposition

Beamlet 1

Beamlet 2

\begin{array}{cccc}
A & B & C & D \\
E & F & G & H \\
I & J & K & L \\
M & N & O & P \\
\end{array}

T = t_1

T = t_2
4D Dose Deposition

Dose deposition defined via voxel identifiers, not position in space!
Interplay between intra-fraction organ motion and MLC motion (IMRT) or beam spot motion (IMPT)

- magnitude of the effect depends on the relative speed of tumor motion and MLC/spot motion
- IMRT in dynamic mode: significance depends on the leaf speed
- effects of leaf motion and leaf window size on gated beam delivery (beam starts always at the same breathing phase)\(^1\)
- impact of displacements of the internal structures (proton dose delivery\(^2\))

\(^1\) Hugo et al. Medical Physics, 29: 2517-2525, 2002.
Dynamic systems in (Monte Carlo) dose calculations\textsuperscript{1,2}

Beam Delivery

- Loop over 3D calculations
- On-the-fly geometry change

\(\rightarrow 4D\)

Patient

- Loop over 3D calculations
- On-the-fly geometry change

\(\rightarrow 4D\)

- Loop over many(!) 3D calculations
- On-the-fly geometry change using arbitrary temporal resolution

\(\rightarrow 4D^2\)

\textsuperscript{1} Paganetti et al. International Journal of Radiation Oncology, Biology, Physics, 60: 942-950, 2004

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