

pCT meeting, April 25 2013

Clinical interests and expectations of proton imaging



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Plan

- I. Introduction on :
 - Proton imaging
 - Proton therapy
- II. Clinical interests of p+ imaging :
 - In diagnostic
 - In therapy
- III. Conclusions

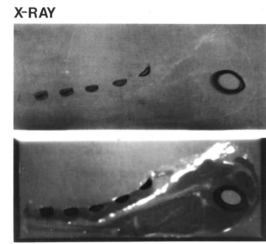
Introduction

- 1963 : Allan Cormack pointed out the possibility of using heavy charged particle for a CT

Initially → diagnostic aims !

- 1968 : 1° p+ radiography by Koehler *et al.* (lamb chop)
- 1972 : 1° CT reconstruction α-CT (with α particles)
- 1976 : 1° pCT prototype

Progress in X-Rays techniques ↗ +++ ⇔ Studies using p+ for imaging ↘



Koehler *et al.* (Harvard)

Nevertheless → Expansion of proton radiation therapy centers
→ Applications for proton therapy = very interesting
→ Improve treatment accuracy

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Historical background of p+ imaging

In 1963 ...

It is important to say that, at this time, ...

But due to the fast progress in X-Rays techniques

Nevertheless, today, because of ...

Because it would improve ttt accuracy

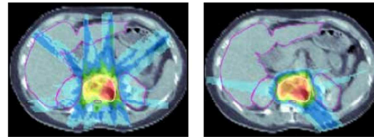
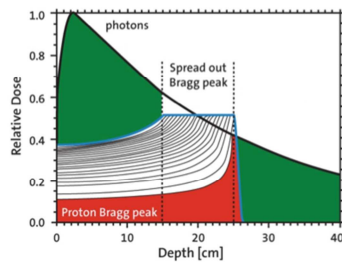
Proton therapy

Radiotherapy with p^+ → high precision treatment of target volume

Clinical interest of p^+ =

- Deposit most of energy at the end of range = Bragg Peak ($\neq h\nu$)
- No Dose beyond Bragg Peak

↳ High conformality



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Effectively

The major interest of using p^+ is that It deposit the most of his energy at the end of his range → it is the so called Bragg Peak

Accordingly, there is No Dose after Bragg Peak, and it allows to sparing tissues beyond BP

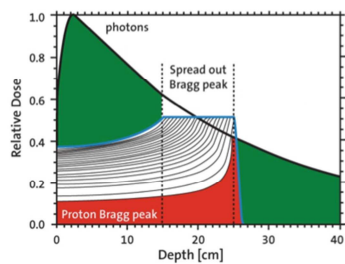
With the poor lateral penumbra, **it is also possible** to spare tissues lateral to the beam

These characteristics of p^+ lead to a High Conformality ttt

Proton therapy

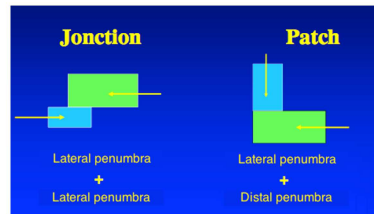
Radiotherapy with p+ → high precision treatment of target volume

More precise a therapy ttt is → More important is the QC



Need to know precisely :

- P+ stopping power in tissues
- P+ path in matter
- P+ range
- Lateral and distal penumbras



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But the key issue is « the more precise a ttt is, the more important is the QC »

And we need to know precisely

Clinical interests of proton imaging

- ◆ In Diagnostic

- ◆ In Therapy :

- ① S/p map determination in tissues for treatment planification
- ② Proton path verification
- ① Checking target volume position relative to the beam (Beam eye view)

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Now, we well focus on the clinical interests of p+ imaging

Firsly in diagnostic

And secondly in therapy



Diagnostic

Proton Diagnostic Images

p^+ /matter interactions \neq $h\nu$ /matter interactions \rightarrow p^+ imaging give a \neq kind of information (loss of E)

Advantages of protons / $h\nu$:

- High-density resolution
 - \rightarrow High contrast on noise ratio between 2 nearby density region
- Very low dose to the patient
 - $\rightarrow p^+ =$ charged particle \Leftrightarrow high detection efficiency

Principal drawback / $h\nu$:

- Poor spatial resolution
 - $\rightarrow p^+$ undergo numerous small angle deflections with nuclei = Multiple Coulomb Scattering (MCS)



N. Depaux and J. Seco
MC Simulation
25/02/2011

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Protons/matter and photons/matter interactions **are quite different**

And thus proton imaging **give us** a different kind of information : a loss of E in matter of protons

The advantages of p^+ **relative to** photons are :

His high density resolution

As we can see on this proton radiography, there is a high contrast on noise ratio between 2 nearby density region

The second advantage is the very low dose to the patient, **because of the high detection efficiency of** a charged particle

The principal drawbacks **relative to** photons is the poor spatial resolution **due to** numerous small angle deflections with nuclei (or multiple Coulomb Scattering)



And now, we will see the clinical interests and expectations for therapy

① S/ρ map determination for treatment planification

Use of a X-CT map for ttt planification :

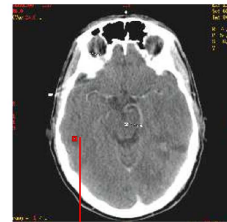
- Target volume and OAR delineation
- Choose of beam strategy arrangements
- Protons ranges calculation in tissues
- Dose distribution calculation

Nowadays → use of X-CT only

- In each voxel → N_{CT}
- Calibration step allows to conversion $N_{CT} \rightarrow S/\rho$

⚡ Conversion ≠ exact :

- Physical interactions of $h\nu \neq p^+$
- Z/A and Z dependances \neq for S/ρ than μ_{RX}
- Systematic errors on the p^+ range
 - Need to \nearrow safety margins
 - lose of potentials benefits of pT



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The first interest would be the Stopping power map determination for ttt planification

Today, we use a X-CT map for 1) 2) 3) 4)

But, because we use a X-CT, in each voxel we measure a CT number N_{CT} and we need a calibration step to conversion of N_{CT} toward protons Stopping Powers

The issue is that the conversion isn't exact

the physical interactions of photons are quite different for protons and it leads to systematic errors ...

In conclusion, we need to ... and we lose a ...

① S/ρ map determination for treatment planification

Results :

- Incomplete modelling of proton physical interaction :
 - Multiple Coulomb Scattering
 - Hadronic collisions
 - Range Straggling
 - Inaccuracies of S/ρ ⇔ deviations between measured / calculated range

Interest of a pCT :

- More accurate estimation of S/ρ ⇔ each voxel encode a S/ρ
- No calibration step ⇔ ↓ systematics errors
- Better knowledge of p+ range ⇔ direct measurement with p+ beam
 - Reduction of range uncertainties : 3 – 10 mm → 1 – 3 mm
 - Reduction of safety margins

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Because of this calibration step, there is an incomplete modelling of proton physical interaction with matter :

an incomplete modelling of ...

id ...

id ...

and inaccuracies in S/ρ estimation

therefore, this incomplete modelling leads to significant deviations ...

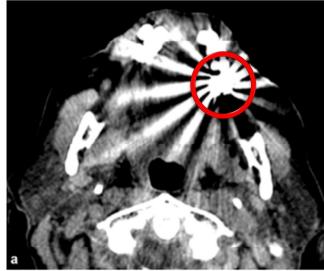
The interest of a pCT is that it could give a more accurate estimation of S/ρ

We expect a reduction of range uncertainties from 3 to 10 mm to 3 to 1 mm

and therefore a reduction of safety margins

① S/ ρ map determination for treatment planification

Improvements on image quality :



- Higher contrast in soft tissues
 - ➔ High precision in soft tissue delineation
- High Z material artefacts avoided
 - ➔ No lost information around the high Z material
 - ➔ Good estimation of S/ ρ in these regions

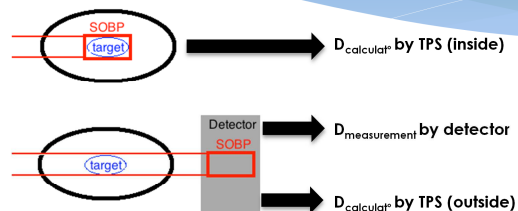
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An other benefit for ttt planification is the improvement of image quality

The Higher constrast in soft tissue **offers** a high precision in soft tissue delineation

And the high Z material artefacts are avoided, and therefore there is no lost information around this type of materials

② Proton range verification



Comparison measured range / calculated range **outside** of the patient

→ Indirect check of D p+ stopped **in** the patient

→ ↓ p+ range uncertainties

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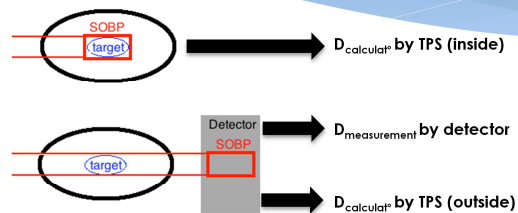
The second potential benefit of proton imaging is the proton range verification

If we check that the measured range and calculated range outside of the patient are **accordingly**

It would provide an indirect verification of dose deposited by stopped p+ in the patient

It leads to a decrease of p+ range uncertainties

② Proton range verification



Range Verification allows :

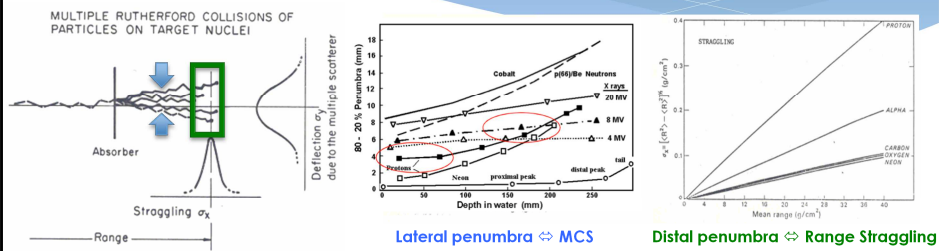
- Check TPS calculation → X-CT Calibration : $\mu_{RX} (N_{UH}) \Leftrightarrow S/\rho$
- Safety margin for each treatment field → better knowledge of distal penumbra
- Check target volume position before irradiation
→ Increase treatment quality

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In fact, the range verification allows

- a check of TPS calculation, meaning the X-CT calibration**
- a precise measurement of safety margins for each ttt field**
- a check of target volume position before irradiation**

③ New beams arrangements



With p+ \rightarrow Sparring OAR with lateral penumbra
 \rightarrow At intermediate depth \leftrightarrow pen_{lat} = **Not better than hv**

If sparing OAR with distal penumbra
 \rightarrow $pen_{dist} < pen_{lat} \rightarrow$ **Real benefit especially for p+**

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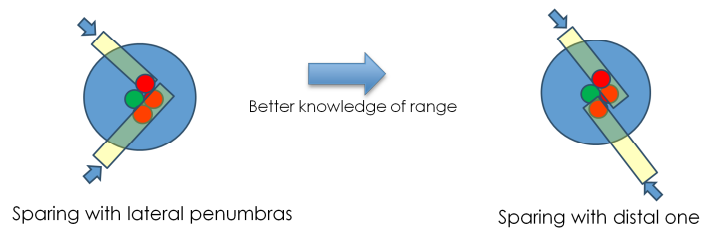
These distal protection would be impossible for ions because of the fragments beyond Bragg Peak

③ New beams arrangements

	OAR sparing		
	Apparent best choice	The safest	Reasons
Protons	Distal range	lateral penumbra	Range uncertainties
Heavy ions	Distal range	lateral penumbra	Range uncertainties and fragments

If precise knowledge of beam range → offer option of distal range sparing of OAR
 → **clinical interests of p+ /_R ions**

Impossible for heavy ions → **fragmentation tail !!!**



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Difficultés faire un Arc avec un bras isocentrique p+

④ Checking target volume position relative to the beam

In proton radiotherapy → target volume position verification = with RX tubes

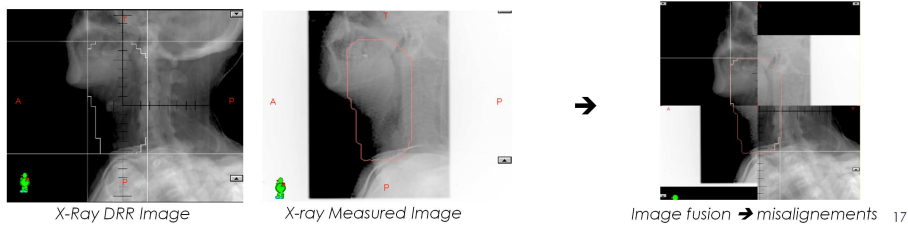
- 2 X-radiography (0° and 90°)
 - Comparaison to DRR
- } **Measurement of alignements defaults**

Drawbacks =

- RX Tube axis \neq proton Beam axis \Leftrightarrow systematic errors (misalignements)
- Irradiated field is not controlled

➤ **Imaging with p+ beam = imaging with treatment field (Beam Eye View)**

→ Provides images with **exactly the same geometrical conditions** encountered during treatment



Difficultés faire un Arc avec un bras isocentrique p+

Même algo pour calcul d ttt que pour calculer im drr

Different kinds of p⁺ imaging device

We can imagine different kinds of proton imaging :

- ◆ Range probe
- ◆ p⁺ Radiography
- ◆ p⁺ Computed Tomography (., CBCT, other ?)

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The more interesting system and the more easiest is the pCT or pCBCT ?

Wath kind of proton computed tomography : classical one, CBCT, or an other system ?

Knowing existing facilities

Proton Computed Tomography

pCT specifications for pT :

	Parameter	Expected value
Source	Energy	> 250 MeV → BP outside of the patient
Accuracy	R_s R_p	< 1 mm → No < 1 % → OK
Time efficiency	Data acquisition Reconstruction	< 5 min < 15 min } → difficult
Dose	D_{max} scan	< 5 cGy → OK

→ The imaging device should be consider the limitations of the pT facilities :

Rotation speed of gantry
Forbidden angles of the gantry
Beam maximum energy
Adapted for active scattering / passive scattering
Detectors intrinsic limitations
etc ...

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We have to consider the « actuelle » limitations of p+ imaging

Adapted for passive scattering as for active scattering

Has to be

Conclusion

Radiotherapy with p+ = increasing ttt technique

- High precision treatment → Need to know precisely p+ path in matter

Negative points =

- No image guidance with ttt beam available
- No direct measurement of S/p patient map $\Leftrightarrow N_{CT} \rightarrow S/p$ calibration step
 - It leads to systematic errors in p+ range estimation

Limiting factor for a p+ imaging device in routine = **lack of R_s** induced by MCS

- **Image guidance in pT → why not ?**
 - Image quality of the DRR could be adapted to RG_{p+}
- **In pCT for ttt planning → impossible**
 - We need a $R_s \approx 1$ mm

Conclusion

However :

- Imaging devices proposed :
 - Expensive detectors (hodoscope + range telescope)
 - List data mode → long reconstruction time
- Gantry pCT → long rotation time

} Imaging devices for pCT proposed
→ not yet realistic in clinical routine



Need to develop systems user friendly in clinical routine



Thank you for your attention