4D ADAPTIVE PROTON THERAPY

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The Patterns Of Practice for Adaptive and Real-Time Particle Therapy (POP-ART PT) questionnaire aims to determine the status of Adaptive Particle Therapy (APT) and (Real-time Respiratory Motion Management RRMM) implementation worldwide.
>90% response rate for Europe and Japan
>50% response rate for the US

Europe:
- all centres are equipped with PBS
- 70% treat moving targets
- 95% use APT
  - → 50% for 4D indications (mainly lung)
- Ad-hoc offline adaptation

Reasons for adaptation per treatment site

Trnkova et al. oral presentation ESTRO 2021
In Europe no center performs online APT (plan libraries or daily adaptation).

A majority of European centres would like to improve APT workflows and would like to implement it for more indications.

The main barrier for the extension of APT is the lack of integrated and efficient workflows.

**Barriers for extending APT**

*Trnkova et al. oral presentation ESTRO 2021*
4D adaptive proton therapy is just translated into the clinical practice with a lot of potential for further development, increasing impact.
4D dose reconstruction & accumulation

Challenges

• interplay effect

Modern PT facilities are equipped with pencil beam scanning (PBS).
Modern PT facilities are equipped with pencil beam scanning (PBS).

PBS-PT treatments are susceptible for interplay effects.
4D dose reconstruction & accumulation

Challenges

• varying motion

den Otter et al. doi: 10.1002/mp.14345
4D dose reconstruction & accumulation

Challenges

• anatomical changes

Fast tumour regression during radiotherapy

Inconsistent patient setup

^Wang et al. doi: 10.1186/s12885-020-07617-3
*Ribeiro et al. doi: 10.1016/j.radonc.2021.01.014
4D dose reconstruction & accumulation

Challenges

- interplay effect
- varying motion
- anatomical changes

→ dosimetric impact*

* Ribeiro et al. doi: 10.1016/j.radonc.2021.01.014
4D dose reconstruction & accumulation

Treatment monitoring

- online motion record via ANZAI belt delivery log files
- weekly repeated 4DCT

floor plan GPTC

Arturs Meijers
4D dose reconstruction & accumulation

Treatment monitoring

Subplan 00%
Subplan 10%
Subplan ...
Subplan 80%
Subplan 90%

Delivery timeline, s
Amplitude, AU
Spot Dose, AU

ANZAI motion record
4D dose reconstruction & accumulation

Treatment monitoring

compute

Subplan 00%

4DCT 00%

Subplan 10%

4DCT 10%

Subplan 80%

4DCT 80%

Subplan 90%

4DCT 90%

warp

…

…

reference CT

Arturs Meijers doi: 10.1002/mp.13371
4D dose reconstruction & accumulation

Treatment monitoring

phase-by-phase ➢ warped to reference CT

➢ Actual delivered fraction dose considering inter-play effects

Arturs Meijers doi: 10.1002/mp.13371
4D dose reconstruction & accumulation

Treatment monitoring

Adaptation
4D dose reconstruction & accumulation

Preliminary clinical results

Fig. 2. DVHs of CTV for reconstructed fraction-wise 4D dose distributions and accumulated course dose. DVHs are corresponding to cases 1 and 2. Fraction doses are shown in color, while accumulated course dose is shown in black. Fraction doses that have been calculated on the same 4DCT also share the same color. Assigned colors are red, yellow, green, light blue and blue, corresponding from an earlier 4DCT to a more recent in this order.
Preliminary clinical results

- Fraction-wise loss of target dose homogeneity due to interplay and organ motion showed no systematic pattern and smeared out with fractionation.

- Contrary to findings in prospective simulation studies, clinical 4D dose monitoring did not observe any relevant loss of target dose homogeneity due to interplay and motion effects.

- Dose degradation caused by anatomical changes showed to be more severe and caused treatment adaptations in five out of ten patients.
4D dose reconstruction & accumulation

Further improvements

• Daily anatomical information via CBCT based synthetic CT

Thummerer et al. oral presentation ESTRO 2021
Manuscript under consideration at PMB
Further improvements

- Consideration of motion variations

Zhang et al. doi: 10.1088/0031-9155/58/24/8621
Boye et al. doi: 10.1118/1.4801914. PMID: 23718581
von Siebenthal et al. doi: 10.1088/0031-9155/52/6/001
4D dose reconstruction & accumulation

Further improvements

• Improve / validate dose warping

DVHs of CTV, PTV, ipsilateral lung, heart and spinal cord of the initial treatment plan (solid line) and the accumulated treatment dose (light coloured band), warped with different DIRs.

Nenoff et al. doi: 10.1016/j.radonc.2020.04.046
4D treatment planning and 4D dose reconstruction & accumulation enable safe and efficient proton therapy treatments for thoracic indications. Monitoring the daily delivered 4D dose could pave the way for real-time adaptive proton therapy.
Towards real-time adaptive proton therapy

Real-time Adaptive Particle Therapy of Cancer (RAPTOR)

https://raptor-consortium.com/

- International consortium comprising clinical, academic and industry partners
- Marie Skłodowska-Curie Innovative Training Network (ITN) for 15 ESRs
Towards real-time adaptive proton therapy

Real-time Adaptive Particle Therapy of Cancer (RAPTOR)

→ https://raptor-consortium.com/

RAPTOR strives to enable a paradigm shift from a currently manual step-wise treatment approach towards a future **automated seamless workflow**, integrating imaging, treatment planning, quality assurance and treatment verification into a **real-time adaptive particle therapy (PT)** treatment loop.
Thank you very much for your attention!

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