Update on fluence modulated proton CT activities and a new pCT artifact reduction method

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On behalf of:
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7th Loma Linda University Algorithm Workshop
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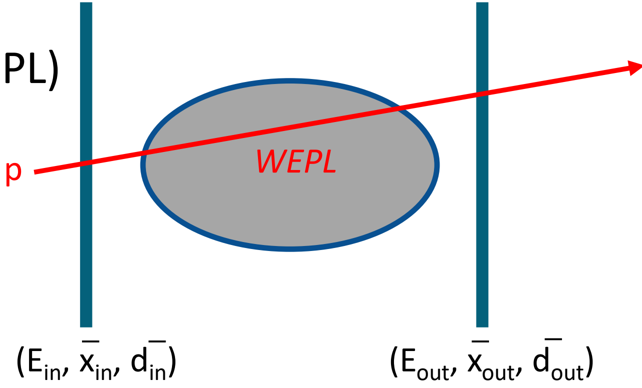
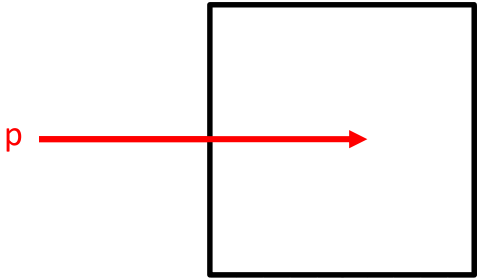
Part I: An empirical artifact correction for proton computed tomography

Proton imaging

- Sufficiently high energy to traverse patient
- For every proton measure water equivalent path length (WEPL) or energy loss in object, or residual energy, or residual range
- WEPL is the line integral of relative stopping power (RSP)
- Positions and directions may also be measured
- Two main solutions for WEPL determination:
  - Range telescope
  - Calorimeter
  - (other alternatives are currently explored)

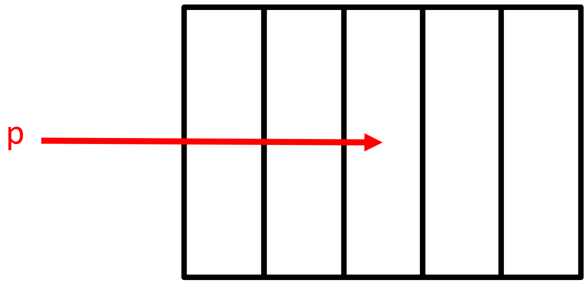


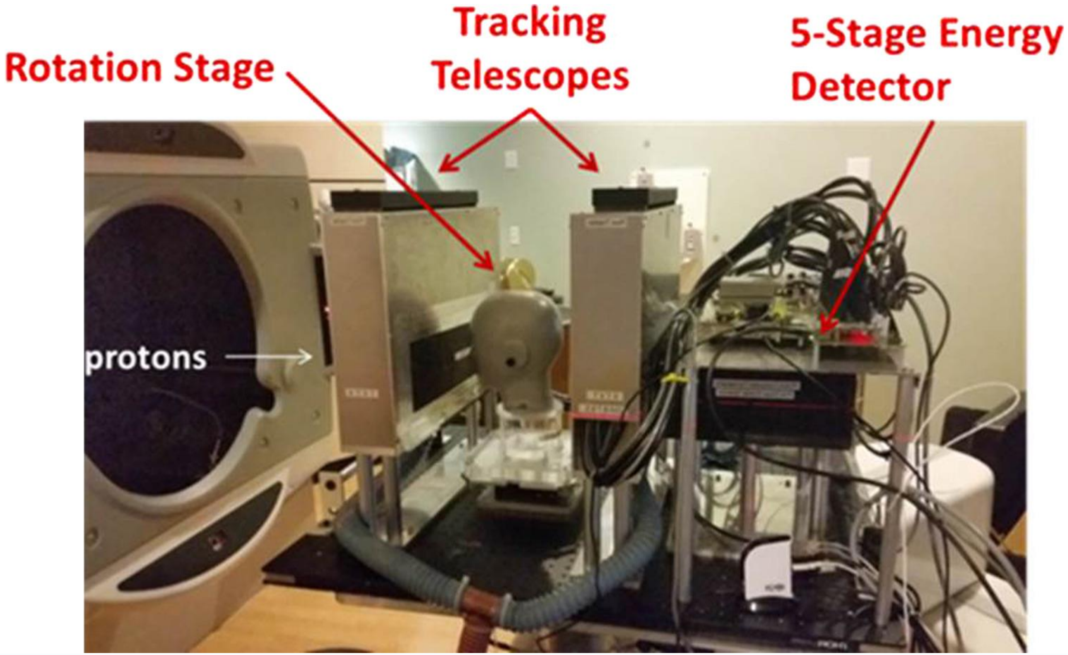


pCT phase II prototype scanner

- Built by Loma Linda University and University of Santa Cruz
  Operated by the US pCT collaboration (LMU is member)

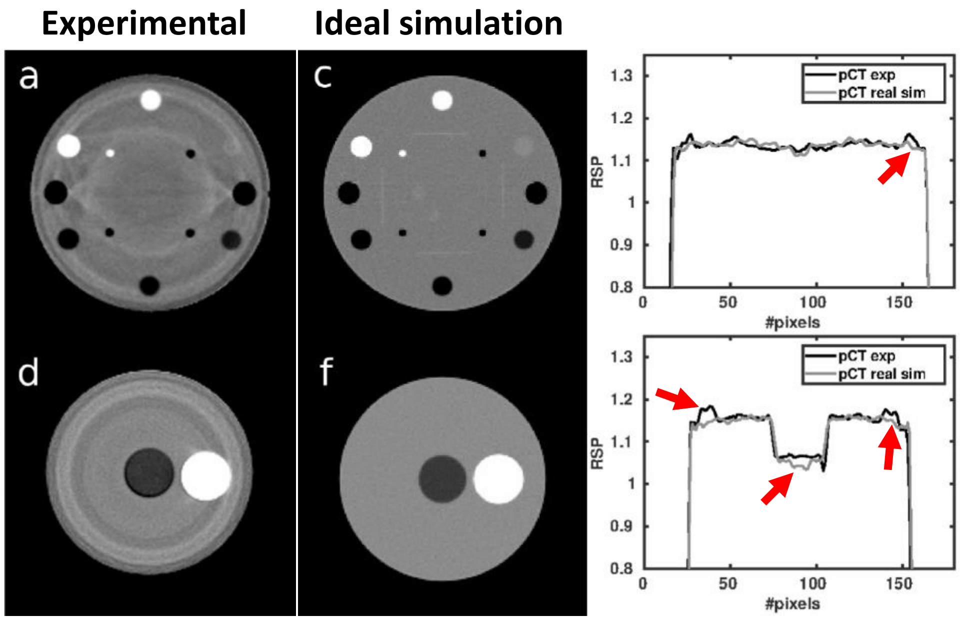
- Hybrid energy detector:





The problem

- Images reconstructed with the distance driven filtered backprojection algorithm
  Rit *et al. Med Phys*. 2013 Mar;40(3):031103
- Experimental pCT (RSP) images have been shown to suffer from artifacts
- Larger than 1% of RSP in amplitude
- May strongly affect the quantified RSP accuracy



Dedes *et al.* 2019 *Phys. Med. Biol.* **64** 165002

Method

- Adapted an empirical cupping correction from x-ray CT: Kachelrieß *et al. Med Phys*, 33 (2006), pp. 1269-1274

- Start with the measured projection (WEPL) values q

- Define a set of (Gaussian) WEPL correction functions $P_n(q)$, each covering a WEPL interval (σ=2mm) and interspaced by s=4mm:

$$P_n(q) = A \cdot \exp\left[-\left(\frac{q-(n-1)\cdot s-s_0}{\sqrt{2}\sigma}\right)^2\right]$$

- The initial projection values can be corrected by applying a weighted sum of the correction functions, with weights c_n:

$$P(q) = q + \sum_{n=1}^{N} c_n P_n(q) = q + \vec{c} \cdot \vec{P}(q).$$

Method (continued)

- Utilizing the linearity of the Radon transform (RSP->WEPL)

$$f(\vec{r}) = R^{-1}p = R^{-1}q + \sum_{n=1}^{N} c_n f_n(\vec{r}) = f_0(\vec{r}) + \vec{c} \cdot \vec{f}(\vec{r})$$

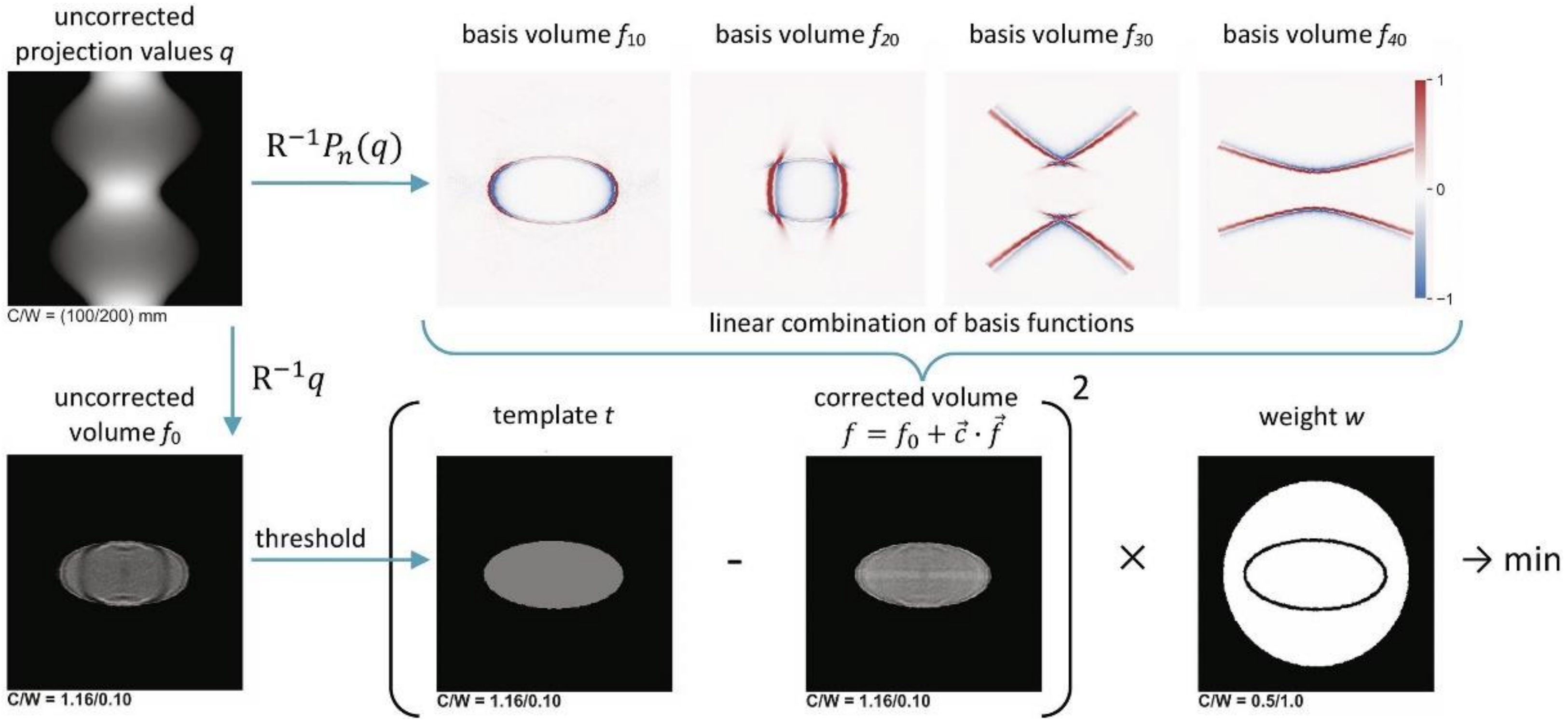
- With $f_n(\vec{r}) = R^{-1} P_n(q)$ being the reconstructed RSP image of a WEPL correction function applied on the projection

- We use the images (RSP) of the reconstructed correction functions (WEPL) in order to find weights which bring us closer to the desired/known image (RSP)

- But because of the Radon transform linearity, these weights can be applied to the any measured WEPL distribution (projection) of an unknown object

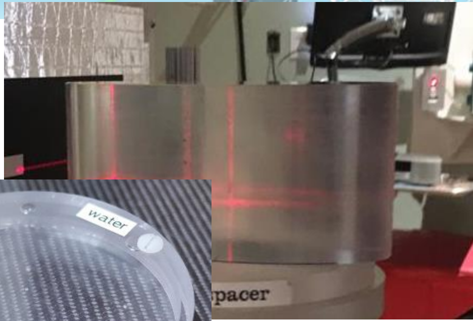
Method (continued)

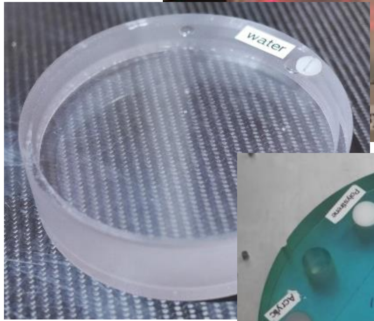
- The full workflow: Dickmann *et al. Phys Med.* 2021 Jun;86:57-65

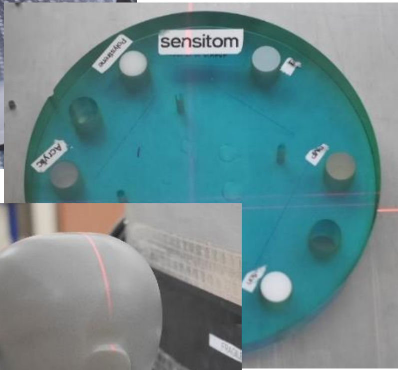


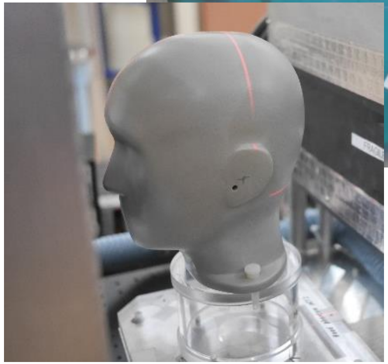
Phantoms

- A PMMA ellipse (165mm/80mm axes, 80mm thickness, RSP=1.160) – “known” RSP phantom
- A water phantom (150.5mm outer diameter, 6.35mm wall, RSP=1.0)
- The CTP404 module of the Catphan 600 phantom (several inserts with RSP ranging from 0.88 to 1.79)
- The pediatric head phantom (ATOM, Model 715 HN, CIRS Inc) mimicing the head of a 5-year old child using tissue-equivalent materials
- Max WEPL: 191mm (ellipse), 152mm (water phantom), 173mm (CTP404) and 176mm (head phantom)







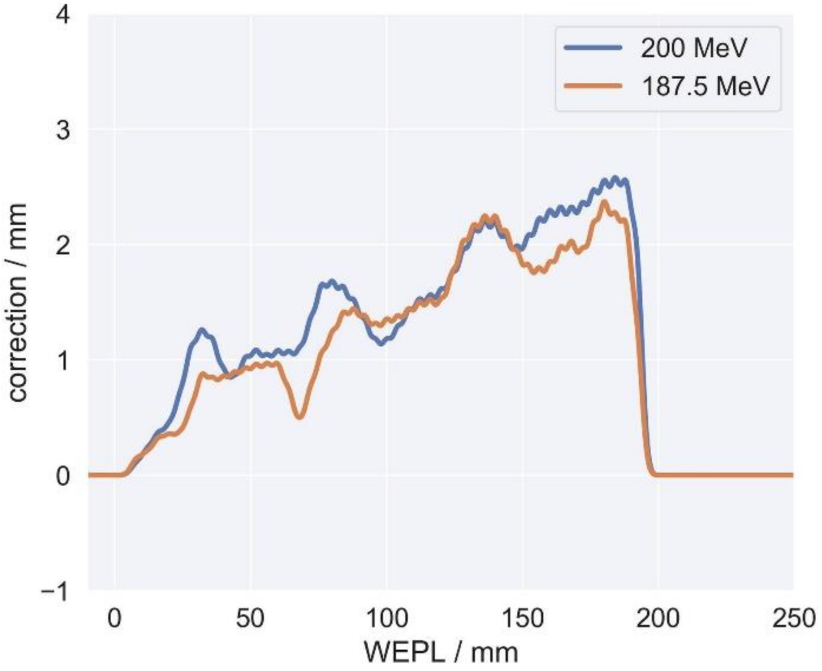


Results - correction

- Scanned all phantoms at two energies and derived the correction for each energy

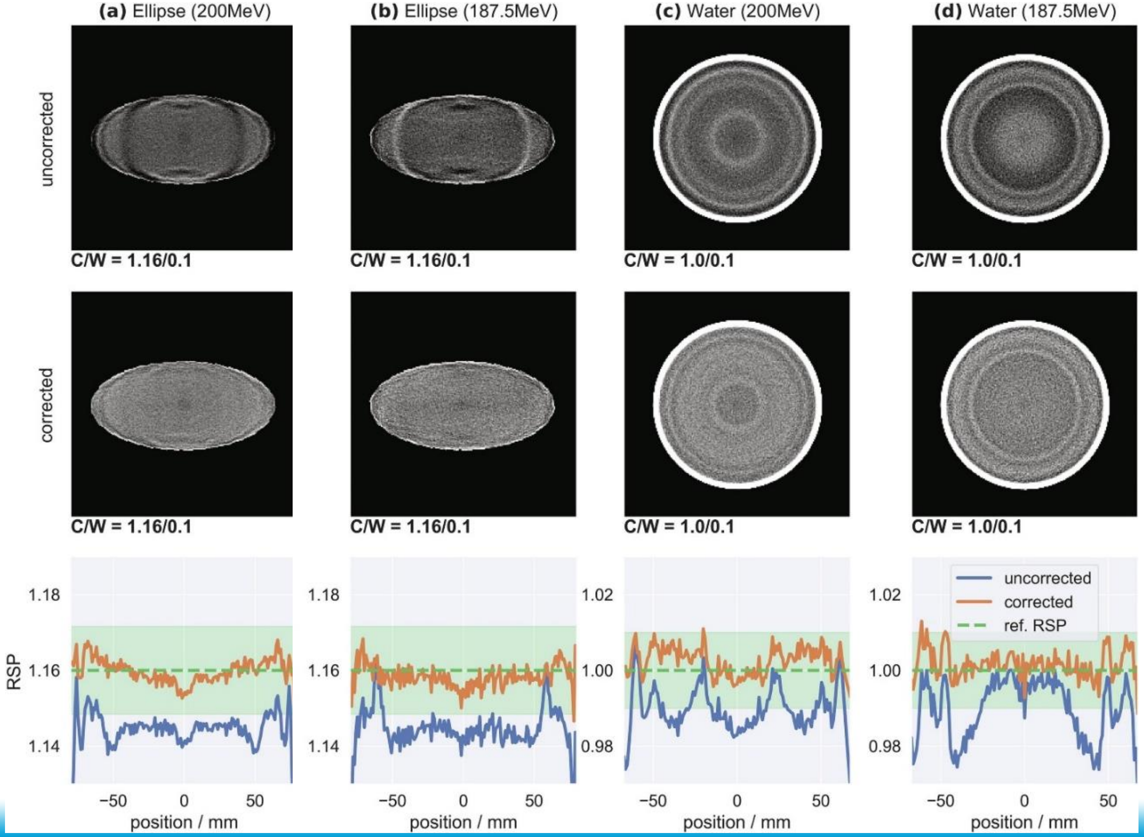
- Several structures related to stage interfaces, calibration kinks regions etc.

- Observed a slope of about 1.3%



Results – images

- Reconstructed images with and without correction



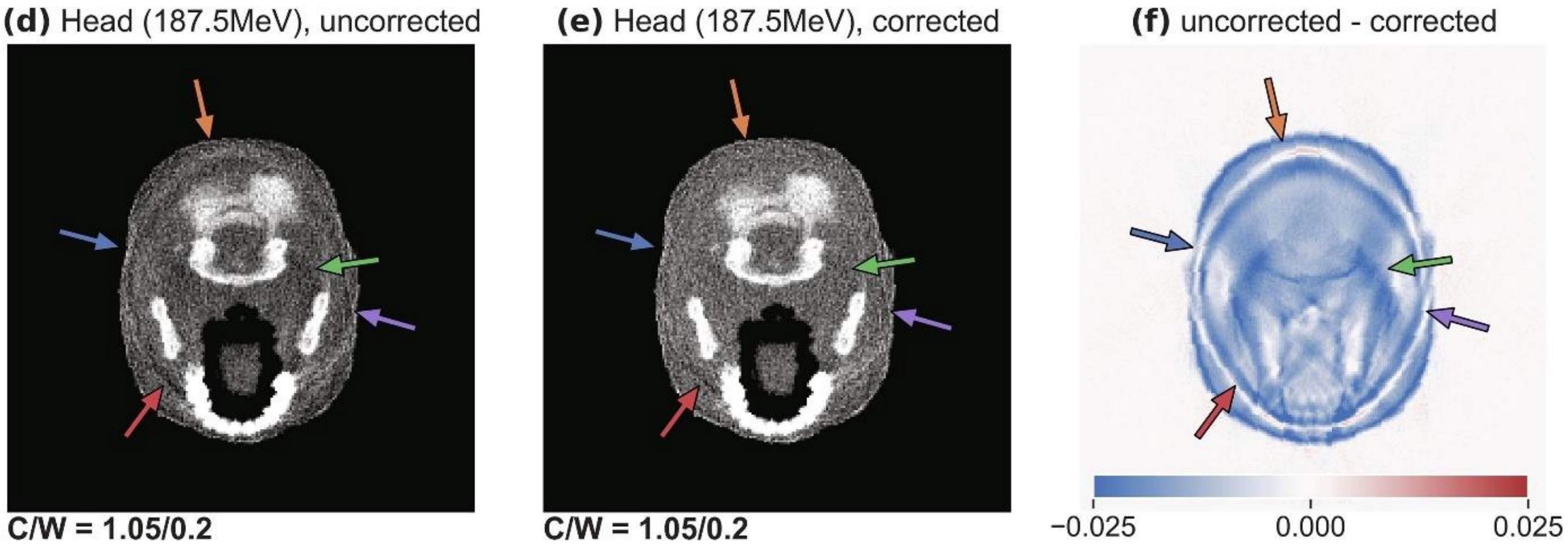
Results – RSP accuracy

- Overall improvement in the RSP accuracy (consistently around 0.5%)
- The correction can be used as the fast calibration of the day without the need of the more time consuming wedge calibration

		MAPE / %		
dataset	energy / MeV	*uncorrected*	*corrected*	improvement
high energy	200	0.87 ± 0.02	0.44 ± 0.02	−49%
low energy	187.5	0.86 ± 0.03	0.48 ± 0.03	−44%
Dedes 2019	200	0.72 ± 0.03	—	—
old calibration	200	1.94 ± 0.03	0.32 ± 0.03	−84%

Results – head phantom

- Works also in more complicated anatomies (pediatric head phantom)
- Piece-wise homogeneous, no RSP variations expected within each piece



Summary

- Successfully adapted an x-ray cupping correction to pCT and experimental demonstration of it
- Significantly reduced amplitude of image artifacts with the phase II scanner
- Achieved about 50% improvement and consistently better than 0.5% RSP accuracy
- Applicable also to clinically relevant anatomies

Full details:

ELSEVIER

Physica Medica
Volume 86, June 2021, Pages 57-65

Technical note

An empirical artifact correction for proton computed tomography

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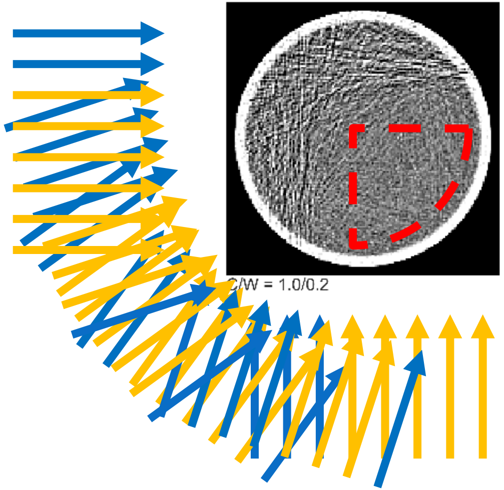
Part II: Performance Evaluation of An Optimization Method for Fluence-Modulated Proton CT with Dose and Variance Objectives

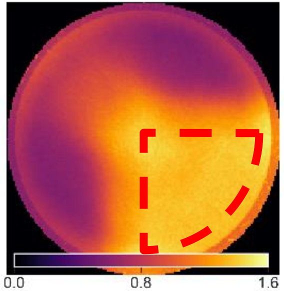
Fluence modulated proton CT (FMpCT)

Aim: to use **modulated pencil beams for** achieving arbitrary **image noise targets** with FMpCT

RSP
(relative stopping power)

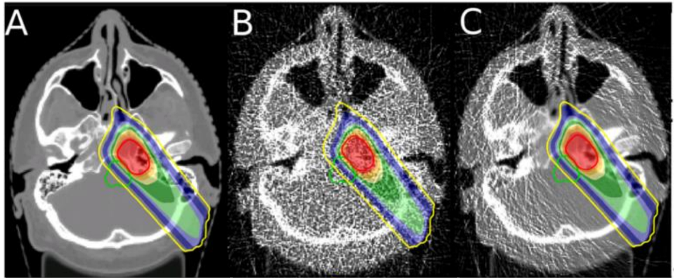


Dose / mGy



Dickmann et al. (2020), Med. Phys., 47, 4
Dickmann et al. (2020), PMB

Motivation: frequent imaging for particle therapy



noise in ROI	Low	High	Low
dose outside ROI	High	Low	Low

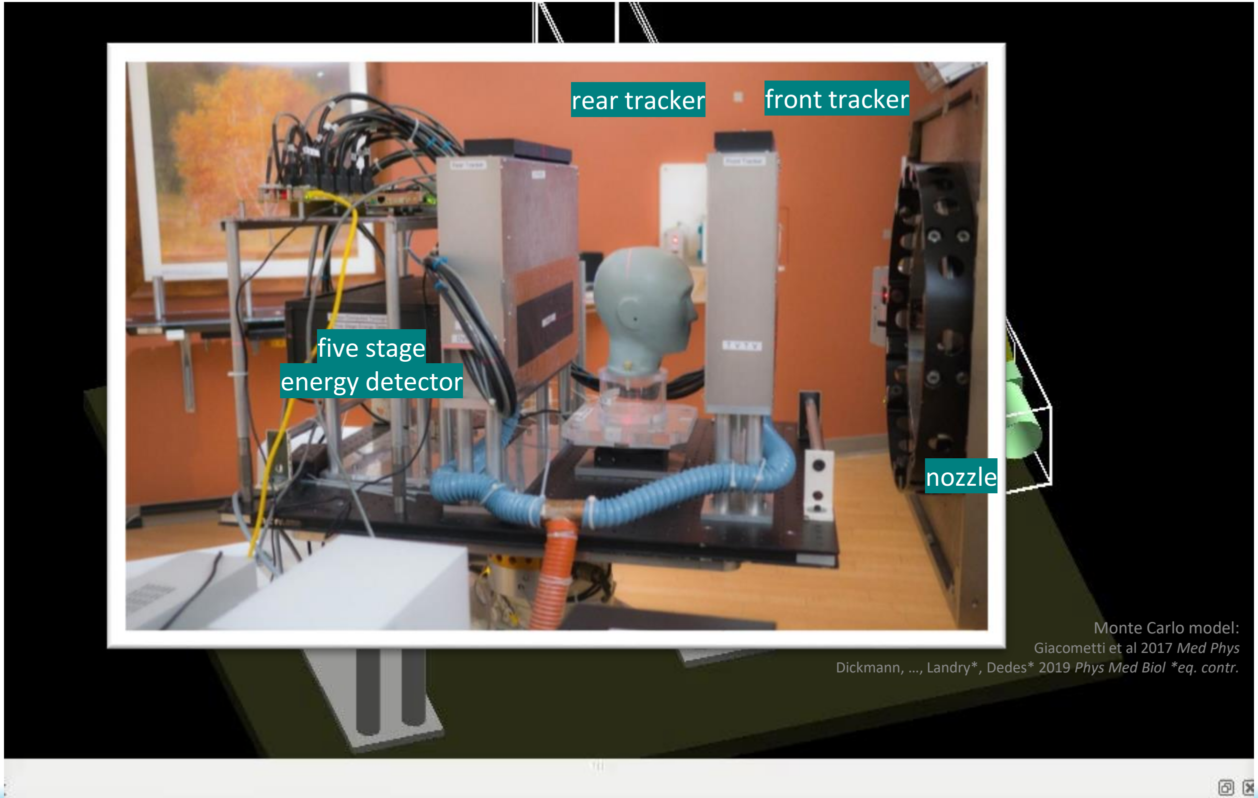
Dedes et al. (2017), PMB, 62, 6026

Goal of this **study**:

- Include both **dose** and **variance** in **FMpCT optimization**

Prototype pCT scanner

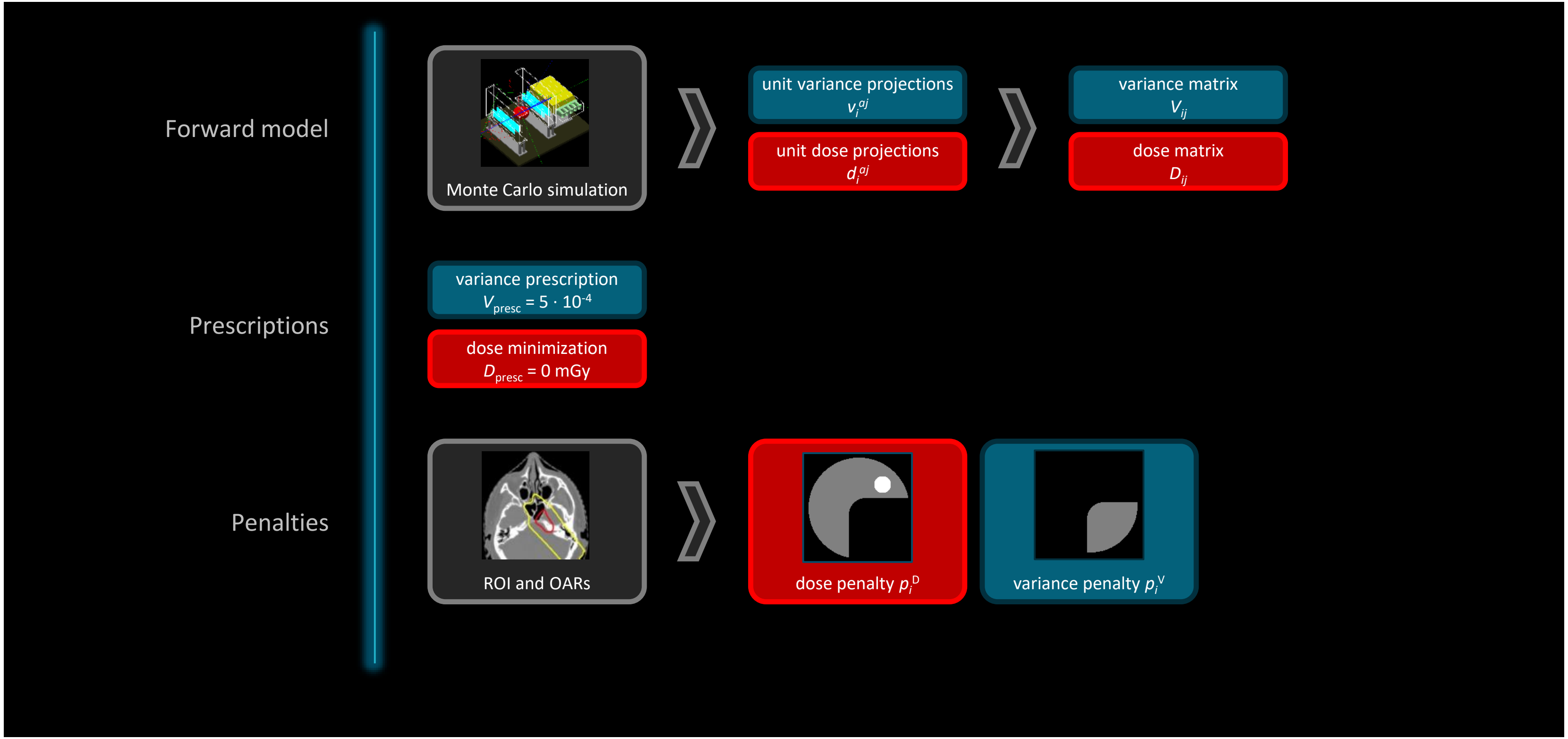
- Validated MC simulation platform, used in this study



Monte Carlo model:
Giacometti et al 2017 *Med Phys*
Dickmann, …, Landry*, Dedes* 2019 *Phys Med Biol* *eq. contr.*

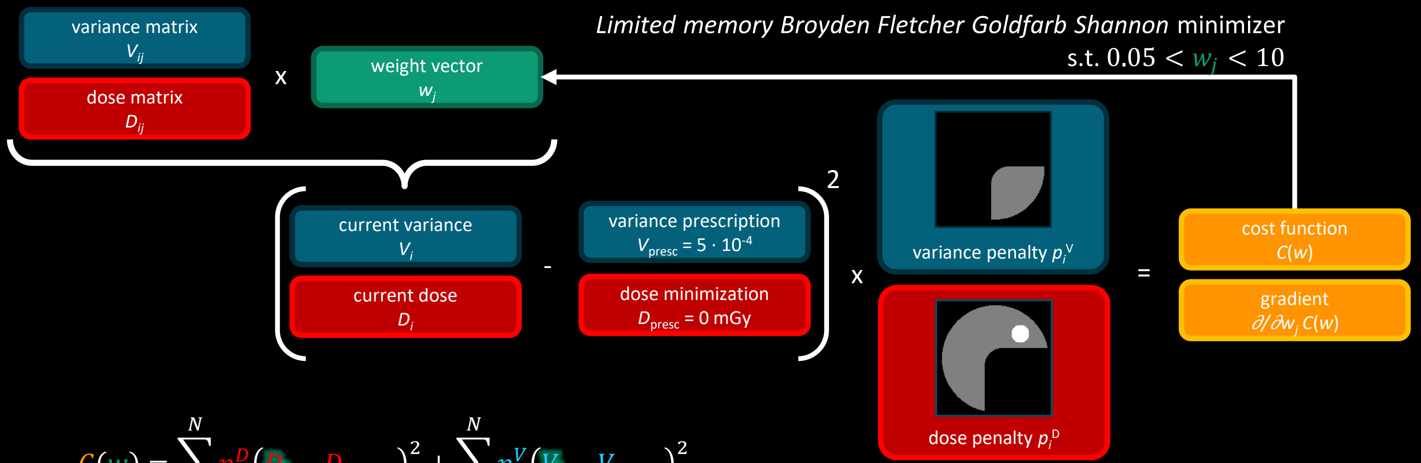
Joint optimization

- Dose and variance optimization



Joint optimization

- Bixel-based approach



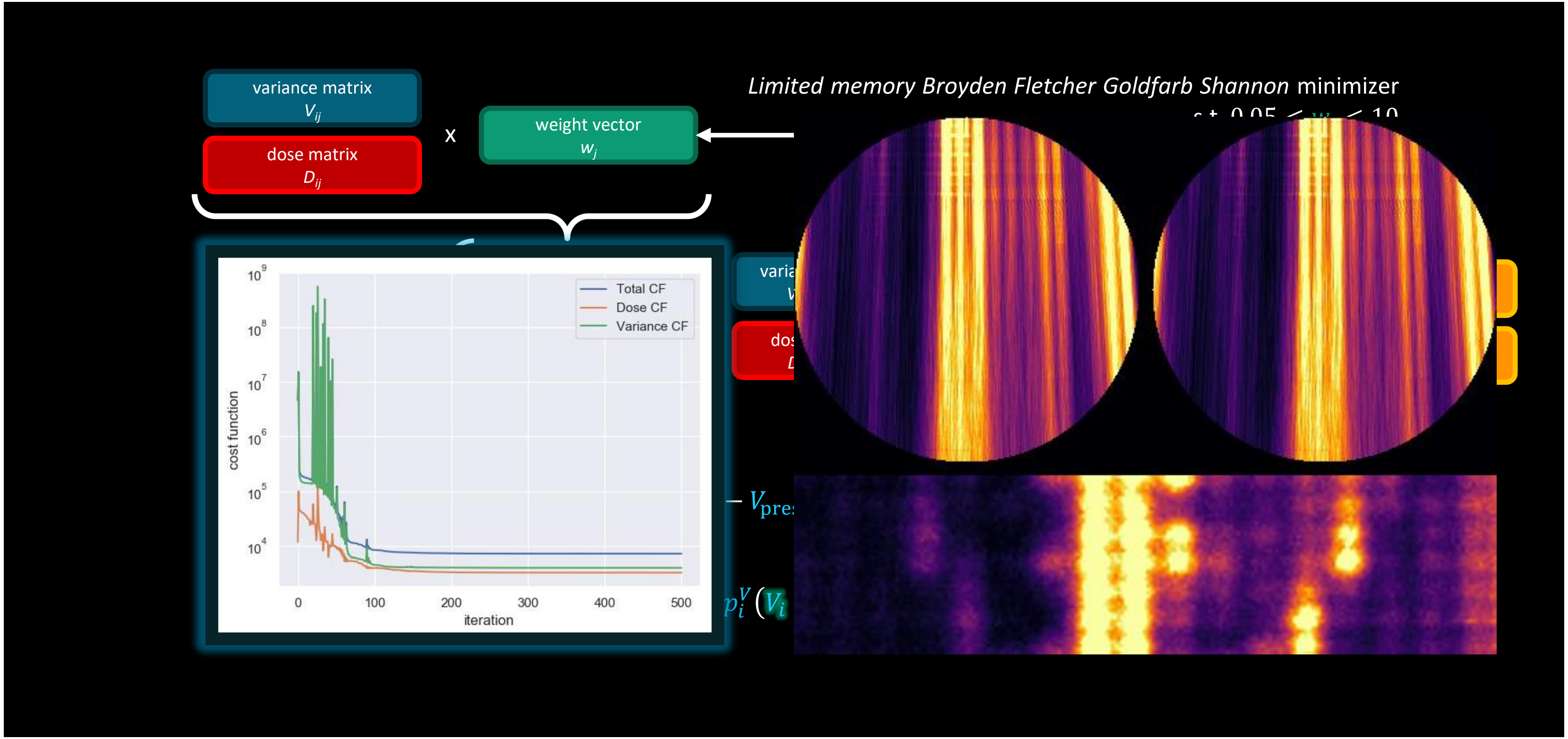
$$C(w) = \sum_{i=1}^{N} p_i^D \left(D_i - D_{\mathrm{presc}}\right)^2 + \sum_{i=1}^{N} p_i^V \left(V_i - V_{\mathrm{presc}}\right)^2$$

$$\frac{\partial}{\partial w_j} C(w) = 2 \sum_{i=1}^{N} p_i^D \left(D_i - D_{\mathrm{presc}}\right) D_{ik} - 2 \sum_{i=1}^{N} p_i^V \left(V_i - V_{\mathrm{presc}}\right) \frac{V_{ik}}{w_j^2}$$

Dickmann, ..., Dedes, Landry 2021 *Phys Med Biol*

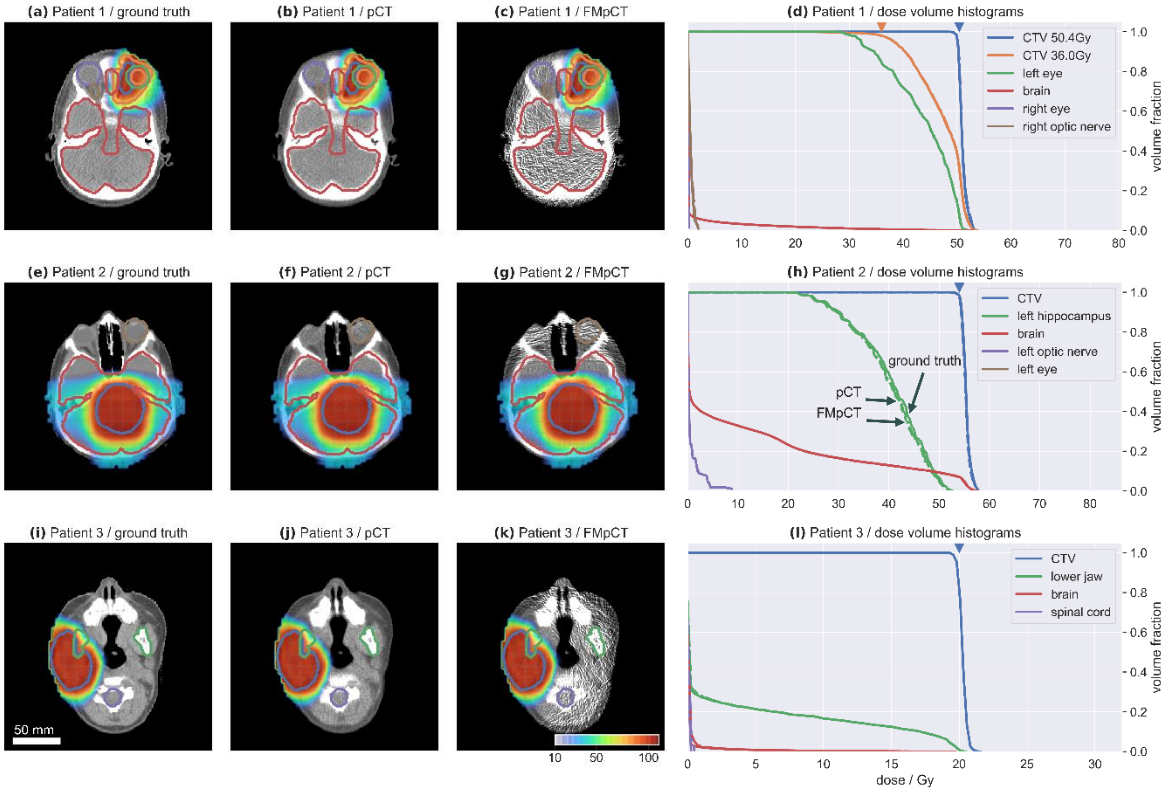
Joint optimization

- Bixel-based approach



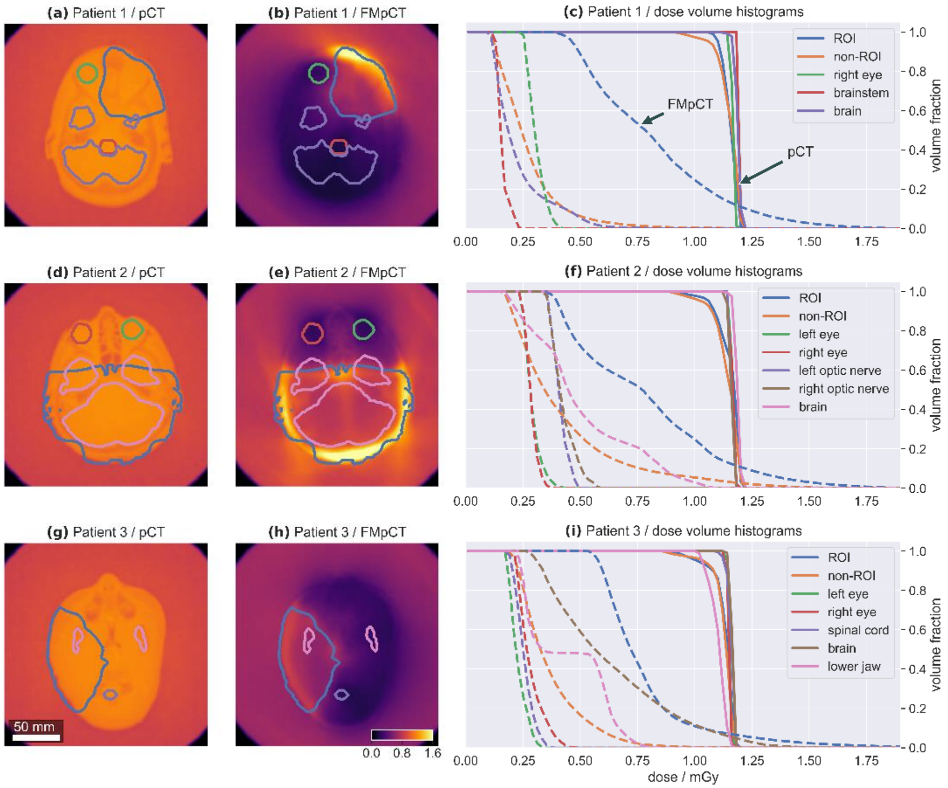
Dickmann, …, Dedes, Landry *2021 Phys Med Biol*

FMpCT in treatment planning



- three **pediatric cases** treated with IMRT selected
- **proton treatment plans** generated on the basis of the IMRT dose distributions using **ground truth RSP**
- **ground truth RSP** from the patient model in the pCT MC **simulation** with **full detector modelling**
- **treatment dose recalculated** on pCT and FMpCT images

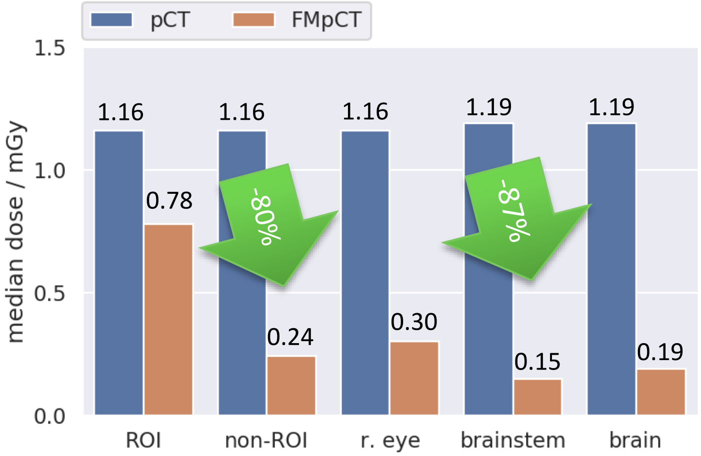
Imaging dose



- **DVH** for **imaging** dose
- Important **dose reduction** for all **out-of-ROI areas**
- **Dose** can be slightly increased **in-ROI** where **treatment dose** is also **high**
- **OAR dose** can be **pushed down**

Summary

- **Inverse planning** approach yields optimal fluence distributions
- FMpCT allows **substantial imaging dose savings** while preserving dose calculation accuracy
  - **80%** outside the ROI
  - **87%** in some OARs
- Results expected to be **applicable** to **real world** due to fully realistic simulations
- Previous work showed **imaging plans** are **deliverable**



Full details:

Physics in Medicine & Biology

IPEM Institute of Physics and Engineering in Medicine

PAPER

Fluence-modulated proton CT optimized with patient-specific dose and variance objectives for proton dose calculation

J Dickmann[1], F Kamp[2,*], M Hillbrand[3], S Corradini[2], C Belka[2,4], R W Schulte[5], K Parodi[1], G Dedes[1] and G Landry[1,2]

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NIU Northern Illinois University

George Coutrakon
Chistina Sarosiek

Northwestern Medicine

Mark Pankuch

CREATIS

Simon Rit
Nils Krah

Lockdown era experiment

- Late evening in Chicago

- 12 AM to 5 AM in Munich