Significance of time-dependent geometries for Monte Carlo simulations in radiation therapy

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Modeling time dependent geometrical setups

Key to 4D Monte Carlo:

Geometry changes during the simulation via C++ class architecture based on GEANT4

Geometry update command in DetectorMessenger

DetectorConstruction:

```cpp
rot_RMW = new G4RotationMatrix();
rot_RMW->rotateZ(Wheel_angle*degree);
RMW_Phys -> SetRotation(rot_RMW);
G4RunManager* theRunManager = G4RunManager::GetRunManager();
theRunManager->DefineWorldVolume(WorldPhys);
theRunManager->GeometryHasBeenModified();
theRunManager->ResetNavigator();
```
Modification of the GEANT4 source code

Instead of re-doing the optimization for the entire geometry, only re-optimize parts of geometry
Types of variations:
- IMRT: moving leaves
- Tomotherapy: rotating beam
- Protons: rotating wheel
- IMPT: changing magnetic field
Proton Therapy
Proton Beam Therapy

Goal 1: Modulation in depth (energy variation)

Goal 2: Lateral modulation (broad beam)
4D Monte Carlo: Scanning Magnet
4D Monte Carlo: Range Modulator Wheel

<table>
<thead>
<tr>
<th>Depth [mm]</th>
<th>Dose [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>50</td>
<td>20</td>
</tr>
<tr>
<td>100</td>
<td>40</td>
</tr>
<tr>
<td>150</td>
<td>60</td>
</tr>
<tr>
<td>200</td>
<td>80</td>
</tr>
</tbody>
</table>
4D Proton Delivery

Tumor in the Paranasal Sinus

>95% prescription dose (dark red), >80% (red), >70% (orange), >60% (yellow), >50% (green), >30% (blue), ≤30% (dark blue)
4D IMRT
4D IMRT delivery

CORVUS plan

Monte Carlo
Step-and-Shoot

Monte Carlo
Sliding-Window
Dynamic Systems in Radiation Therapy
- Breathing Patient -

• posterior view
• posterior cut

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Time-resolved anatomy using 4D CT

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Four-dimensional Monte Carlo simulation based on 4D CT

Inhale

Intermediate

Exhale

Graph showing dose-response curves for GTV and CTV.
Four-dimensional Monte Carlo simulation
- Based on 4D CT information -

Volume Displacement Information

Software: CISG Kings College London
[T.Hartkens, BVM 2002, Springer-Verlag, March 2002]
4D Dose Deposition

Beamlet 1

Beamlet 2

A B C D E
F G H I J
K L M N O
P

T = t₁

T = t₂
4D Dose Deposition

Dose deposition defined via voxel identifiers, not position in space!
Dose calculation during non-rigid motion

\[ T = t_1 \]

\[ T = t_2 \]
Four-dimensional Monte Carlo simulation based on 4D CT

Solid lines: Patient in inhale
Dashed lines: Considering the entire breathing phase
Moving patient in IMPT (double dynamic)
Single-dynamic (patient movement; static beam delivery)
Double-dynamic (patient movement; dynamic beam delivery)

Effect can be reduced by ‘repainting’
4D Monte Carlo of IMPT

- Beamlets and patient are moved continuously (rigid)

- Assumptions:
  - Irradiation time per slice is 0.4 seconds (on average)
  - Changing the cyclotron beam energy with a degrader takes a few seconds
  - Breathing cycle is 4 seconds

- Choose a specific scanning pattern
- Choose a specific number of protons per second
- Update the beam delivery setup and the patient setup every 0.1 virtual seconds
4D Monte Carlo of IMPT

DVH for left anterior field

- Static
- Patient moves ±0.5 cm
- Patient moves ±1.5 cm
- Patient moves ±0.5 cm; repainting
- Patient moves ±1.5 cm; repainting
Conclusion

Four-dimensional Monte Carlo (based on GEANT4) is a technique capable of simulating geometry variations (beam delivery or patient) during dose calculation. The technique allows the investigation of interplay effects for any given dose rate.
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PUBLICATIONS

Paganetti “Four-dimensional Monte Carlo …”
Phys Med Biol 2004: 49, N75-N81
Paganetti et al “Monte Carlo simulations with time-dependent …”
Int J Radiat Oncol Biol Phys 2004: 60, 942-950
Paganetti,Jiang,Trofimov “4D Monte Carlo simulation of proton beam …”
Phys Med Biol 2005: 50, 983-990