Protontherapy treatment planning with passive scattering

Alejandro Mazal,
Institut Curie, Paris, France

in cooperation with
R.Ferrand, L.DeMarzi, S.Zefkili, M.Robilliard, S.Delacroix,
Ch.Dauphinot, F.Lacroix, G.Gaboriaud, J-C.Rosenwald,

Special thanks to :
M.Goitein, B.Schaffner, M.Engelsman, Nieck Schreuder

Acknowledgments: Varian, Canceropole, Dosisoft ,Inca
PTCOG Japan
What can we see when we are used to plan with photons … and move to protons?

Let's see one beam first:

Software: Varian's Eclipse // Beam Data: IBA // Calcs: I.Curie

→ «Easy!!»
(Sub)liminal message

BUT PLANNING

IS NOT ONLY

ISODOSES and HISTOGRAMS

→ The planning process
The planning process

(from Michael Goitein’s thoughts…)

First simple case: Ophthalmologic tumors

Patient Evaluation

Ex choices: Enucleation, plaques, protons

Imaging & fiducials

Clips

The planning process
3. Delineate the target volumes and normal tissues

4. Establish the planning aims for the treatment

Gragoudas, Suit, Munzenrider, Goitein et al, MGH & HCL team
5. Beam design

Choice of the gaze angle to avoid critical organs

Margin: 2.5 mm

In the beam’s eye view:

Design a collimator

Calculate dose distribution

Penumbra

Ray tracing

Fall off

(ex 30%/mm)
6 & 7 : Evaluation & final prescription

Isodoses in eye fundus as usual tool in ophtalmology

DVH
Back to the real world:

Eye care and ocular protection setup in simulation
9 & 10 : Daily set-up control

Infrared camera :

« Image Guided Radiation Therapy  IGRT»
<table>
<thead>
<tr>
<th>step</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Evaluate the patient using all relevant diagnostic tools, and decide whether to employ radiation therapy.</td>
</tr>
<tr>
<td>2</td>
<td>Obtain and inter-register imaging studies with the patient lying in the position to be used for therapy.</td>
</tr>
<tr>
<td>3</td>
<td>Delineate on the planning CT the target volumes (GTV, CTV and PTV) and normal tissues.</td>
</tr>
<tr>
<td>4</td>
<td>Establish the planning aims for the treatment.</td>
</tr>
<tr>
<td>5</td>
<td>Design one or more sets of beams, together with their weights, each of which fulfills, to the extent possible, the requirements of the prescription.</td>
</tr>
<tr>
<td>6</td>
<td>Evaluate these plan(s) and either select one of them for use or revise the planning aims and return to step 5.</td>
</tr>
<tr>
<td>7</td>
<td>Finalize the prescription.</td>
</tr>
<tr>
<td>8</td>
<td>Simulate the selected plan to ensure it is deliverable.</td>
</tr>
<tr>
<td>9</td>
<td>Deliver the treatment, and verify that the delivery is correct.</td>
</tr>
<tr>
<td>10</td>
<td>Re-evaluate the patient during the course of treatment and, if necessary, return to step 5, or even 2, to re-plan the remainder of the treatment.</td>
</tr>
<tr>
<td>11</td>
<td>Document and archive the final treatment plan.</td>
</tr>
<tr>
<td>12</td>
<td>Review the treatment plan at the time of patient follow-up or possible recurrence.</td>
</tr>
</tbody>
</table>

The planning process in general

(M.Goitein)

Steps are common for any approach in RT...
### The planning process in general – and the differences between protons and x-rays

<table>
<thead>
<tr>
<th>step</th>
<th>Description</th>
<th>protons vs. photons</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Evaluate the patient using all relevant diagnostic tools, and decide whether to employ radiation therapy.</td>
<td>~same</td>
</tr>
<tr>
<td>2</td>
<td>Obtain and inter-register imaging studies with the patient lying in the position to be used for therapy.</td>
<td>Same</td>
</tr>
<tr>
<td>3</td>
<td>Delineate on the planning CT the target volumes (GTV, CTV and PTV) and normal tissues.</td>
<td>~same</td>
</tr>
<tr>
<td>4</td>
<td>Establish the planning aims for the treatment.</td>
<td>Same</td>
</tr>
<tr>
<td>5</td>
<td>Design one or more sets of beams, together with their weights, each of which fulfills, to the extent possible, the requirements of the prescription.</td>
<td>different</td>
</tr>
<tr>
<td>6</td>
<td>Evaluate these plan(s) and either select one of them for use OR revise the planning aims and return to step 5.</td>
<td>same</td>
</tr>
<tr>
<td>7</td>
<td>Finalize the prescription.</td>
<td>same</td>
</tr>
<tr>
<td>8</td>
<td>Simulate the selected plan to ensure it is deliverable.</td>
<td>same</td>
</tr>
<tr>
<td>9</td>
<td>Deliver the treatment, and verify that the delivery is correct.</td>
<td>~same, but QA harder.</td>
</tr>
<tr>
<td>10</td>
<td>Re-evaluate the patient during the course of treatment and, if necessary, return to step 5, or even 2, to re-plan the remainder of the treatment.</td>
<td>same</td>
</tr>
<tr>
<td>11</td>
<td>Document and archive the final treatment plan.</td>
<td>Same</td>
</tr>
<tr>
<td>12</td>
<td>Review the treatment plan at the time of patient follow-up or possible recurrence.</td>
<td>Same</td>
</tr>
</tbody>
</table>

- **protons vs. photons**
  - Large targets
  - Complex geometry
  - Meaning of PTV may be different
  - Immobilization and verification
  - Beam delivery techniques
  - Dose algorithm
  - Compensation for inhomogeneities
  - Compensating set up & movements
  - Design of single beams and plans
  - Uncertainty analysis

- **Not here:** Passive

- **Here:** Passive

---

(M.Goitein)
Beam models

3 families:

1) Ray tracing

2) Pencil beam

3) Monte Carlo
1) Ray tracing:

Penumbra = f (beam line, distance to aperture, depth)

Depth Dose: ray from source (library or analytical)
Ray tracing:

- straight protons (no scattering), coming from a punctual source
- Precalculate a compensator
  (see later)
- latéral pénumbra model => takes into account scattering due to:
  - initial beam line
  - compensator + air-gap
  - patient (radiological depth)

⇒ Limitations in inhomogeneous areas and for high gradients in compensators

Old, simple, fast and relatively efficient
2) Pencil Beam

Eclipse pencil beam algorithm - Concept

- **Principle**
  - Convolution of 3D undisturbed proton fluence in air with a ‘beamlet’ in water.

- **In practice**
  - Superposition of inhomogeneity - corrected beamlets and multiplication with fluence at calculation position.
Pencil Beam:

- Scattering = broadening of each pencil beam (as a function of depth & upstream parameters)

- Well-suited for changes in range (inhomogeneities, compensator, …)

The most used at present, good compromise speed-precision
Tracking of each particle: protons, électrons, neutrons...

Take into account effects on the beamline and in the patient body

Tracking of all types of interactions: electronic, nuclear (important to take RBE into account → ion beams)

*Powerful, benchmarking,*

*not widely used yet in clinics,*

*will expand in the future*

Comparison PB-MC (Paganetti)
TPS beam models : Monte Carlo

H. Paganetti
# The planning process in general – and the differences between protons and x-rays

*(mod from M.Goitein)*

<table>
<thead>
<tr>
<th>step</th>
<th>Description</th>
<th><em>protons vs. photons</em></th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Evaluate the patient using all relevant diagnostic tools, and decide whether to employ radiation therapy.</td>
<td>~same</td>
</tr>
<tr>
<td>2</td>
<td>Obtain and inter-register imaging studies with the patient lying in the position to be used for therapy.</td>
<td>Same</td>
</tr>
<tr>
<td>3</td>
<td>Delineate on the planning CT the target volumes (GTV, CTV and PTV) and normal tissues.</td>
<td>~same</td>
</tr>
<tr>
<td>4</td>
<td>Establish the planning aims for the treatment.</td>
<td>Same</td>
</tr>
<tr>
<td>5</td>
<td>Design one or more sets of beams, together with their weights, each of which fulfills, to the extent possible, the requirements of the prescription.</td>
<td>different</td>
</tr>
<tr>
<td>6</td>
<td>Evaluate these plan(s) and either select one of them for use OR revise the planning aims and return to step 5.</td>
<td>same</td>
</tr>
<tr>
<td>7</td>
<td>Finalize the prescription.</td>
<td>Same</td>
</tr>
<tr>
<td>8</td>
<td>Simulate the selected plan to ensure it is deliverable.</td>
<td>Same</td>
</tr>
<tr>
<td>9</td>
<td>Deliver the treatment, and verify that the delivery is correct.</td>
<td>~same, but QA harder.</td>
</tr>
<tr>
<td>10</td>
<td>Re-evaluate the patient during the course of treatment and, if necessary, return to step 5, or even 2, to re-plan the remainder of the treatment.</td>
<td>Same</td>
</tr>
<tr>
<td>11</td>
<td>Document and archive the final treatment plan.</td>
<td>Same</td>
</tr>
<tr>
<td>12</td>
<td>Review the treatment plan at the time of patient follow-up or possible recurrence.</td>
<td>Same</td>
</tr>
</tbody>
</table>

- Large targets
- Complex geometry
- Immobilization and verification
- Beam delivery techniques
- Dose algorithm
- Compensation for inhomogeneities
- Compensating set up & movements
- Design of single beams and plans
- Uncertainty analysis
- 3D dose measurement capability needed
Compensating inhomogeneities

Target Area

Proton Beam

Patient Contour

Inhomogeneity (Air Pocket)

AM/ Modified from Niek Schreuder
Compensator

Aperture

Air

Target

Range

Modulation
Plot of calculated \((H_{sc}, S_{rel})\) pairs and linear fits

Importance of CT calibration & QA = RANGE

Schneider, Schaffner, Lomax, …
Compensating heterogeneous bodies...

("pristine" = not modulated beams to show the effect)
Compensator with a «hole»

Isodoses adapted to the radiological depths to target
But what if drilling a too tiny hole?

Getting a too small beam

Multiple scattering

Isodoses not adapted
Smearing the compensator

Need to work out the compensator in order to get the desired deep peak effect

(but this is only one of the reasons...)
TPS : compensator design

1. Geometrical ray-tracing

2. Smearing (2-> 6 mm)

3. Dealing with borders (no target)

4. Tool simulation (⇔ 2\textsuperscript{nd} smearing)

5. Milling file generation
   → workshop → Quality Control
Target Contour

Compensator

Air

Range

Modulation

Over modulation

Too much Hardware!

= « robust »?
Compensating setup uncertainties & movements

(2nd reason to « smear a compensator »)

In depth:
Spread out Bragg Peak 1D scanning

Ex:
600 rpm
4 scans/rotation

= 40 scans/sec in depth
(« fast repainting »)
Now, with a compensator...
Imagine you have the right peak for the right target...

200 MeV proton Beam

Final Collimator

Water Level

Critical organ
2nd reason to smear:
Imagine you have the right peak for the right target...

But everything moves (or misalignments)!!
2nd reason to smear: setup errors and target movements

Imagine you have the right peak for the right target...
2nd reason to smear: misalignments & movements
If priority is given to treat the target

Critical organ

Water Level
2nd reason to smear: misalignments & movements
If priority is given to treat the target

Final Collimator

Water Level

200 MeV proton Beam

Critical organ
2nd reason to smear: misalignments & movements
If priority is given to treat the target

Final Collimator

Water Level

200 MeV proton Beam

Critical organ
2nd reason to smear: misalignments & movements
If priority is given to treat the target
2nd reason to smear: misalignments & movements
If priority is given to treat the target
Of course smearing has its own limits:

a) Smearing too much, we can touch a lateral critical organ

b) And we create « rays » going behind the target volume

→ Need to recalculate a final dose distribution, emulating the real compensator, and evaluate the dose distributions, histograms and risks related to uncertainties
Going to the « real » world, also for « precise » techniques like stereotactic approaches …

Court. G.Chen, Boston
(Real moving targets : ex lung)

Margins, gating, tracking ... as in the photon world
What is specific to particles?
Lung: change of radiological iso-depths & isodoses

Normal density tissue, moving in a low density environment: care behind !!

Eike Rietzel, Martin Hengelsman et al, MGH 2004
Treating moving organs with passive protons

A few logical steps:

- Evaluate the degree of movement (e.g., free ITV from 4D-CT)
- Evaluate the incidence on the plan & related uncertainties
- Define the strategy to treat: e.g., gating when necessary
- Evaluate residual movement: ITV
- Choice of (single or multiple) beam angles
- Each covering the full target with "homogeneous" profiles
- Realistic margins, range + compensator smearing
- Collimator, modulator,…
- **Recalculate** & evaluate doses
- Patient setup, monitoring & data acquisition (anatomy, fluoroscopy, delivered doses,…)
- Adaptive radiation therapy? From off-line to online… as with photons
Still another problem: in presence of «complex» heterogeneities, protons does not follow a «ray tracing approach», but have multiple scattering
Need to change the range!

Urie et al
TPS Passive beam properties

- Classical SOBP proton depth dose (they stop!, but… where?)
- Good lateral penumbra
  (~10-15%/mm) shaped by aperture
- « 2,5 D » tumor shaping
  (lateral and distal shaping, not proximal)
- Lateral penumbra sensitive to air gap
  (between aperture and patient)

*With this approach :*
Get profit of proton characteristics
Minimize risks and drawbacks
Not yet the full « potential » of protons
Limits: Degradation of ballistic properties

High entrance dose (& small buildup)

Small field size < peak/entrance

Degradation
After complex Inhomogeneities (and problem of CT artifacts)

⇒ Check that TPS takes all this into account
As for every complex (and simple) radiation therapy technique, we need a comprehensive QA program.

Let see one ex on the TPS validation & QA … (+ O.Jaeckel’s specific presentation)
Effect of density changes (e.g., in the target volume)

Effect of density changes (e.g., in the target volume)

Need to survey the anatomical changes in the path after the planning CT and till the end of the treatment.
TPS validation & QA : « Perturbations » by heterogeneities :
Depth dose curves & profil
TPS models : QA and validation (example)

- antropomorphic phantom (skull + fat + air)

⇒ gamma function 3%-3mm as in (some) IMRT with photons?

(R.Ferrand, L.DeMarzi et al)
Uff, quality is « good »…

😊

We can finally start to play !
Planning Conformal RT for Pituitary adenoma : eg 7 non coplanar beams

G.Gaboriaud, Pontvert et al, I.Curie (since 90s)
7 beams conformal 5 beams IMXT

Optic nerve

Brain stem
Demo/exercise: replacing beam per beam...

(not for real clinical practice)

Software: Varian’s Eclipse // Beam Data: IBA // Calcs: I.Curie
Planning basics

Abutting fields

- Lateral penumbra
  + Lateral penumbra

Patch fields

- Distal penumbra
  + Lateral/distal penumbra
General planning tricks and some useful rules

- Entrance dose (++) =>
  - multiply the ports, combine with photons

- Patch fields risky (hot & cold spots) =>
  - limit the dose/patch (eg < 8 CGE)
  - design several patch fields

- Uncertainties on distal edge position (mask, inhomogeneities) + RBE =>
  don’t stop beams with high dose in front of OAR (if possible…)

- avoid « risky » ports (through nose, tongue, …)
Conclusions (I)

- Planning with (passive) protons is easy:
  - no dose behind the target
  - homogeneous dose to target
  - no max dose at entrance
  - easy to conform lateraly (as photons)
  - simple, not optimized but robust

- But be aware of the limitations and take care with:
  - Uncertainties in range
  - Deformations if complex heterogeneities
  - High entrance dose mainly for superficial tumors
  - Small beams or complex shapes
  - Sensitivity to anatomical changes
  - Sensitivity to movements (more than photons, less than scanning)
  - Need hardware ++ for each beam
Conclusions (II)

- Importance of QA and users‘ experience
  for the Treatment Planning System,
  for each plan,
  for the full process

- Synergy & shared experience with photons, electrons, IMXT, IGRT

- Comparative results in general:
  Passive protons >> conventional photons
  Passive protons ~ > IMXT
  Intensity Mod PT > IMXT

- NEED GANTRIES to have all orientations as always in RT

- Constant Evolution
  MonteCarlo, IMPT, biological modelling...
Now I invite you to next movie:

Intensity Modulated  IMPT-IMZT

But before:
It is time for 2 questions:

1) **How could we get profit of a Tomotherapy unit to calculate a compensator for protontherapy in presence of artifacts from high density heterogeneities?**

2) **If we set up a prostate patient daily using ultrasound (or cone beam CT) what should we do with the compensator of a lateral proton beam passing through the femoral head?**