Influence of target motion on (scanned) particle beam irradiation

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Learning Objectives

• Ability to define the different types of target motion

• Understand the implications the radiological path-length has on the definition of the planning target volume

• Name detriments and advantages of scanned beam delivery and scattered beam delivery for the irradiation of a moving organ

• Explain the principles of gating, rescanning, and beam tracking
Outline

• Target motion
  – Types, quantification
  – Internal Target Volume concept
  – Implications of particle range

• Mitigation of respiratory motion
  – Broad beam
  – Beam scanning
  – Adaptive radiotherapy

• Summary
Organ motion [Langen & Jones, 2001]

• Position related organ motion
  – Patient positioning prior daily delivery
  – Patient sitting during beam delivery but laying during CT scan
    • Magnitude depends on location
      (<2mm in H&N, most severe in abdomen [Urie 1995])
    – Prone vs. supine positioning
• Inter-fractional organ motion
  – Time scale: several hours … days
  – Cause: digestive system, weight changes, tumor shrinkage
  – Sites: gynecological tract, prostate, bladder, rectum, …
• Intra-fractional organ motion
  – Time scale: seconds … minutes
  – Cause: heart beat, respiration
  – Sites: lung, liver, kidneys, pancreas, …
Target motion

Patient positioning
scale: minutes - days

Gut filling
scale: minutes
Target motion

heart beat
scale: seconds

respiration
scale: seconds
4D quantification of organ motion - lung

- 3D time-resolved motion detection and quantification
  - 4D CT, 4D MR
  - non-rigid registration techniques for quantification

[Brock et al., IJROBP 64(4) 2006]
Motion monitoring examples - lung

Internal - fluoroscopy

External surrogate - Varian RPM

[Jiang, Sharp, Berbeco (MGH)]
Respiratory motion

Motion influence on range

[Bert, Rietzel, MGH]
Respiratory motion - beam range

tumor

beam
Respiratory motion - beam range

⇒ mitigation of range/longitudinal changes required
How do we handle organ motion

- ICRU reports:
  - Report 50: Electron-Beam Therapy
    • GrossTumorVolume, ClinicalTargetVolume, PlanningTargetVolume
  - Report 62: Photon-Beam Therapy
    • InternalTargetVolume = CTV + InternalMargin
    • IM compensates for respiration, bowel movement, heart beat, …
    • ITV concept is not widely used and not considered compulsory in report 71
  - Report 78: Proton-Beam Therapy
    • Incorporates proton specific aspects such as particle range
    • Based on individual and/or population based motion data
Planning target volume concept

GTV
CTV
PTV
ITV - lung

CTV per motion phase

Internal Target Volume

[data courtesy E. Rietzel, MGH]
Margin design for ion beams

- ITV/PTV need to be port specific
- Not only geometrical extent of target motion has to be considered but also range
  - 4DCT data required to determine patient-specific ITV
  - ITV shaping in water-equivalent space, i.e. margin description in water-equivalence rather than geometrical
Margin design – ion beams

geometrical

motion states

CTV

Twice in radiological pathlength

beam

[Rietzel & Bert, Med Phys, accepted]
Margin design – ion beams

[Rietzel & Bert, Med Phys, accepted]
Margin design – ion beams

geometrical

water-equivalent

motion states

Spatial ITV

ITV

beam
Margin design – ion beams

Spatial ITV

Motion states

beam
Lung cancer patient – average range fluctuation

[according to Moori et al., IJROBP 70(1) 2008]
ITV design including range - lung

exhale

inhale

CTV

ITV

CTV

ITV
Outline

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  – Adaptive radiotherapy

• Summary
Broad beam delivery

customly fabricated for each field

[www.advanced-cancer-therapy.org]
**ITV via compensator design**

Range fluctuation in beam’s eye view

[Moori et al., IJROBP, 70(1) 2008]
Motion mitigation - Gating

Target motion

gating window / residual motion

40 mm

7 mm
2 mm
Motion mitigation - Gating

Target motion

Beam request

Beam pulse

Gating window / residual motion
40 mm
7 mm
Motion mitigation - Gating

- Target motion
- Beam request
- Beam pulse
- Beam extraction

Beam pulse

Gating window / residual motion

40 mm

7 mm
ITV via compensator design

[Moori et al., IJROBP, 70(1) 2008]
ITV / range change - gating

[Moori et al., IJROBP, 70(1) 2008]
Broad beam delivery - moving target

- Little influence of target motion
- ICRU ITV/PTV concept applicable if ion beam’s range is considered
- Can be combined with gating to decrease target motion amplitude
  - Smaller margins
  - Longer treatment time
- Used as therapy option for several years
- Excellent clinical results – see clinical talks of educational sessions
Beam scanning

lateral: dipol magnets

longitudinal: beam energy

$^{12}\text{C}$

Photons 18 MV

range in water [cm]

rel. dose

$^{12}\text{C}$ 250 MeV/u

$^{12}\text{C}$ 300 MeV/u

$^{12}\text{C}$ 300 MeV/u
Rasterscanning – GaFChromatic film
Rasterscanning – target motion - Interplay
**Interplay - parameters**

**Influence of scan speed**

\[
T_{tot} = 94\text{s} \quad T_{tot} = 132\text{s} \quad T_{tot} = 217\text{s}
\]

**Influence of motion direction**
Interplay - simulation data

4D treatment planning study:

→ IM / ITV / PTV not sufficient

[Bert et al, Phys Med Biol, 2008]
4D treatment delivery

- Rescanning
  - N irradiations with 1/N dose
  - large margins

- Gating
  - only part of motion period
  - residual interplay requires mitigation

- Tracking
  - compensation of target motion
  - lateral: scanner
  - longitudinal: wedge, active

www.brainlab.de
Principles of rescanning

- Interplay / misdosage pattern very sensitive to motion / irradiation parameter changes
- Multiple irradiations per fraction
  - Averaging of interplay patterns
  - Homogeneous target coverage if no. rescans high enough
Rescanning
Rescanning – experimental data
Rescanning - # rescans

Experiment
(preliminary)

Simulation

\[
\text{rel. homogeneity}
\]
\[
\text{number of rescans}
\]

- amplitude: 2 cm p2p
- amplitude: 3 cm p2p

\[
\text{Mittl. Vol. bei 95% Dosis [cGy]}
\]
\[
\text{Anzahl an Mehrfachbestrahlungen}
\]

[Graphs showing experimental and simulation data related to rescanning]
Proton therapy at PSI – Organ motion management

Dose homogeneity and re-scanning factor

Analysis of Cos⁴ motion with 1cm peak-to-peak amplitude

- Cylindrical target volume
- Re-scanned different times to same total dose
- Scan times calculated for realistic beam intensities and dead times between spots
- Analysis carried out for different periods of motion

Not always improving homogeneity with number of re-scans!

Motion management for active scanning: Re-scanning, gating and
Rescanning - Summary

- Multiple irradiations per fraction
- Minimal solution does not require motion monitoring
- Technical effort low

- IM/ITV/PTV covers full motion extent
  $\Rightarrow$ large normal tissue dose
- Works on statistical average; outliers, especially for regular motion parameters, possible
Gating

- Target motion
- Beam request
- Beam pulse
- Beam extraction

Beam pulse

40 mm

7 mm
gating window / residual motion

Target motion

Beam request

Beam pulse

Beam extraction

09/29/2009

PTCOG 48 - Heidelberg
Gating with a scanned beam

- Residual motion within gating window leads to residual interplay

- Mitigation of residual interplay:
  - Combination with rescanning
  - Increased overlap of adjacent beams
details: Bert et al., *IJROBP* 73(4), 2009
Beam overlap

Gating: residual motion in gating window
Mitigation: increase pencil beam overlap

2 mm grid
5 mm FWHM spots

grid spacing
residual motion
spot size

2 mm grid
15 mm FWHM spots
Increased range and lateral overlap

lateral

scan grid: 1 mm

scan grid: 4 mm

[Bert et al., IJROBP 73(4) 2009]
Experimental data

[Bert et al., IJROBP 73(4) 2009]
Simulation data

[Bert et al., IJROBP 73(4) 2009]
Gating for beam scanning - summary

- Pause beam based on motion surrogate
- Beam scanning \(\Rightarrow\) residual interplay in gating window
- Mitigation of interplay:
  - (Phase-controlled) rescanning
  - increased pencil beam overlap
- Implementation: Fair technical effort
- IM/ITV/PTV smaller than for rescanning due to reduced motion amplitude within gating window
Beam Tracking

lateral compensation: scanner magnets
longitudinal compensation: energy modulation system

4D TP
TCS

target motion
motion monitoring
Beam Tracking
Range modulation

absorber wedges

beam

Eindringtiefe
Range modulation

absorber wedges

beam

![Graph showing range modulation with absorber wedges and beam.](image-url)
Range modulation

absorber wedges

beam
Range modulation

absorber wedges

air

beam

bone

tissue

Eindringtiefe

0 2 4 6 8 10 12 14 16 18 20
Range modulation

absorber wedges

air

beam

bone

tissue

Eindringtiefe

0 2 4 6 8 10 12 14 16 18 20
Range modulation

- absorber wedges
- air
- bone
- tissue
Range modulation

absorber wedges
beam
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Eindringtiefe

0 2 4 6 8 10 12 14 16 18 20

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[Bert et al., Med. Phys. 34(12) 2007]
Beam Tracking - summary

- Adaptation of pencil beam position (lateral and longitudinal/range)
- Requires dedicated 4D treatment planning
- Precise motion monitoring
- Implementation: large technical and medical physics effort
- ITV=CTV
Possible future of mitigation techniques

- All techniques are planned to be used
  - Individually or in combination
  - Clear emphasis on gating

- Class solutions seem likely
  - Irregular motion or small amplitude: rescanning
  - Large amplitude: gating or beam tracking
    - Beam tracking: pro: smaller margins, faster treatment
    - Con: regular motion only

- More clinical research required
Adaptive treatment planning

- Adaptive radiation therapy is a closed-loop radiation treatment process where the treatment plan can be modified using a systematic feedback of measurements. [Yan et al., Phys. Med. Biol. 42(1), 1997]

- Several styles of adaptive radiotherapy

- Common goals
  - Dose escalation / reduction of normal tissue burden
  - Patient-specific field margins
  - Reduction of systematic and random setup uncertainties

- Use of image guided radiation therapy methods to determine patient geometry
Online Treatment Planning

- Most advances adaptive radiotherapy concept:
  - Online Treatment Planning
    - Reduction of systematic and random setup errors
- Requirements
  - TP-suitable on-board 3D imaging
  - Fast segmentation and plan optimization
  - Quick treatment delivery
- Not suitable for classical broad beam beam shaping due to compensator and collimator fabrication

[Letourneau et al., IJROBP 67(4) 2007]
Summary

- Target motion affects geometry and range
- Dedicated margin concepts required
- Broad beam delivery
  - Insensitive to target motion
  - Margin concepts can be applied
  - Several years of clinical experience
  - Advances concepts (tracking, adaptive Rx, …) most likely not feasible due to patient-specific hardware
- Scanned beam delivery
  - Affected by interplay
  - Rescanning, gating, and beam tracking technically implemented for motion mitigation
  - Clinical implementation can be expected in the next years
  - Adaptive / online protocols feasible (fully active beam delivery)
Acknowledgements

Motion Team at GSI

Third-party support
  Siemens AG, Particle Therapy
  German Research Foundation, KFO 214