Concepts of synthetic imaging

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Disclosures

- Research support from Raysearch and NIH

3D Imaging

- Traditionally:

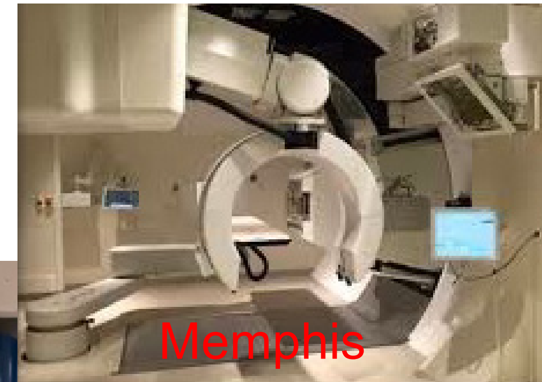
Signal → **Reconstruction** → **3D Image**

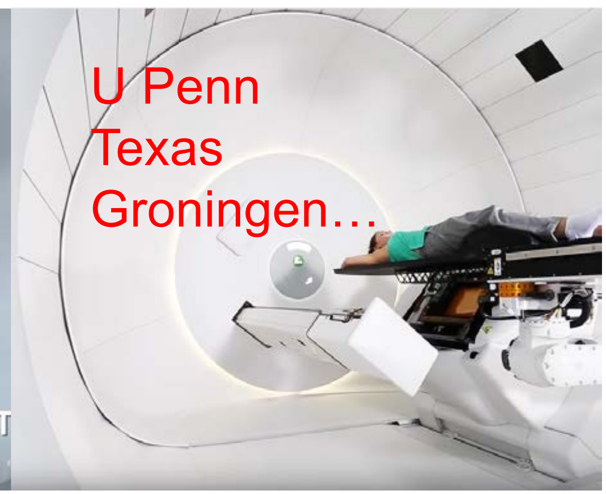
- Signal:
  - Photons
  - RF
  - Others
- Reconstruction:
  - Backprojection
  - Decoding
  - Can include corrections
- 3D Image:
  - CT
  - MRI
  - PET

- Ex: FDK for CBCT

3D Imaging options

- CBCT:
  - Varian CBCT
  - IBA CBCT (x2)
  - MedPhoton
  - Forte





3D Imaging options

- CT:
  - In Room

J Appl Clin Med Phys. 2017 May; 18(3): 130–136.

PSI

MEVION AND MEDPHOTON BRING ADVANCED CONE BEAM CT IMAGING TO PROTON THERAPY

Mevion to integrate in-room CBCT imaging with its MEVION S250 Series; invites customers to learn more at ESTRO 36

LITTLETON, Mass., May 2, 2017 – Mevion Medical Systems, the leader in compact proton therapy, is announcing a strategic agreement with medPhoton GmbH to integrate ImagingRing, an innovative cone beam computed tomography (CBCT) system for volumetric image guidance, with

3D Imaging future

- MR:
  - In Room

Hoffmann *et al. Radiation Oncology* (2020) 15:129
https://doi.org/10.1186/s13014-020-01571-x

Radiation Oncology

REVIEW Open Access

MR-guided proton therapy: a review and a preview

Aswin Hoffmann[1,2,3], Bradley Oborn[4,5], Maryam Moteabbed[6], Susu Yan[6], Thomas Bortfeld[6], Antje Knopf[7], Herman Fuchs[8,9], Dietmar Georg[8,9], Joao Seco[10,11], Maria Francesca Spadea[10,12], Oliver Jäkel[13], Christopher Kurz[14,15] and Katia Parodi[15*]

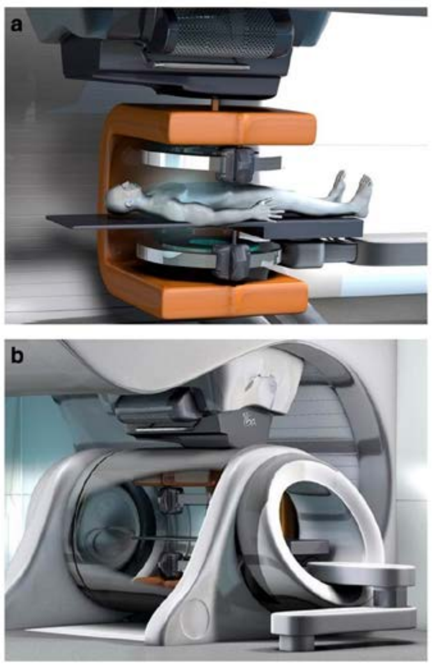


Fig. 3 Artist impressions of (**a**) a rotating biplanar open in-beam MRI scanner integrated in a (**b**) compact proton therapy gantry treatment room (Image courtesy: Ion Beam Applications SA, Louvain-la-Neuve, Belgium)

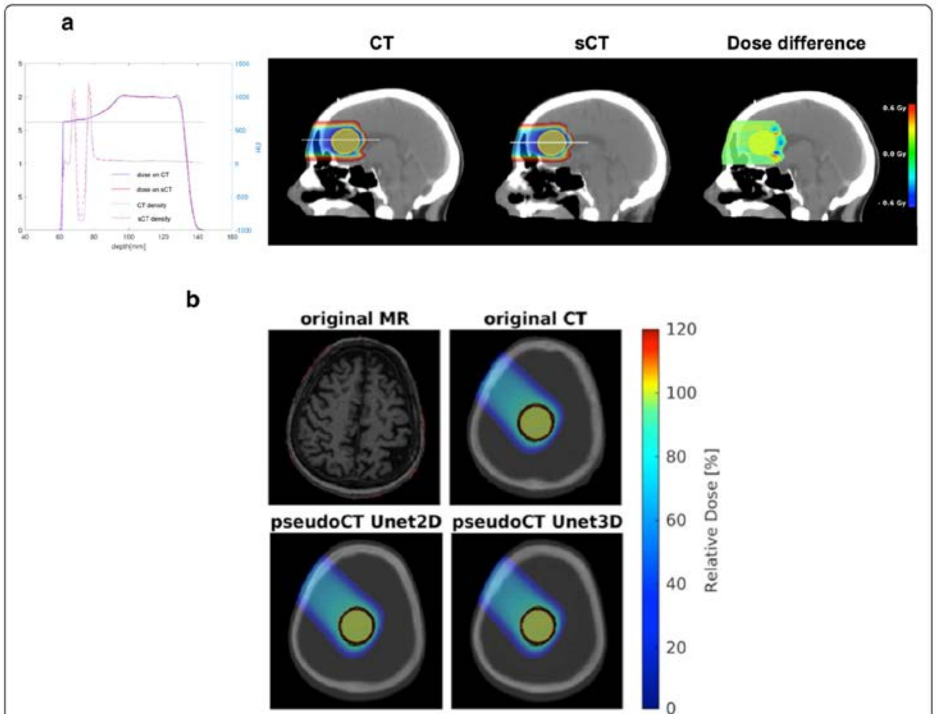


Fig. 5 **a** From left to right: HU and dose profile of a proton spread-out Bragg peak (SOBP) for a beam entering via the frontal sinus. SOBP dose and dose difference distribution in a 2D sagittal plane as planned on the sCT and then delivered on the CT using a prescribed dose of 2 Gy. Adapted from [48]. **b** Original MRI, CT and pseudoCTs generated with a 2D and a 3D Unet for an exemplary brain case. The SFUD proton dose distribution for a single gantry angle is depicted on the original CT and the two pseudoCTs. The generic target volume is marked in red, the 95% iso-dose line in green. Adapted from [49]

Imaging Needs:

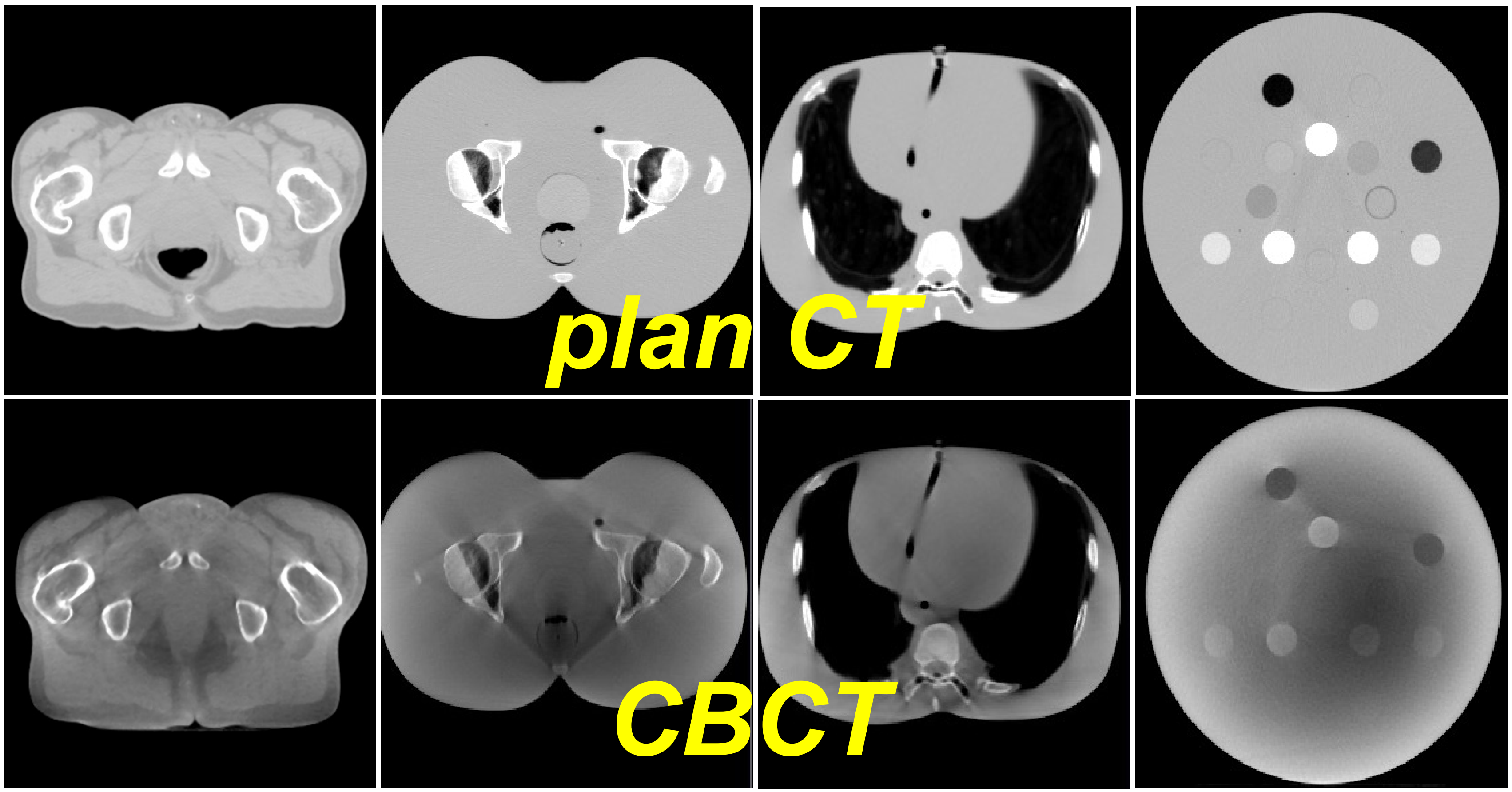
- Image Quality (registration, contouring, and dose calculations)
  - HU or SPR Accuracy
  - Soft tissue Contrast
- 4D Motion for thoracic/abdominal
- Workflow Integration

Image Quality Issues

- Artifacts: streaks, scatter, beam hardening
- HU/RSP conversion (MR)
- Geometric Accuracy (MR)
- Gantry Flex/Sag
- Motion

M Zhu et al *Med Phys* 2014

CBCT Artifacts

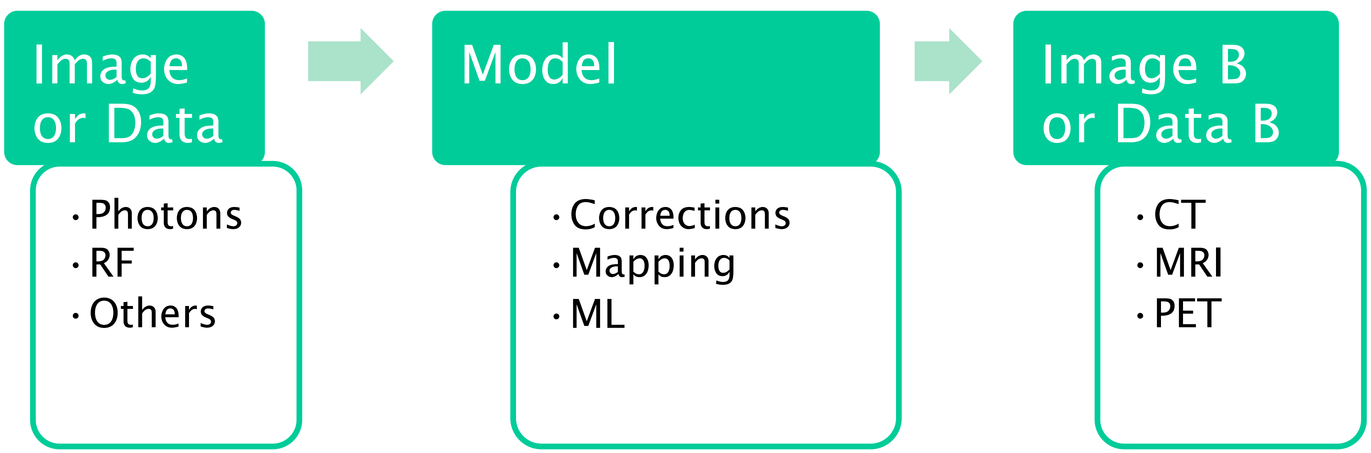


Synthetic Imaging

- Some Examples:
  - Patient modeling
  - Correct Image Artifacts (CBCT, MR, CT):
    - Scatter
    - Intensity
    - Motion
    - Geometry
  - Convert from type A to type B
    - Convert MR to CT/SPR
    - Multiple MR Sequences

Synthetic Imaging

- Some Examples:
  - Patient modeling
  - Correct Image Artifacts (CBCT, MR, CT):
  - Convert from type A to type B



→The analytic/synthetic distinction is blurry!

Synthetic Image Methods

- Model (low frequency)*
- HU Look Up Table (LUT)^
- Deform CT to CBCT^
- *A priori* CT scatter correction *^
- ML Models*^
- Iterative^

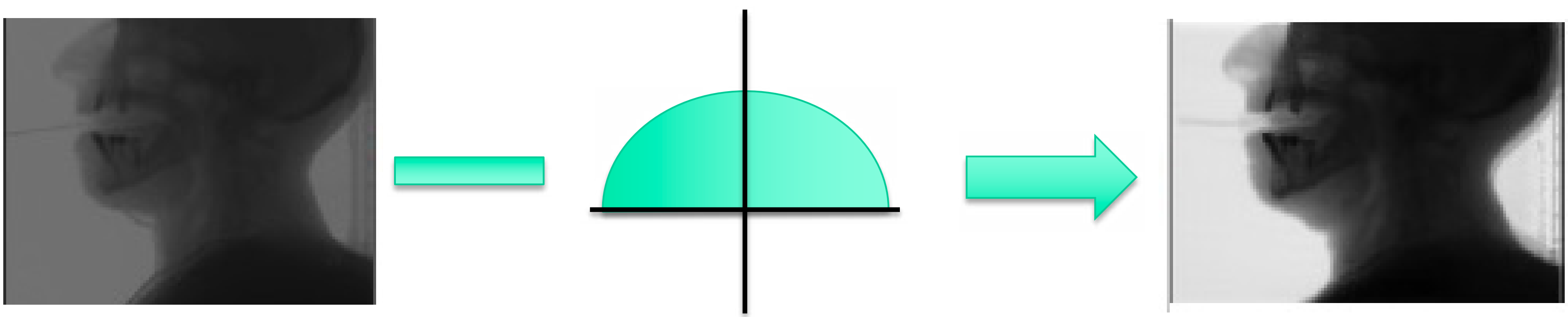
* Projection Domain; ^ Reconstruction Domain

Scatter Model

- Estimate of Scatter based upon Model
  - Early online CBCT devices and reconstructions

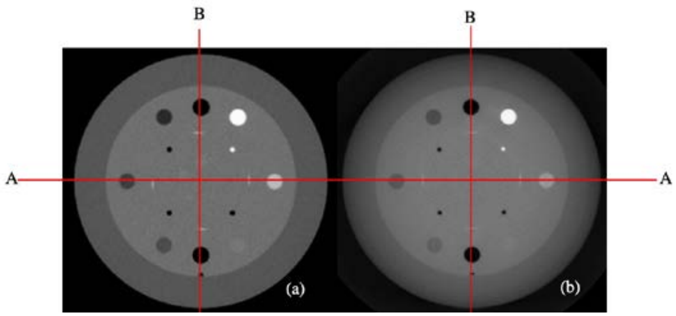
Boellaard, *et al., Radiotherapy & Onc,* 44, 1997, 149-157.

  - Also, simplified model (cylinder) for scatter



LUT

- Basic method: Calibration
  - Mapping of $I_{CBCT} \rightarrow I_{CT}$

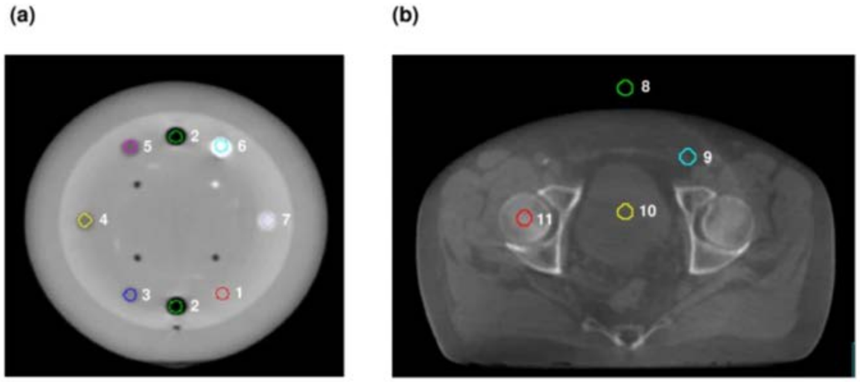


Yang, *et al., PMB,* 52, 2007, 685-705

- Contour/ROI
  - CBCT (many studies)

A. Richter, *et al., Rad Onc,* 3, 2008

Hu, *et al., Rad Onc,* 5, 2010



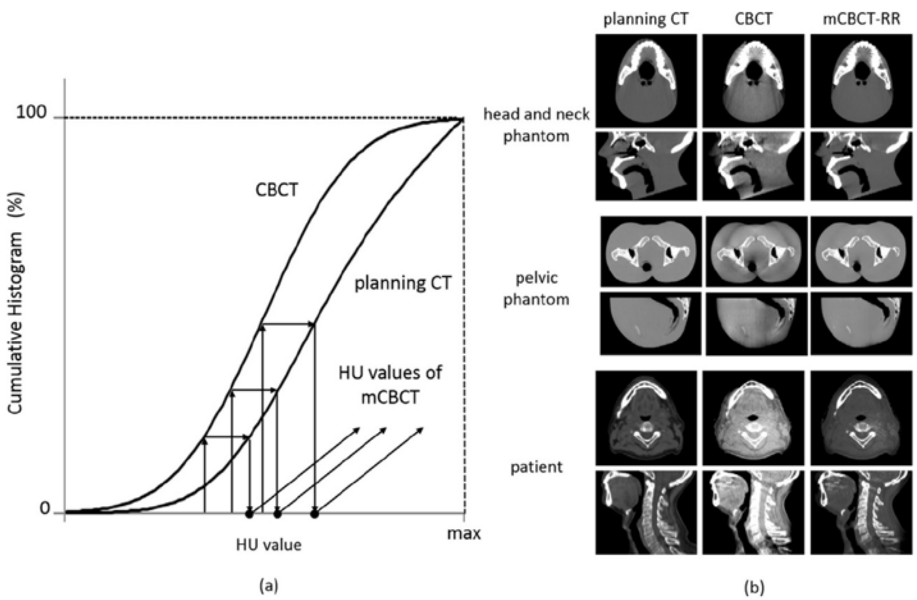
  - MR (many studies)

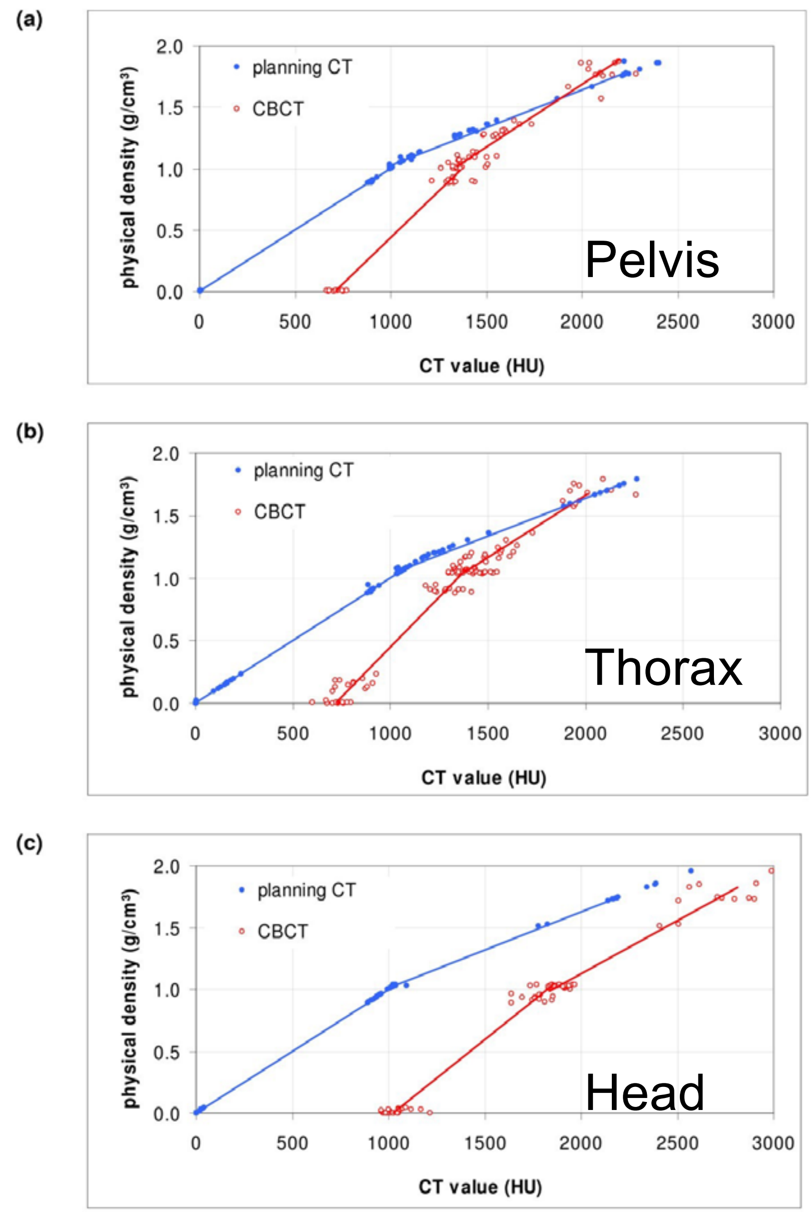
Korhonen, *et al., Med Phys,* 41(1), 2014

LUT

- Challenge for CBCT →
  - Slope and offset
  - Cupping
- Histogram matching

Arai, *et al., Phys Medica,* 33, 2017, 68-76





A. Richter, *et al., Rad Onc,* 3, 2008

Deform CT

- Originally proposed for photon therapy

  Zhen, *et al*. *PMB,* 57(21), (2012), 6807.

Ref CT
CBCT → DIR
CT to CBCT → dCT or vCT

- Investigated for Proton Therapy

  Landry, *et al*. *Med Phys,* 42(3), (2015), 1354-1366.
  Landry, *et al. PMB*, 60(2), 2015, 595-613.

- Various Additional Corrections:
  - CBCT Intensity
  - Air Cavity and Patient Contour

Deform CT

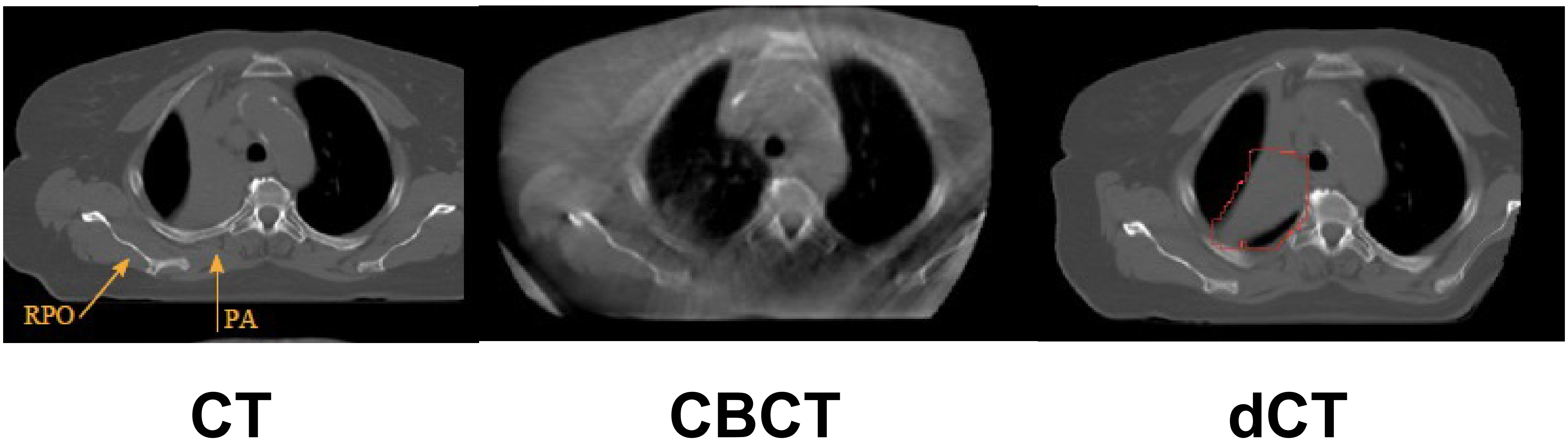
- Clinical Data from Penn

CT CBCT dCT

Veiga *et. al.*, *IJROBP,* 95(1) 2016, 549-559.

Correction Methods

- Deform CT
  - Challenges when anatomy changes too much, especially with air cavities



Veiga *et. al.*, *IJROBP*, 95(1) 2016, 549-559.

A priori Method

- Niu et al (Med Phys 2010) using *a priori* CT information and scatter kernel
- Reconstructions with RTK
- Compared to a uniform scatter correction model and baseline CBCT

A priori Method

- Ni
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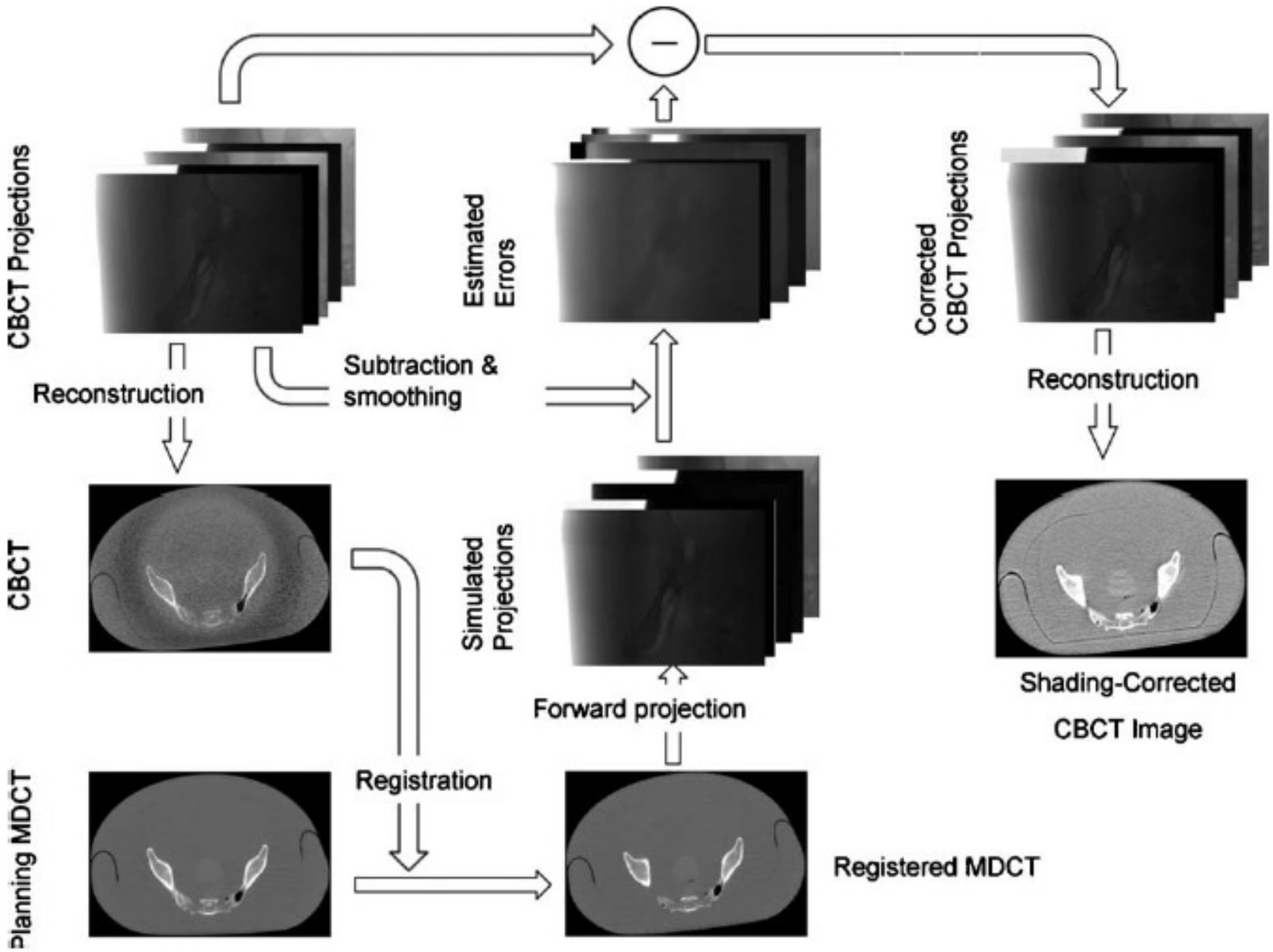
  an
- Re
- Cc
  sc
  ba



a priori Method

Proton dose calculation on scatter-corrected CBCT image: Feasibility study for adaptive proton therapy

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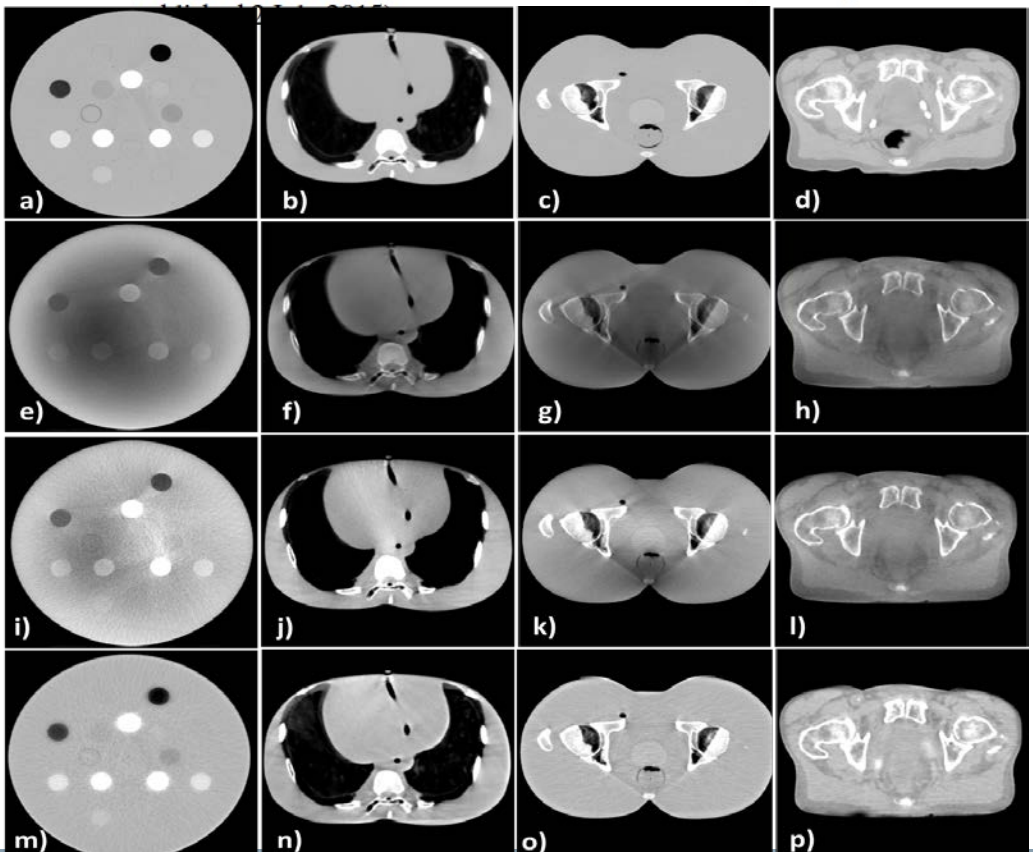
(Received 21 March 2015; revised 16 June 2015; accepted for publication 17 June 2015;



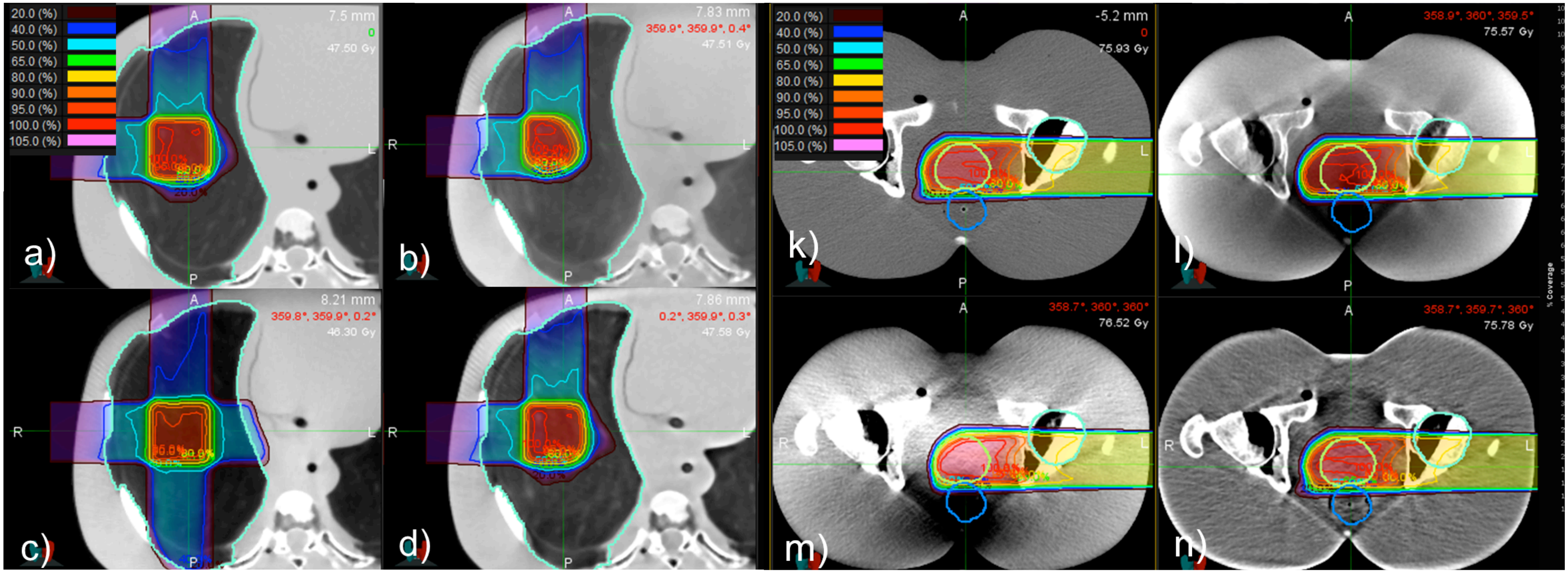
plan CT

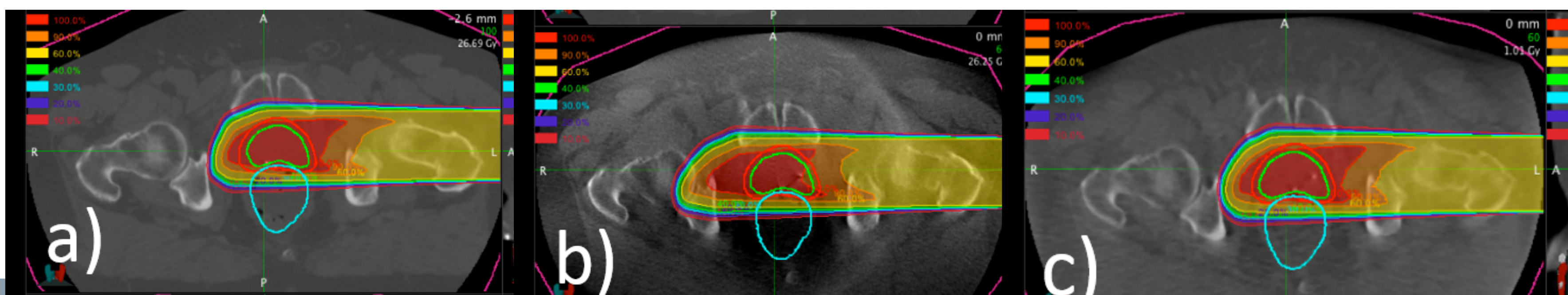
CBCT: Simple FDK

Uniform Corr
(~Elekta/Varian Gen 1)

***a priori* Corr**

Dose Comparison: Phantoms





Investigating deformable image registration and scatter correction for CBCT-based dose calculation in adaptive IMPT

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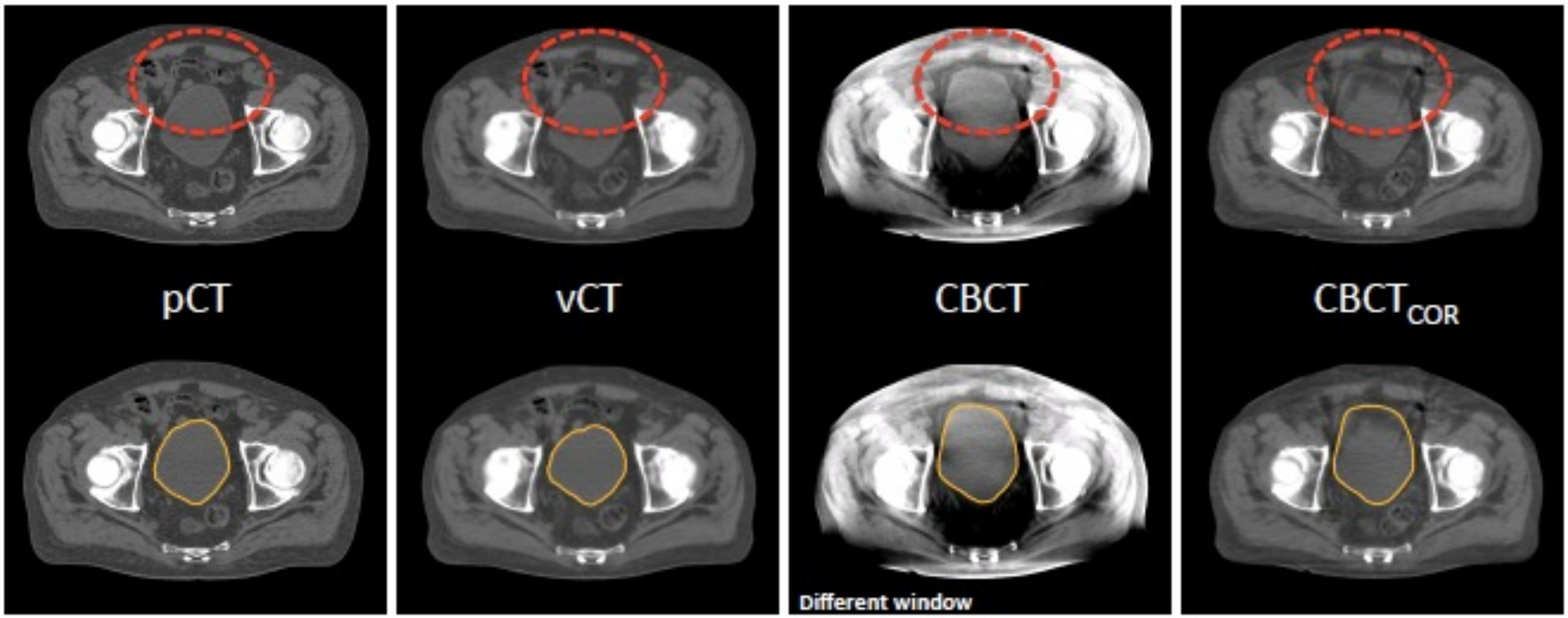
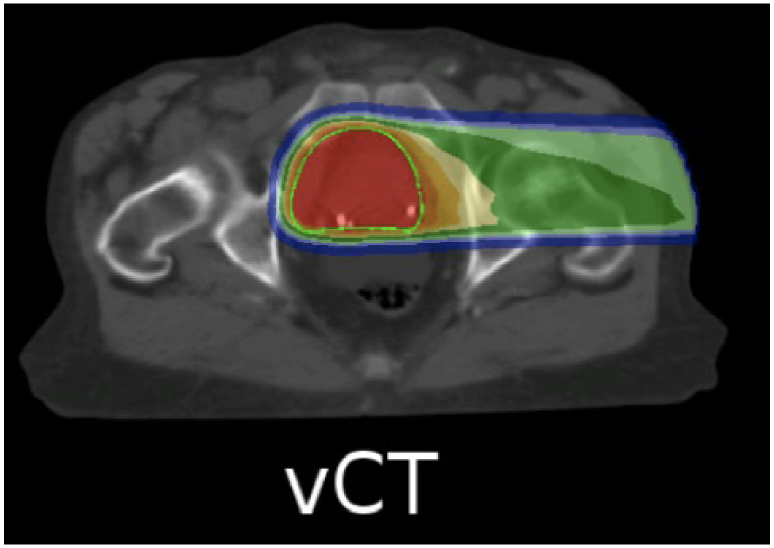
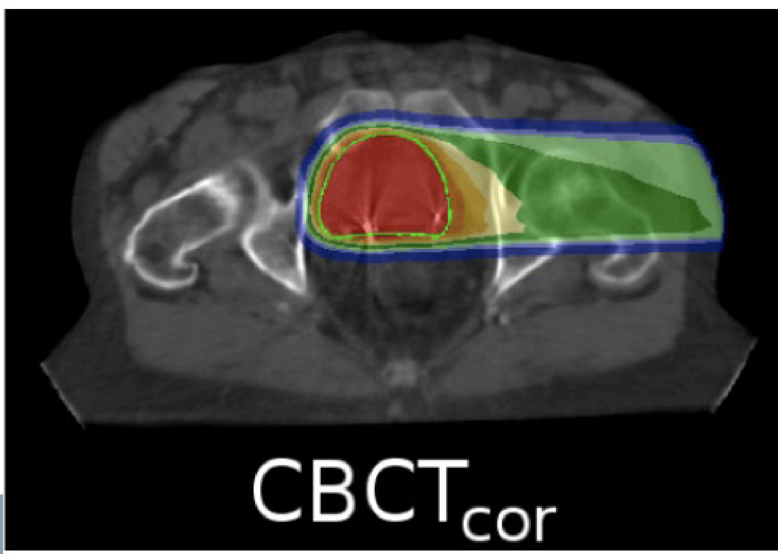
(Received 12 April 2016; revised 30 August 2016; accepted for publication 5 September 2016; published 23 September 2016)

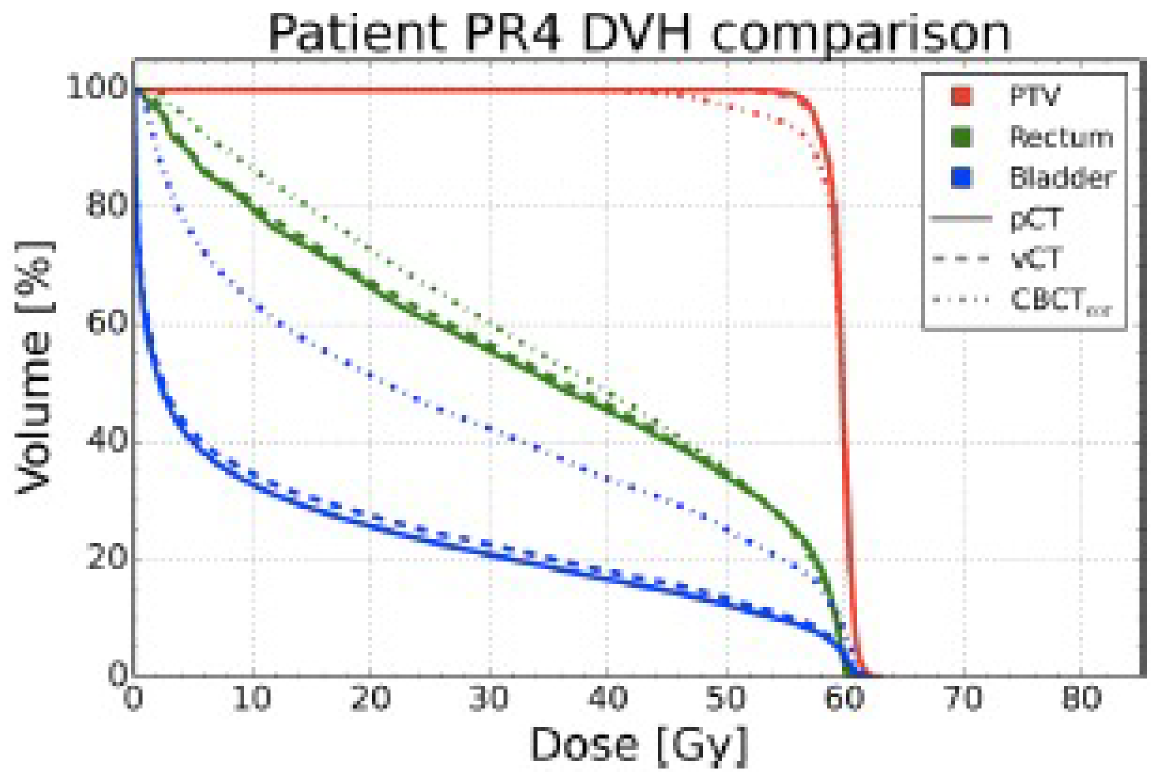
- Deform versus *a priori* (LMU and MGH)



Patient Dose Calculations







Kurz *et al* *Med Phys* 43(10): 5635, 2016.

A Priori Method

- Limitation was time
- Generally found to have HU accuracy and WEPL accuracy within 2-3 mm.
- Beam hardening still needs addressed
- Faster: Machine Learning or Patient Specific Scatter Kernel

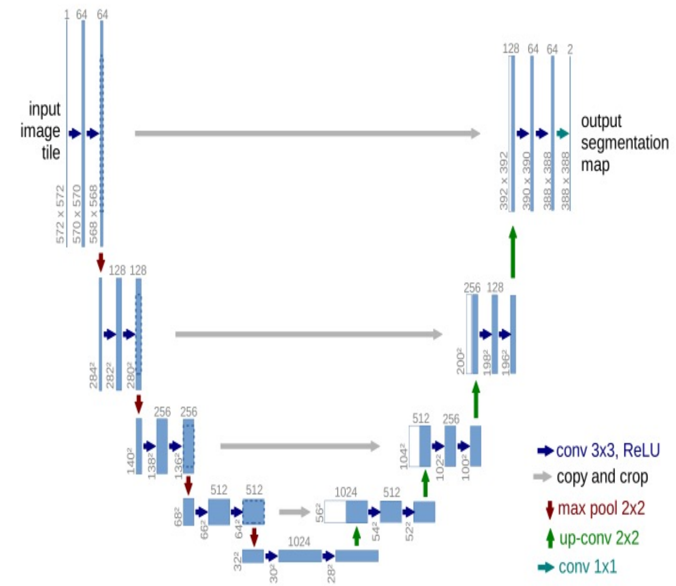


Fig. 1. U-net architecture (example for 32x32 pixels in the lowest resolution). Each blue box corresponds to a multi-channel feature map. The number of channels is denoted on top of the box. The x-y-size is provided at the lower left edge of the box. White boxes represent copied feature maps. The arrows denote the different operations.

Machine Learning

- Use of ML to generate relationship between Image/Data A and Image/Data B.
- Examples:
  - MR to CT
  - CT with Artifacts to CT without
  - MR Sequence 1 to MR Sequence 2

ML for MR to CT

Physica Medica 89 (2021) 265–281

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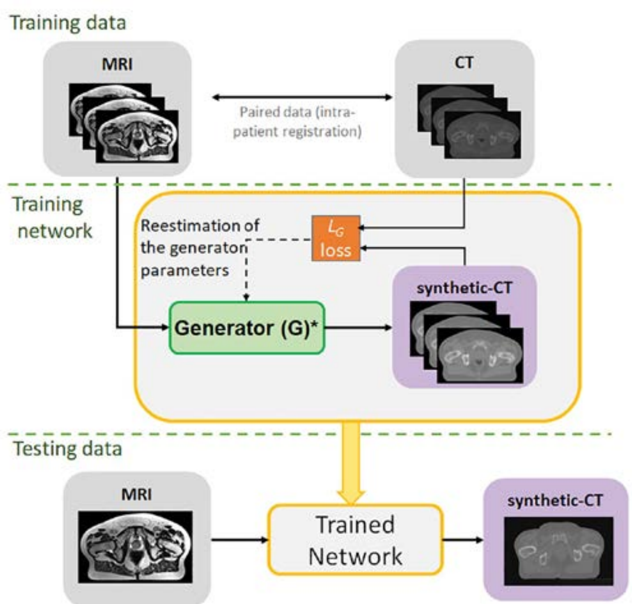
ELSEVIER

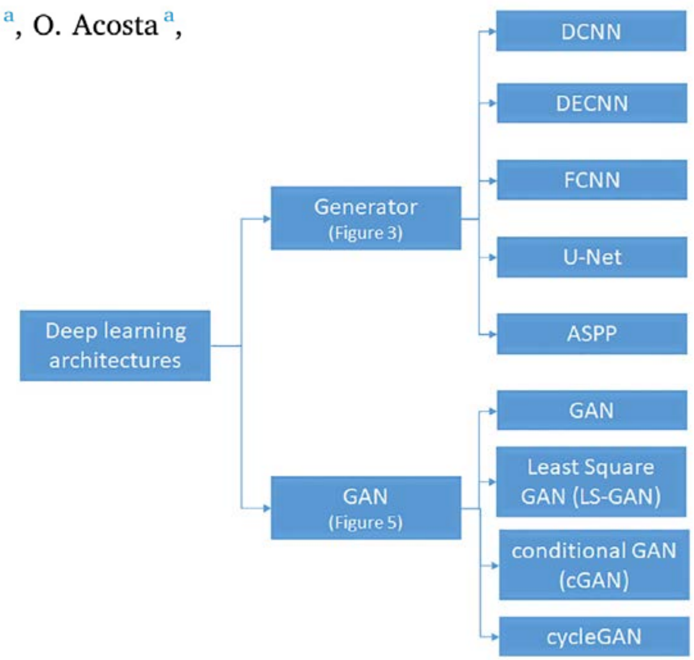
Check for updates

Deep learning methods to generate synthetic CT from MRI in radiotherapy: A literature review

M. Boulanger [a], Jean-Claude Nunes [a,*], H. Chourak [a,c], A. Largent [b], S. Tahri [a], O. Acosta [a], R. De Crevoisier [a], C. Lafond [a], A. Barateau [a]

[a] Univ. Rennes 1, CLCC Eugène Marquis, INSERM, LTSI - UMR 1099, F-35000 Rennes, France
[b] Developing Brain Institute, Department of Diagnostic Imaging and Radiology, Children's National Hospital, Washington, DC, USA
[c] CSIRO Australian e-Health Research Centre, Herston, Queensland, Australia





ML for MR to CT (Protons)

International Journal of
Radiation Oncology
biology • physics

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Physics Contribution

Deep Convolution Neural Network (DCNN) Multiplane Approach to Synthetic CT Generation From MR images—Application in Brain Proton Therapy

Maria Francesca Spadea, PhD,* Giampaolo Pileggi, PhD,*[,†] Paolo Zaffino, PhD,* Patrick Salome, MSc,[†] Ciprian Catana, PhD,[‡] David Izquierdo-Garcia, PhD,[‡] Francesco Amato, PhD,[§] and Joao Seco, PhD[†,||]

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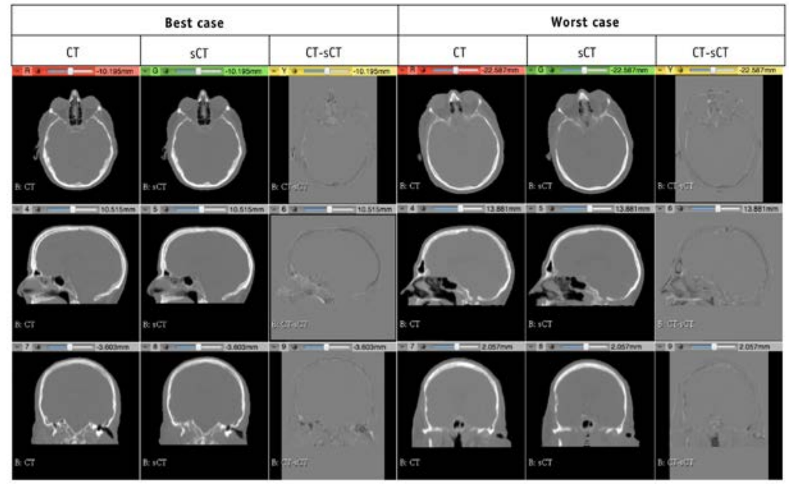
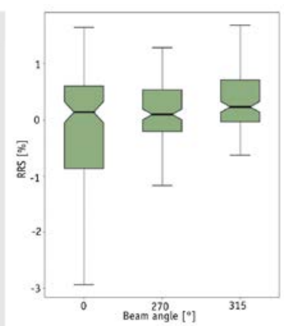
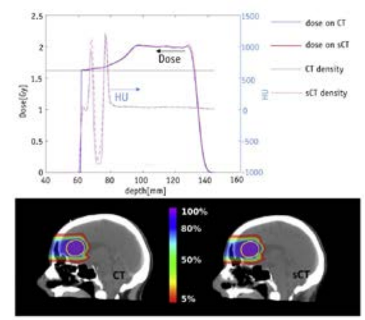


Table 1 Air, soft tissues, fat, and bone HU, MAE, ME, and DSC comparison between CT and sCT (mean ± standard deviation)

Tissue	Mean HU on CT	Mean HU on sCT	MAE (HU)	ME (HU)	DSC
Air (HU <−800)	−940 ± 14	−928 ± 18	53 ± 32	−37 ± 39	0.92 ± 0.03
FAT	−73 ± 3	−49 ± 13	44 ± 8	−4 ± 5	—
CSF	24 ± 2	28 ± 5	10 ± 3	0 ± 9	—
WM	37 ± 3	37 ± 3	6 ± 2	0 ± 4	—
GM	48 ± 4	48 ± 2	8 ± 2	0 ± 6	—
Bone (HU >200)	769 ± 71	767 ± 33	119 ± 17	20 ± 52	0.93 ± 0.02

Abbreviations: CT = computed tomography; DSC = Dice similarity coefficient; HU = Hounsfield units; MAE = mean absolute error; ME = mean error; sCT = synthetic computed tomography.





ML for CBCT to CT

ScatterNet: A convolutional neural network for cone-beam CT intensity correction

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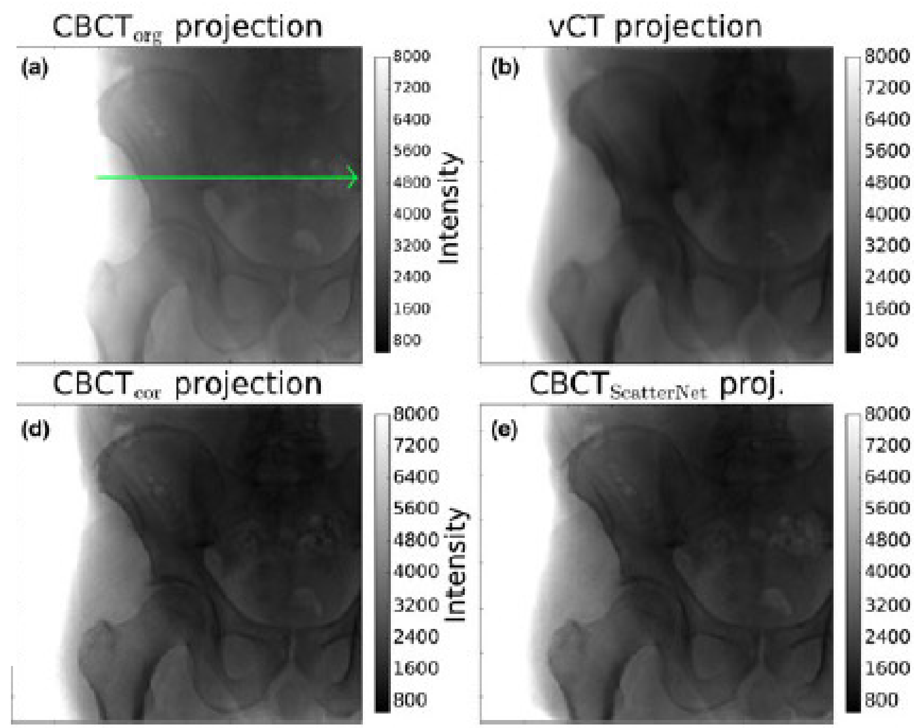
(Received 1 May 2018; revised 5 July 2018; accepted for publication 29 August 2018; published 8 October 2018)



*Highlighting few of many publications. Many groups have published ML algorithms for CBCT correction, in both the projection and reconstruction domains

ML Models

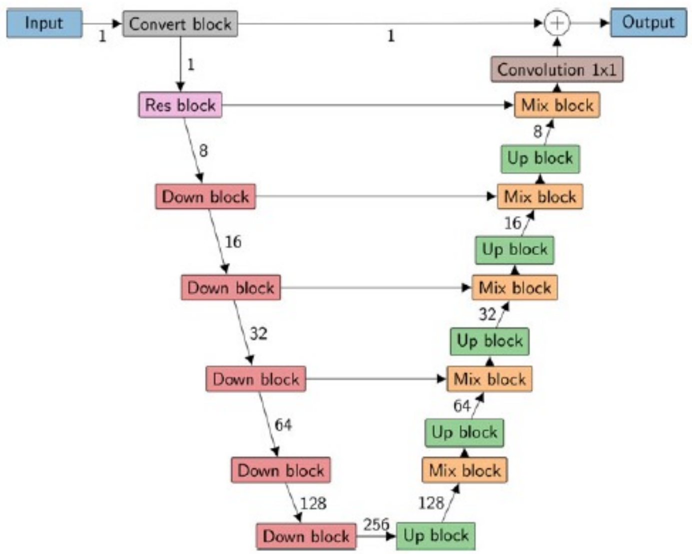
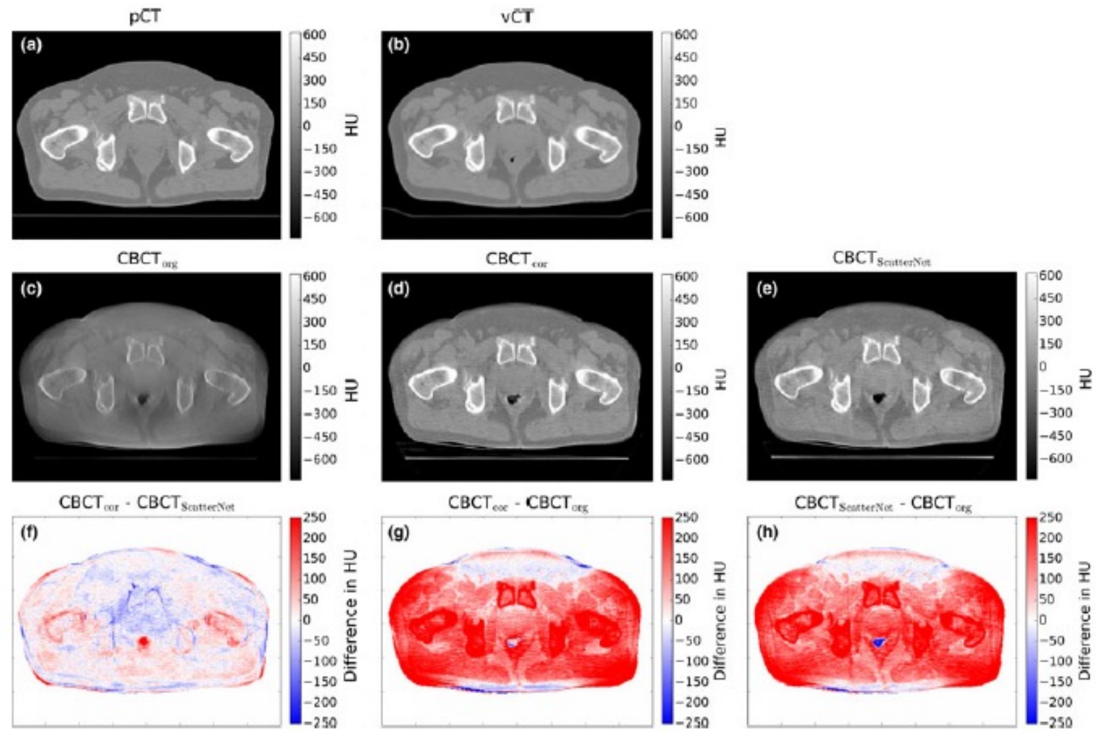
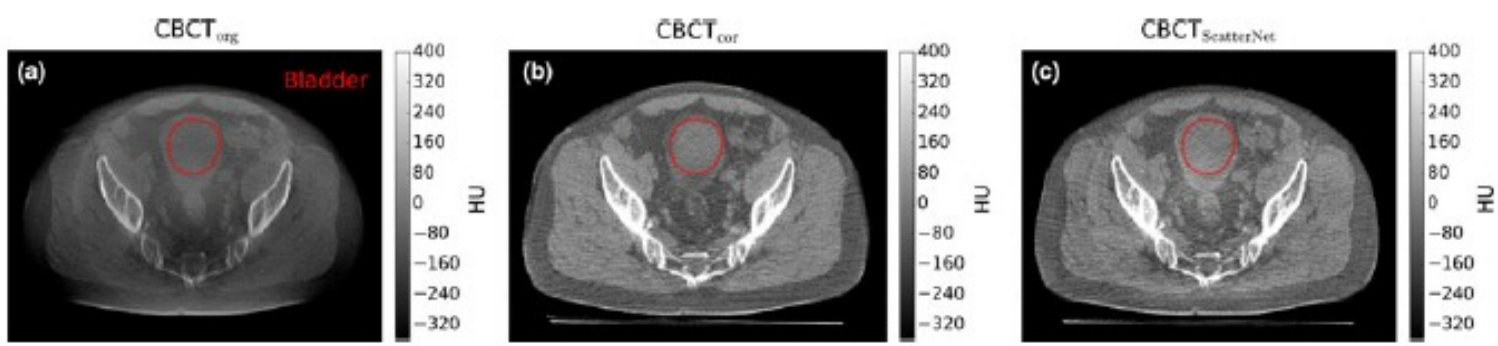


FIG. 3. The full UNet-based ScatterNet architecture. The numbers next to the lines indicate the number of channels. [Color figure can be viewed at wileyonlinelibrary.com]





Hansen *et. al., Med Phys,* 2018.

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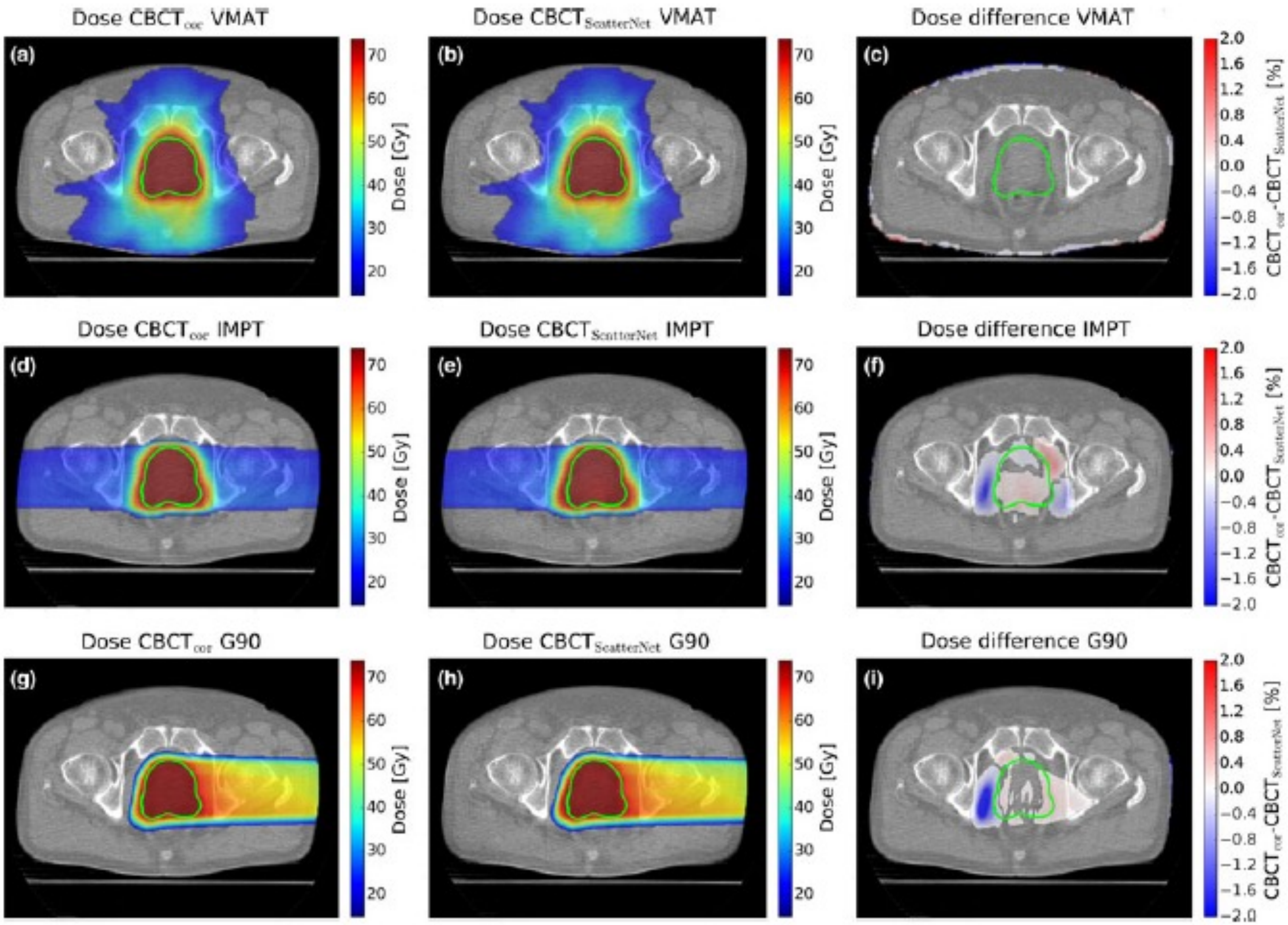
ML Models



Hansen *et. al., Med Phys,* 2018.

ML Models

Evaluation of CBCT scatter correction using deep convolutional neural networks for head and neck adaptive proton therapy

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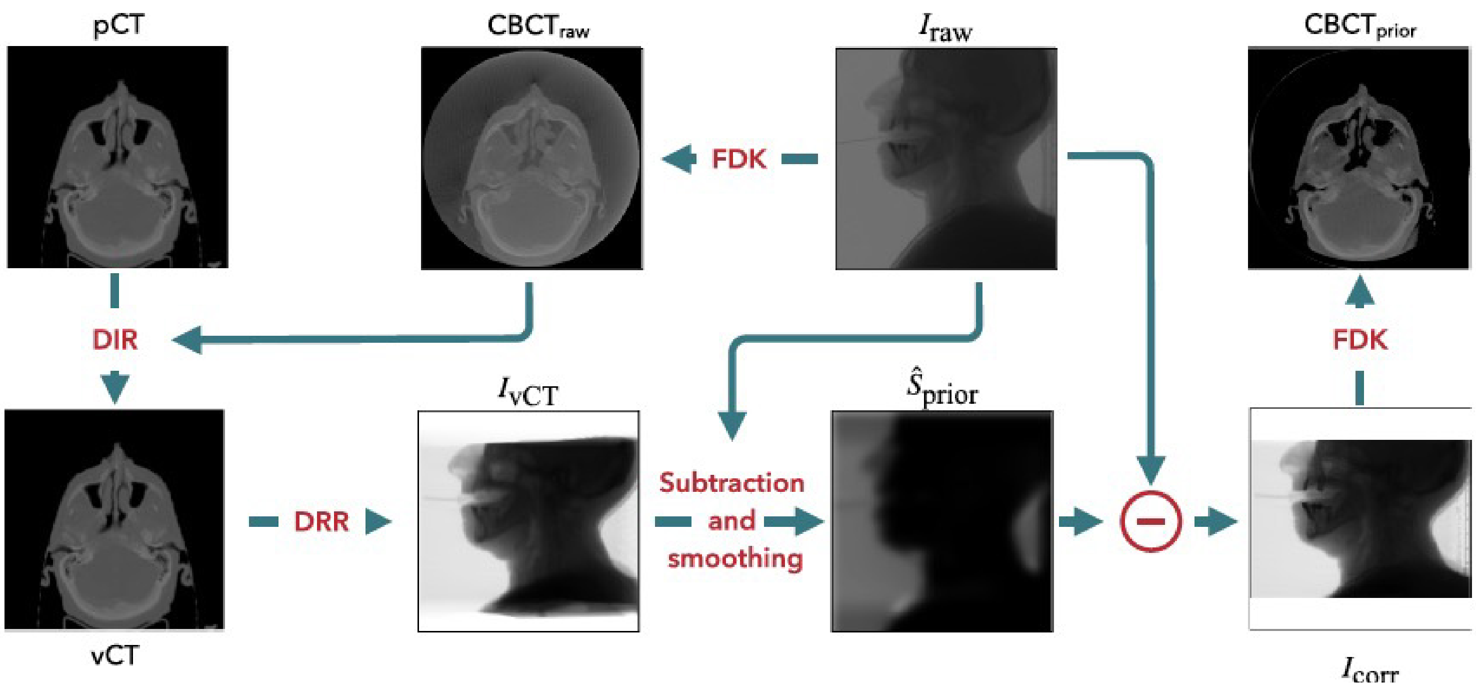


Lalonde *et. al., PMB,* 65(24), 2020.

ML Models

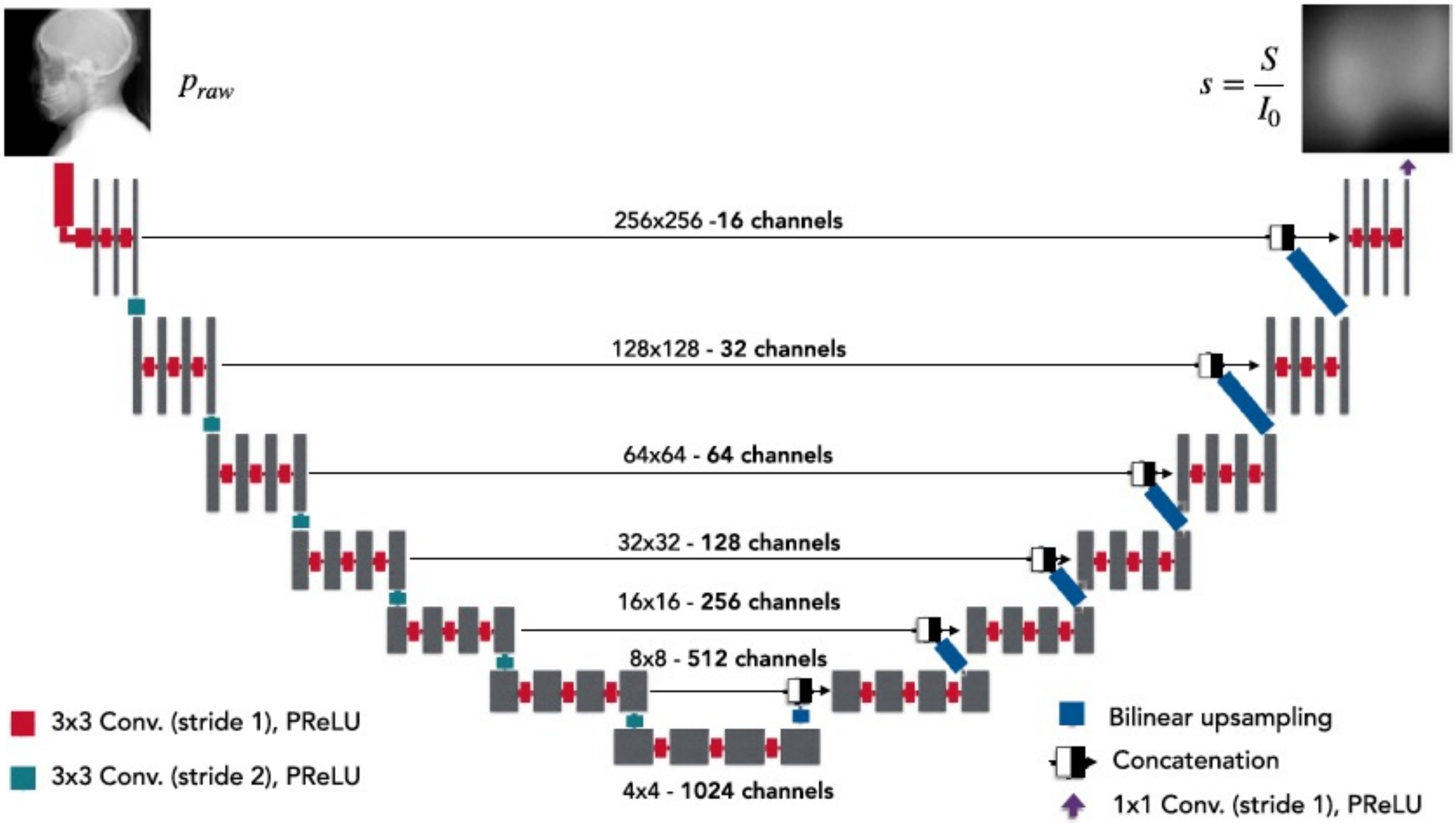
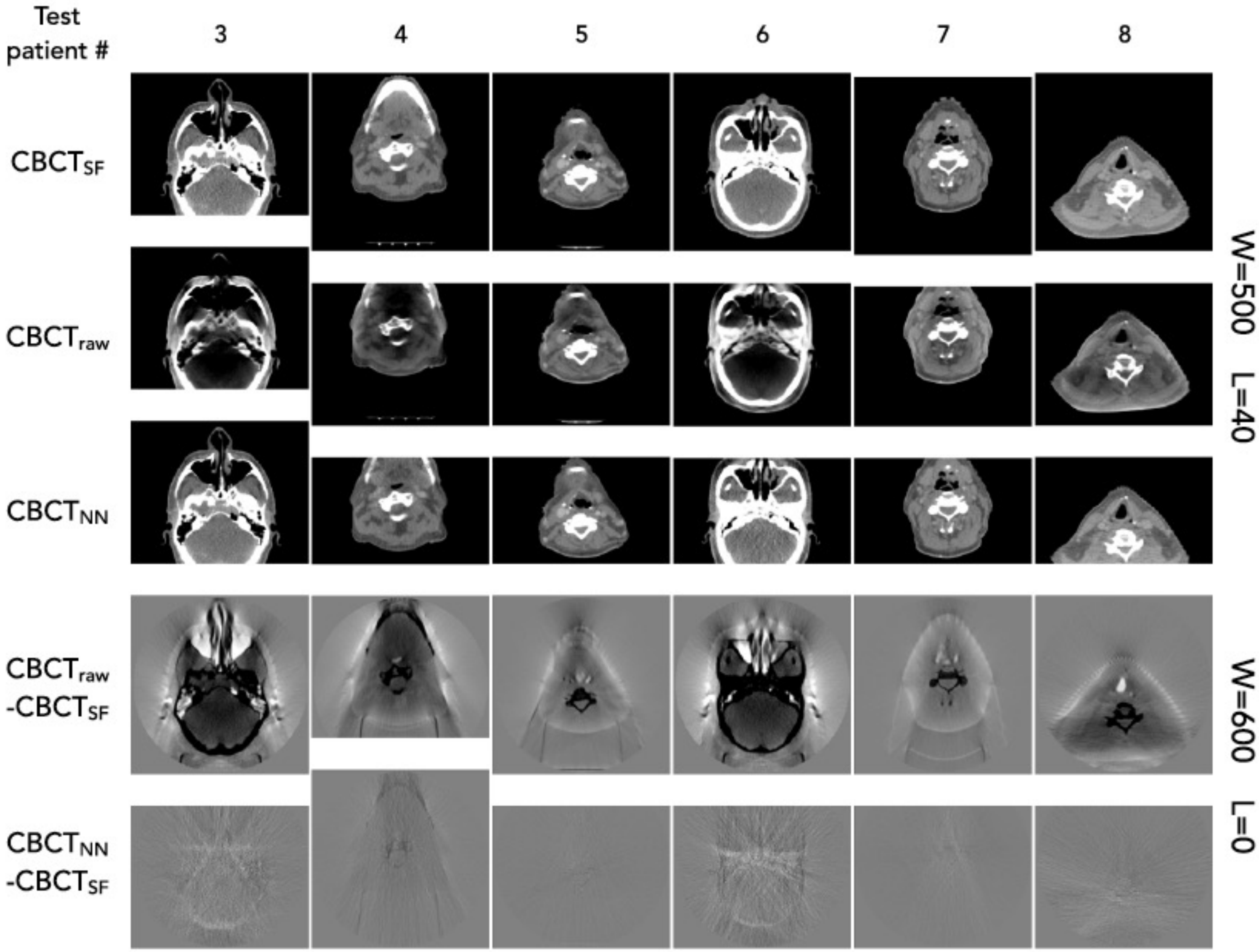


Figure 2. Deep convolutional neural network architecture used in this study.

Uses the CNN to generate the scatter estimate in the projection space instead of the reconstruction domain.

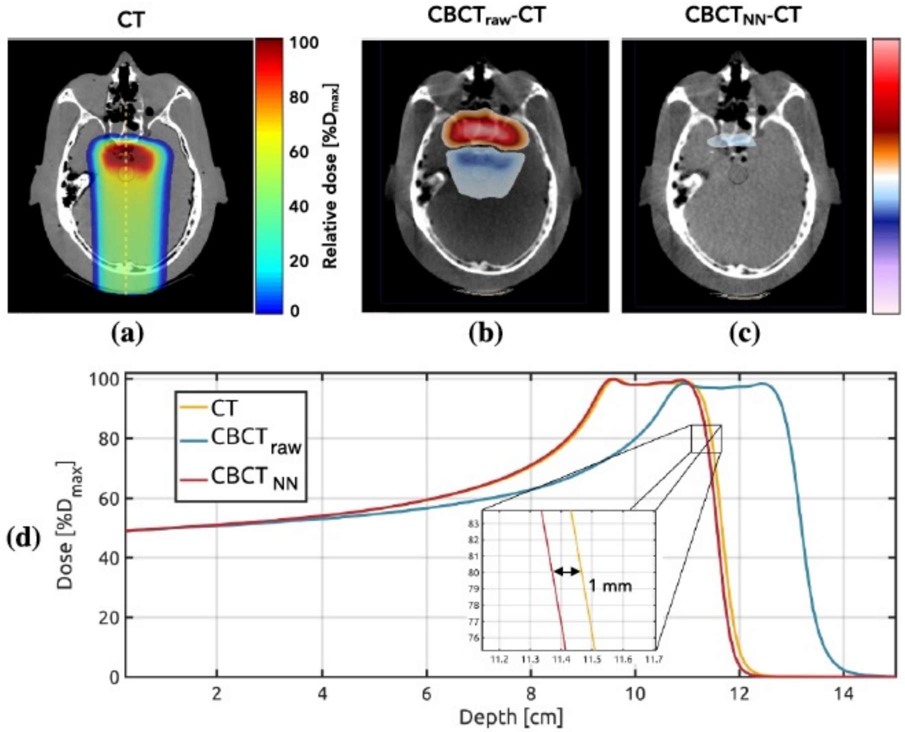
Lalonde *et. al., PMB,* 65(24), 2020.

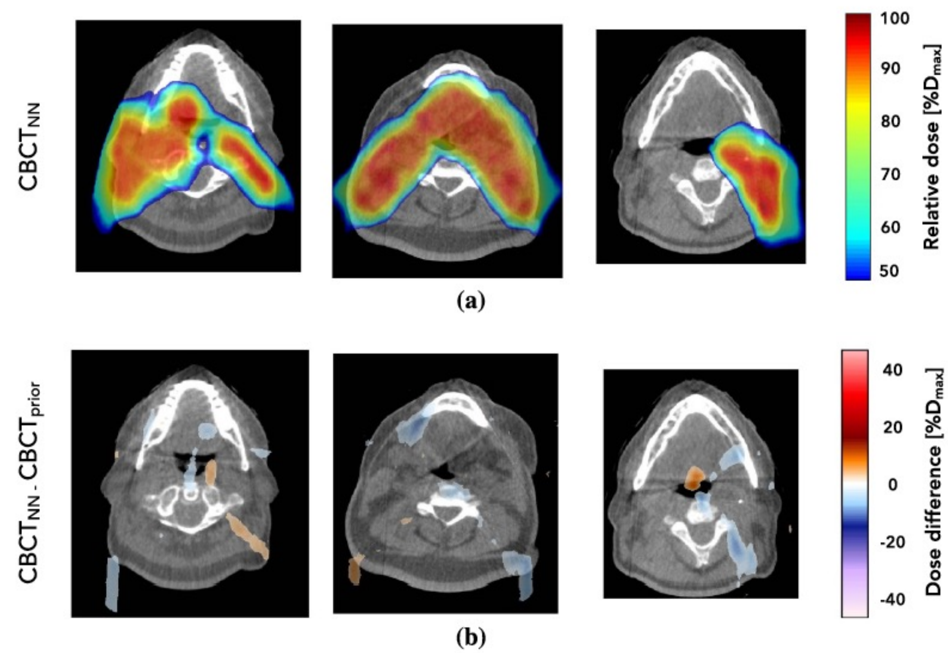
ML Models

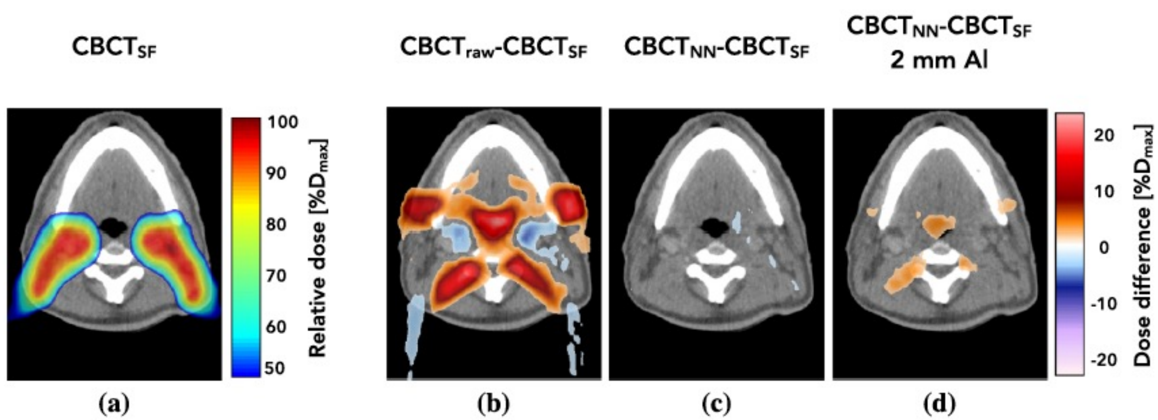


Lalonde *et. al., PMB,* 65(24), 2020.

ML Models







-Working in the projection space is more challenging to integrate into current workflows.

Lalonde *et. al., PMB,* 65(24), 2020.

Comparisons

Phys. Med. Biol. 65 (2020) 095002 https://doi.org/10.1088/1361-6560/ab7d54

Physics in Medicine & Biology

IPEM Institute of Physics and Engineering in Medicine

PAPER

Comparison of CBCT based synthetic CT methods suitable for proton dose calculations in adaptive proton therapy

Adrian Thummerer[1,7], Paolo Zaffino[2], Arturs Meijers[1], Gabriel Guterres Marmitt[1], Joao Seco[3,4], Roel J H M Steenbakkers[1], Johannes A Langendijk[1], Stefan Both[1], Maria F Spadea[2,6] and Antje C Knopf[1,5,6]

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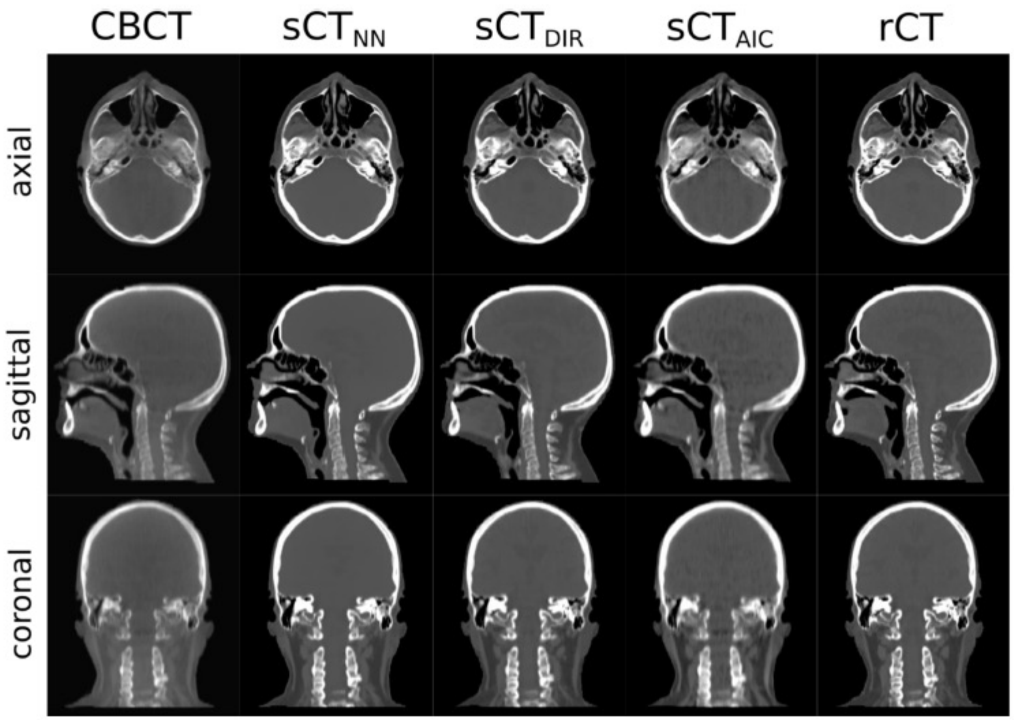
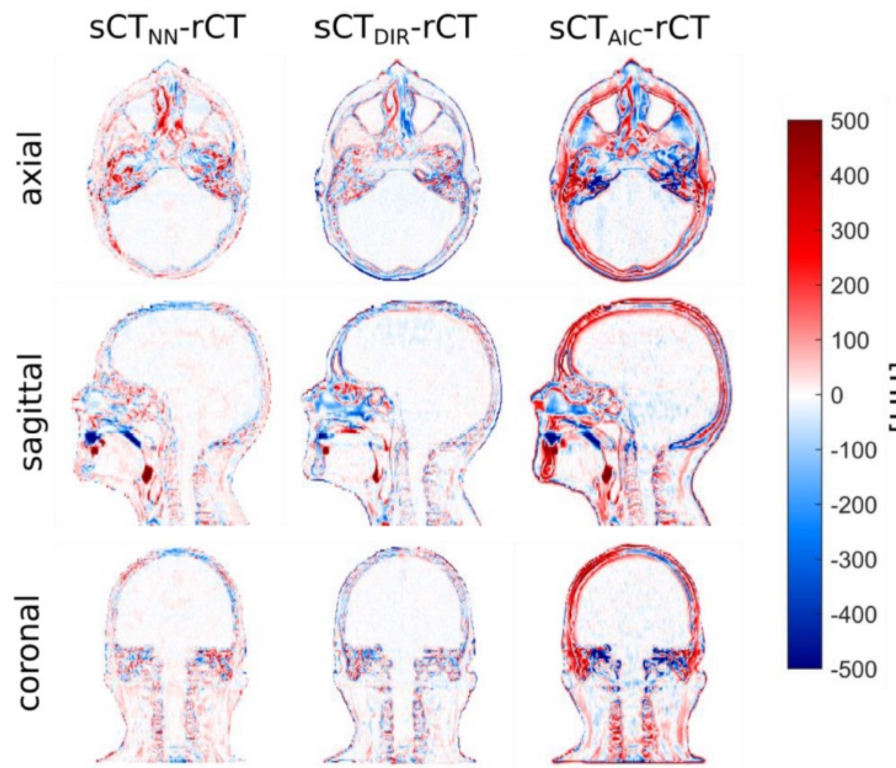
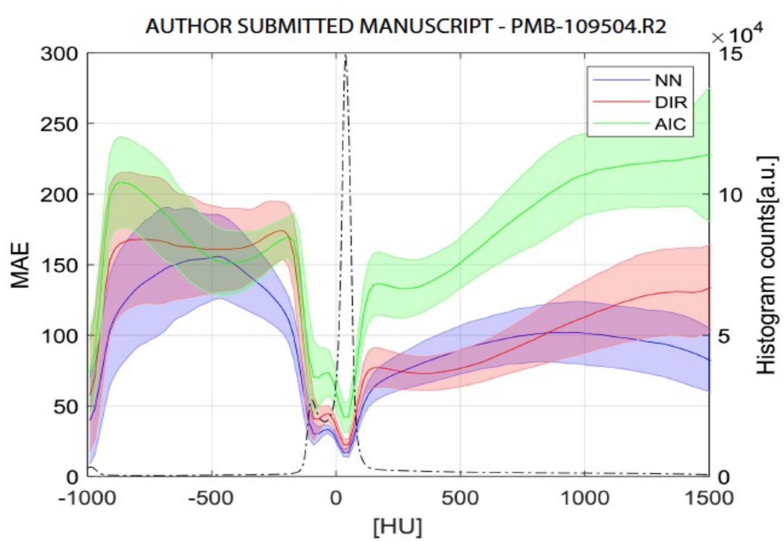
Method	Literature	Anatomical site	Suitability for proton dose calculation
LUT based correction	Kurz *et al* 2015	Head and neck	—
Histogram matching	Arai *et al* 2017	Phantoms, head and neck	—
DIR	Veiga *et al* 2015, 2016, 2017, Kurz *et al* 2015, 2016a, Landry *et al* 2015b	Lung, head and neck, pelvis	++ (H&N), + (pelvis), + (lung)
Projection-based correction	Park *et al* 2015, Kurz *et al* 2016a	Head and neck, pelvis	++
Deep convolutional neural network	Hansen *et al* 2018, Landry *et al* 2019	Pelvis	+

Thummerer *et. al., PMB,* 65, 2020.

Comparisons

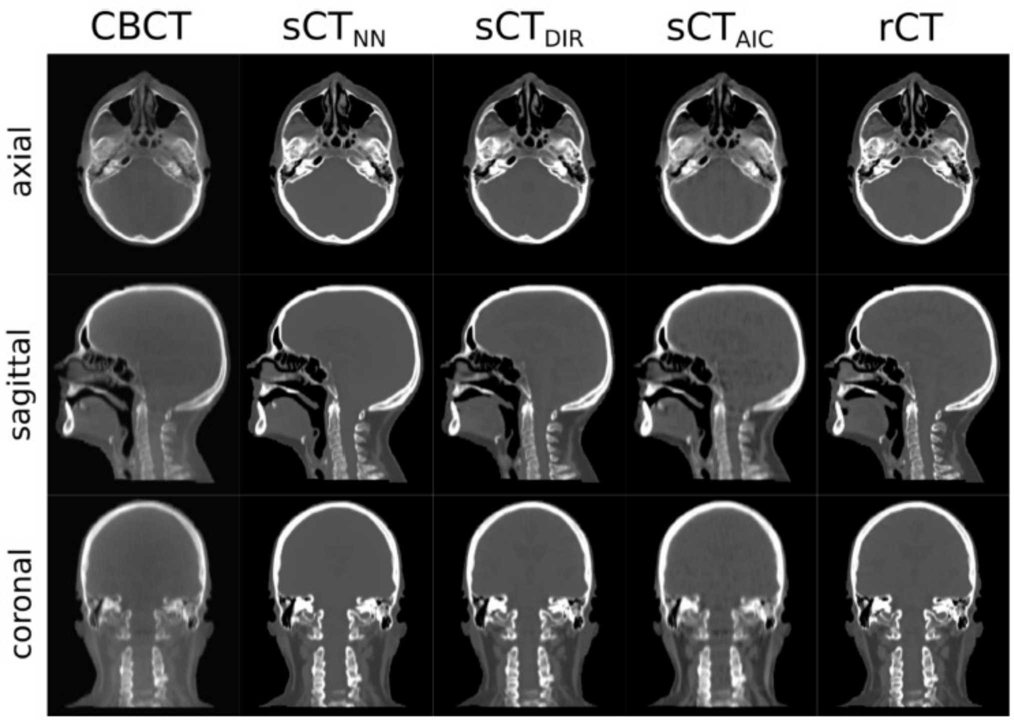


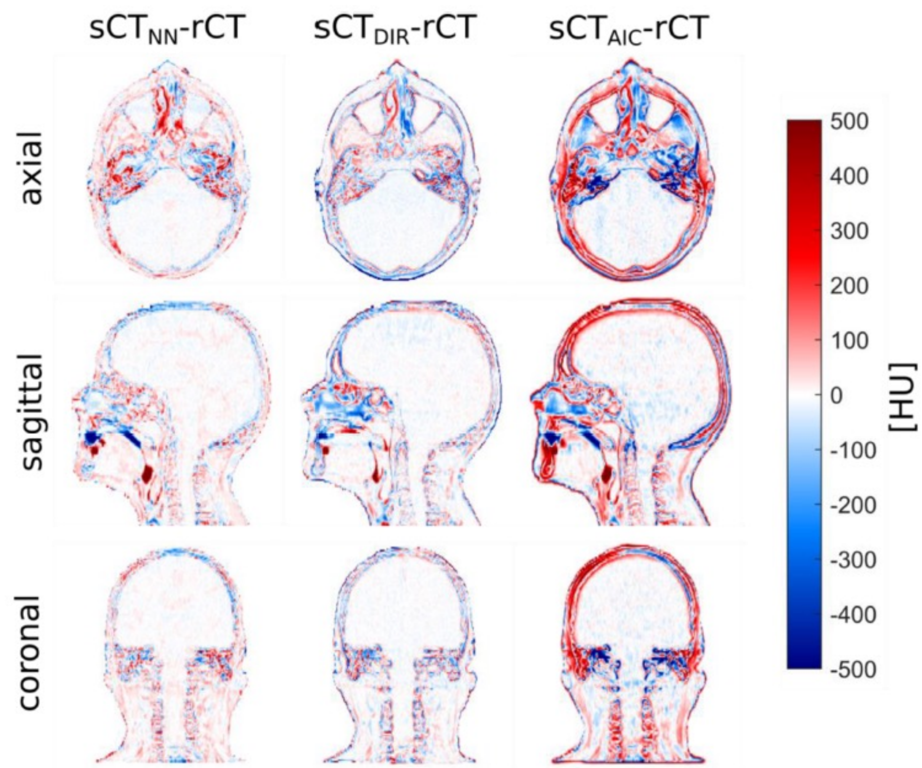


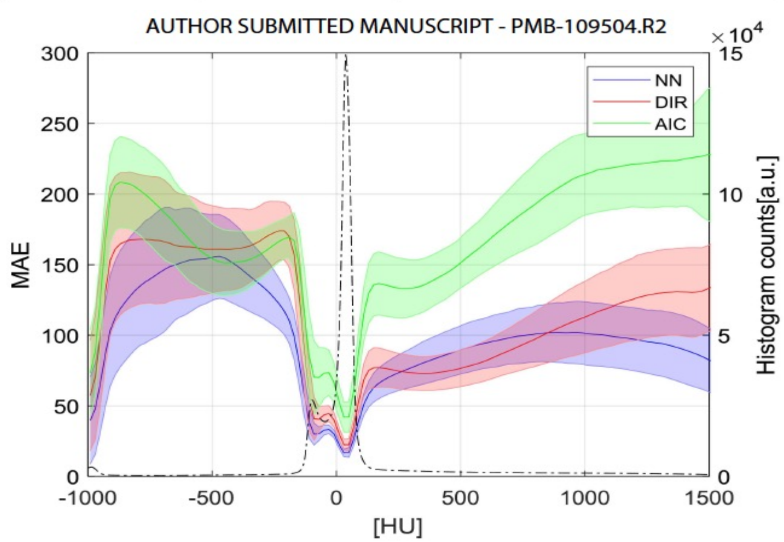


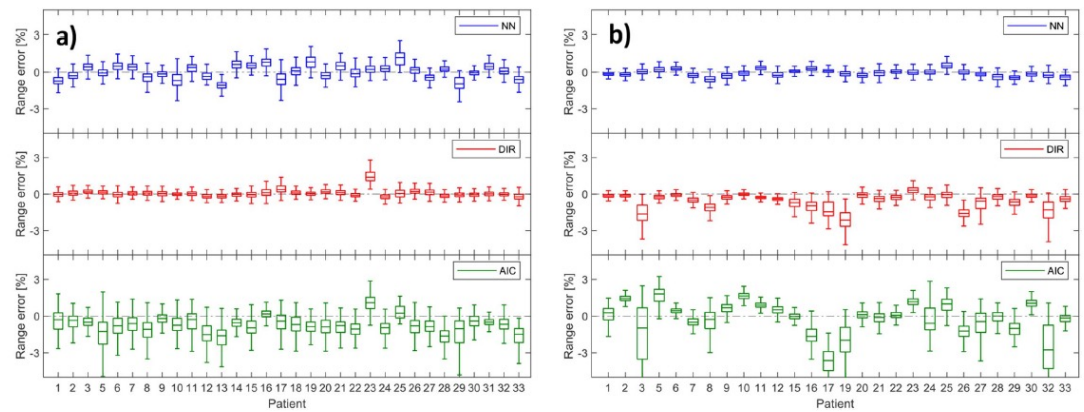
Thummerer *et. al., PMB,* 65, 2020.

More Comparisons









QA of Corrected CBCT

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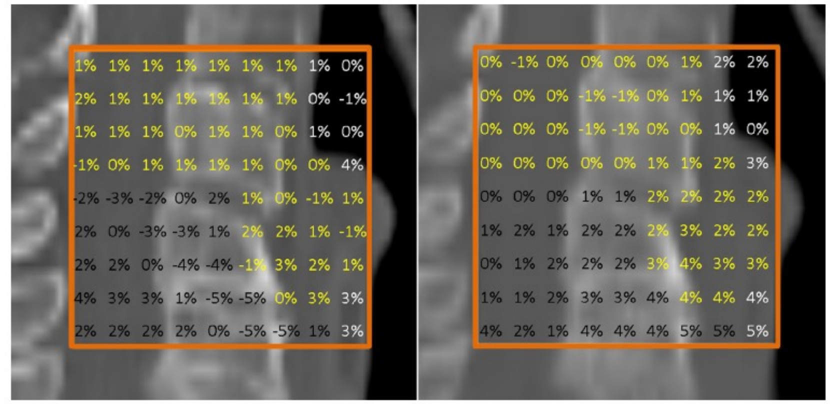
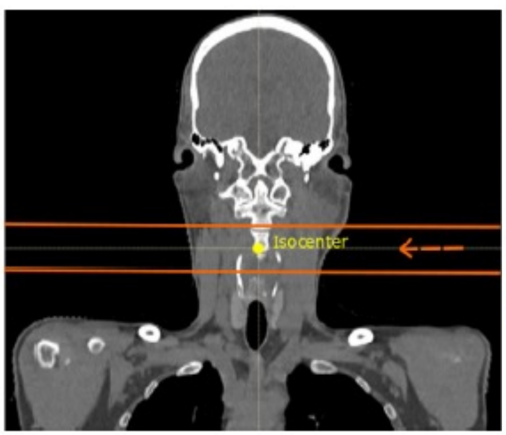
RESEARCH ARTICLE

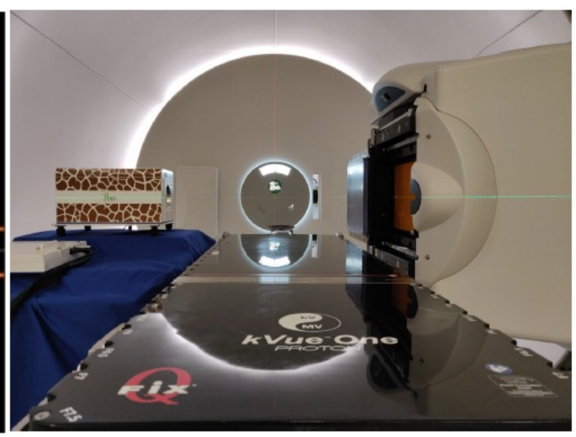
MEDICAL PHYSICS

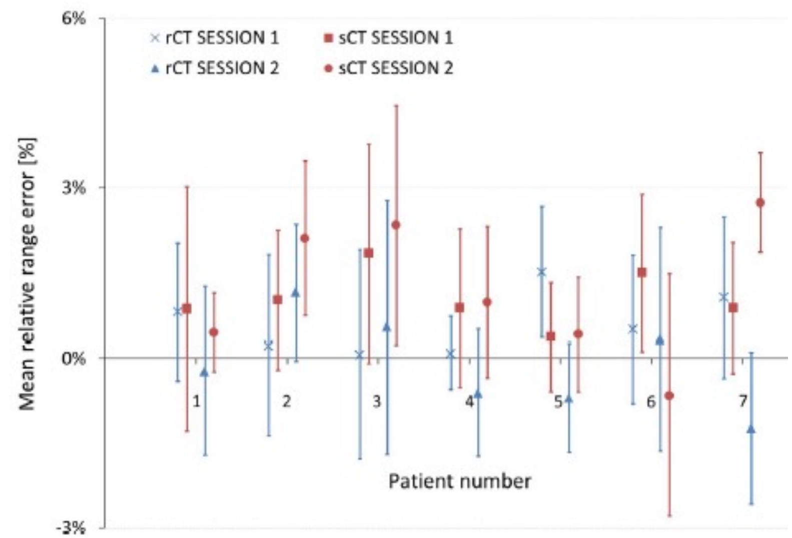
Range probing as a quality control tool for CBCT-based synthetic CTs: In vivo application for head and neck cancer patients

Carmen Seller Oria | Adrian Thummerer | Jeffrey Free | Johannes A. Langendijk | Stefan Both | Antje C. Knopf | Arturs Meijers









QA of Corrected CBCT

Measurement-based range evaluation for quality assurance of CBCT-based dose calculations in adaptive proton therapy

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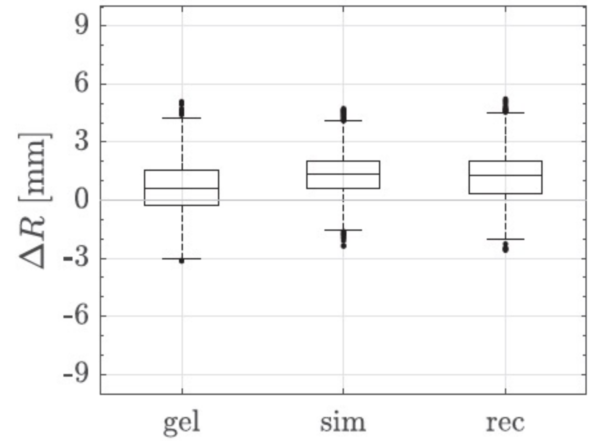
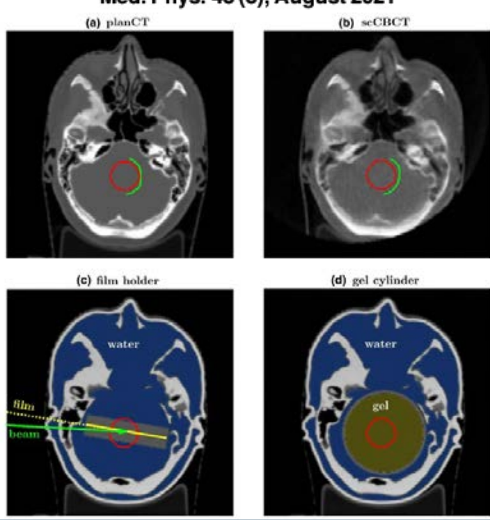
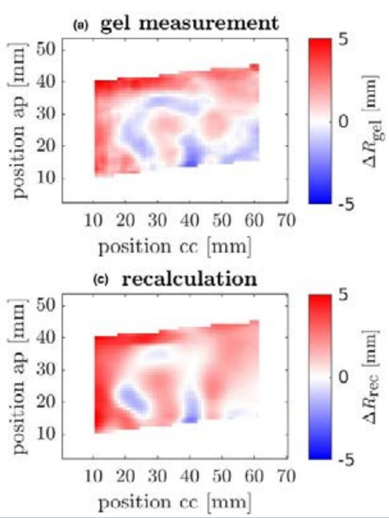
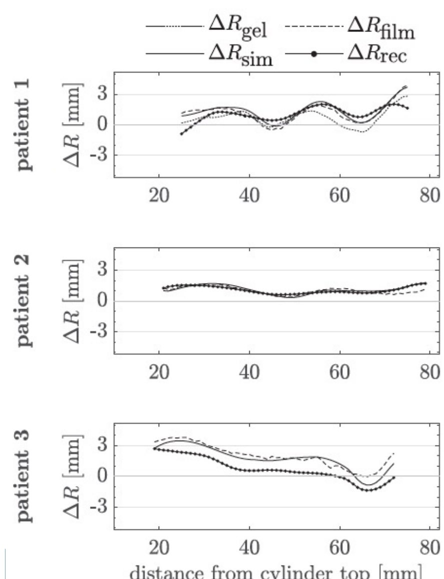
Med. Phys. 48 (8), August 2021









5. CONCLUSIONS

A novel measurement-based evaluation of a scatter corrected CBCT workflow for online adaptive proton radiation therapy was introduced. The evaluation of CBCT image data for proton planning using gel dosimetry showed that the observed range differences agreed well with the expected values from TPS recalculations and optimizations. It is thus an interesting candidate for measurement-based quality assurance of online adaptive proton therapy. The evaluated CBCT correction method seems to be suitable for proton dose calculation. Film measurements provided an additional benchmark in dedicated slices and supported the results obtained with the gel measurements. 98.5% of the range differences observed with the gel measurement agreed with the *simulation approach* within 2 mm. Further studies are needed to evaluate the *measurement*-based *approach* for more patients and preselected beam directions. A development of a 3D printed phantom for other body regions potentially including anatomical variations would make the method applicable for more treatment sites.

Motion?

Synthetic Imaging and Motion

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PAPER

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Validation of proton dose calculation on scatter corrected 4D cone beam computed tomography using a porcine lung phantom

Henning Schmitz[1], Moritz Rabe[1], Guillaume Janssens[2], David Bondesson[3], Simon Rit[4], Katia Parodi[5], Claus Belka[1,6], Julien Dinkel[3], Christopher Kurz[1,5], Florian Kamp[1,7,8] and Guillaume Landry[1,5,8]

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Keywords: 4DCBCT, proton therapy, lung cancer, lung phantom, scatter correction, adaptive radiotherapy, motion management

Supplementary material for this article is available online

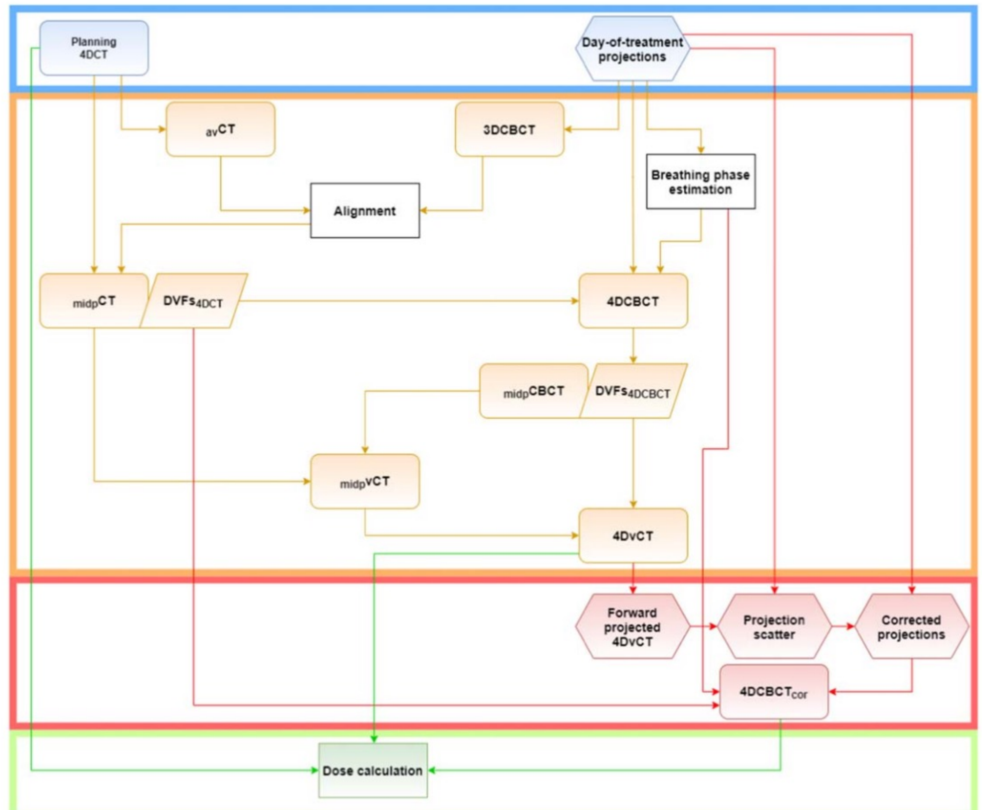

Figure 2. Sketch depicting the most important steps of the complete workflow from input (blue box), via 4DvCT (orange box) and $4DCBCT_{cor}$ (red box) to the final dose calculation (green box). Rounded rectangles show images, hexagons represent projections, rectangles stand for actions, and parallelograms for DVFs.

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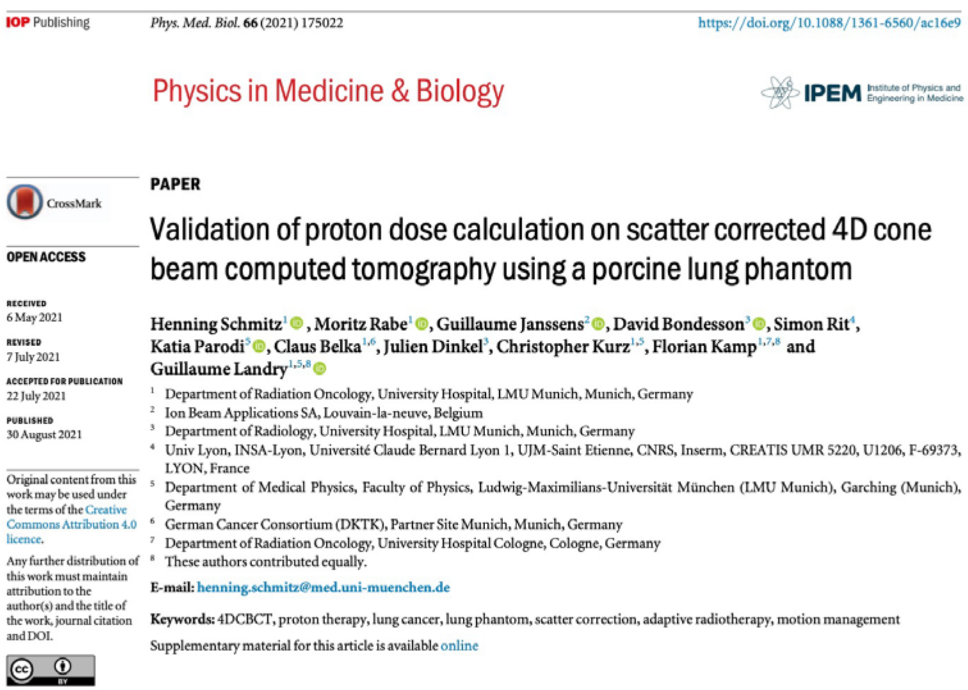
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PAPER

Validation of proton dose calculation on scatter corrected 4D cone beam computed tomography using a porcine lung phantom

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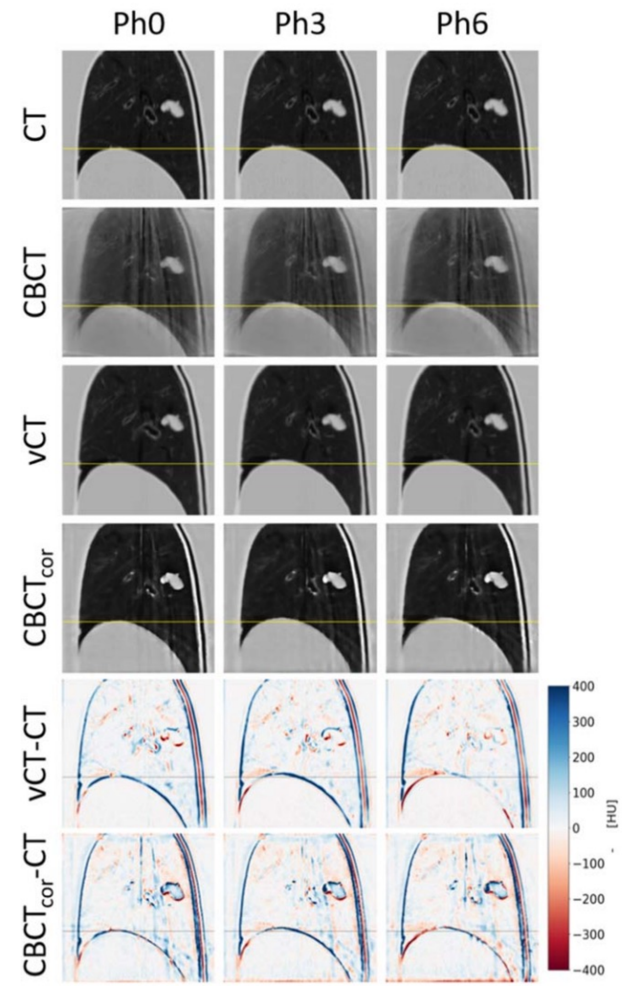

Figure 4. Phase 0 (inhale), phase 3 and phase 6 (exhale) are shown with level = −300 and window = 1600 for 4DCT, 4DCBCT, 4DvCT and 4DCBCT$_{cor}$. Additionally, the differences 4DvCT-4DCT and 4DCBCT$_{cor}$-CT are displayed.

Synthetic Imaging and Motion

Zhang *et al. Visual Computing for Industry, Biomedicine, and Art* (2019) 2:23
https://doi.org/10.1186/s42492-019-0033-6

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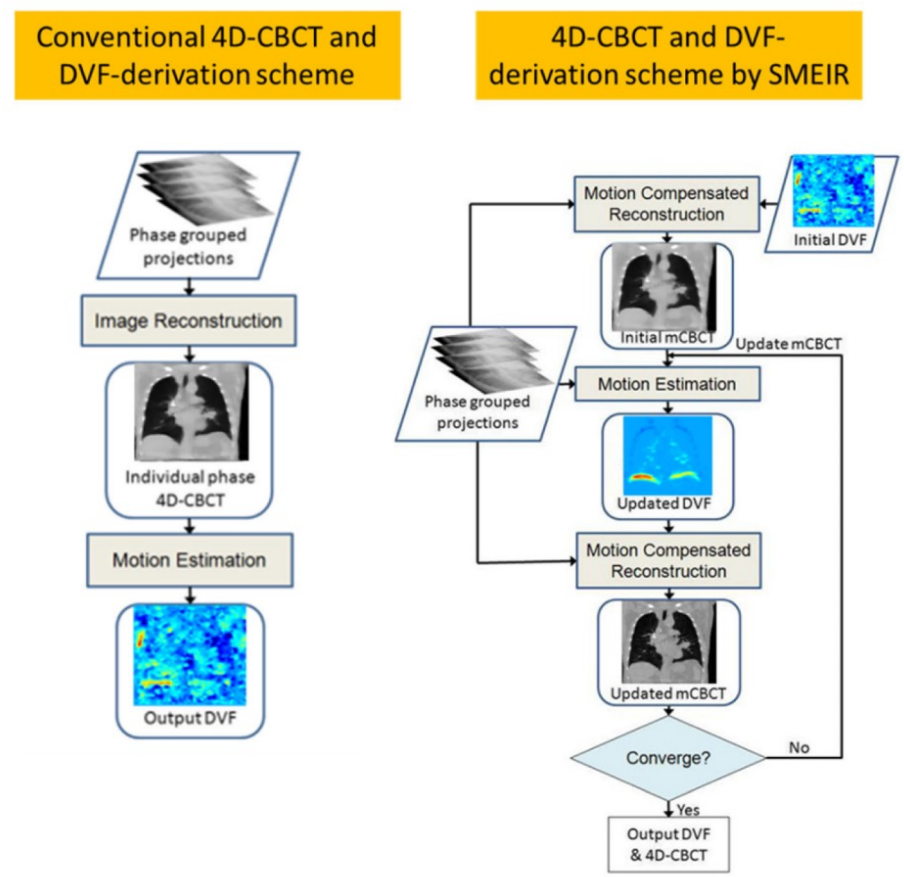
Advanced 4-dimensional cone-beam computed tomography reconstruction by combining motion estimation, motion-compensated reconstruction, biomechanical modeling and deep learning

You Zhang*, Xiaokun Huang and Jing Wang



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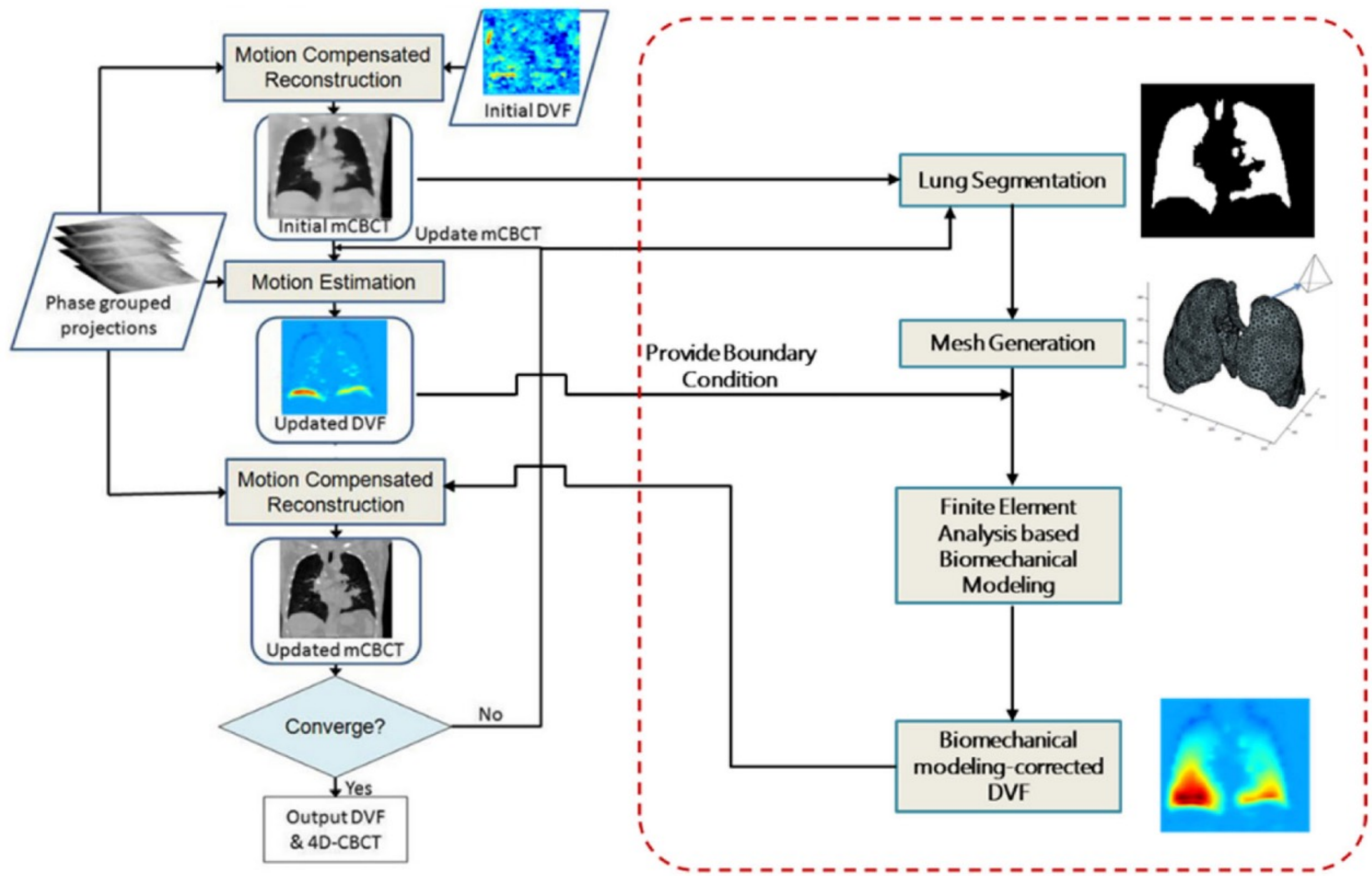

Fig. 3 The general flow of the biomechanical modeling-guided SMEIR scheme. 4D-CBCT: 4-Dimensional cone-beam computed tomography; DVF: Deformation-vector-field; mCBCT: Motion-compensated CBCT

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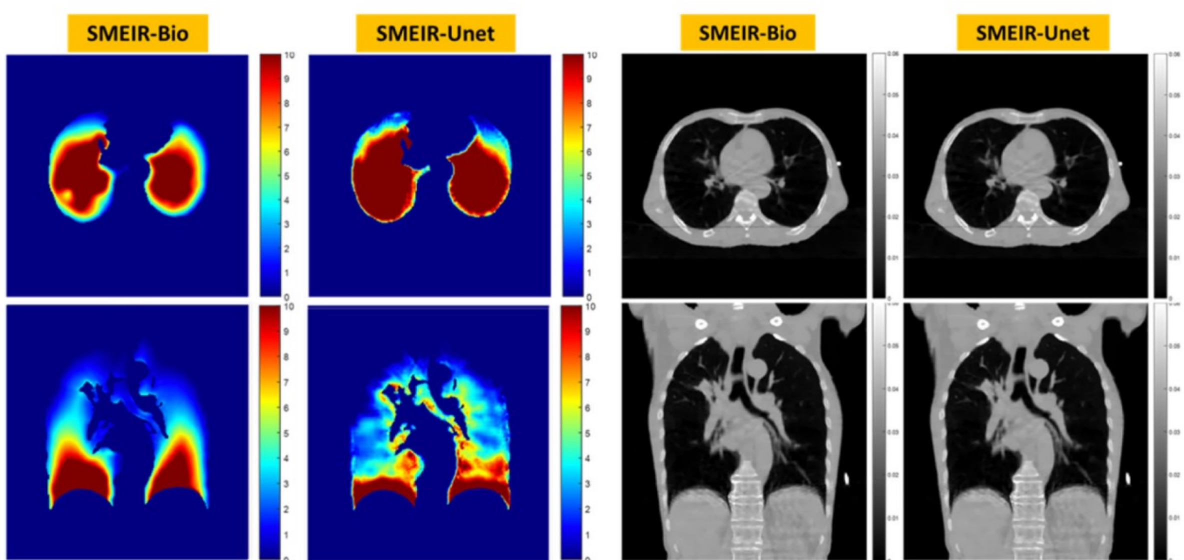

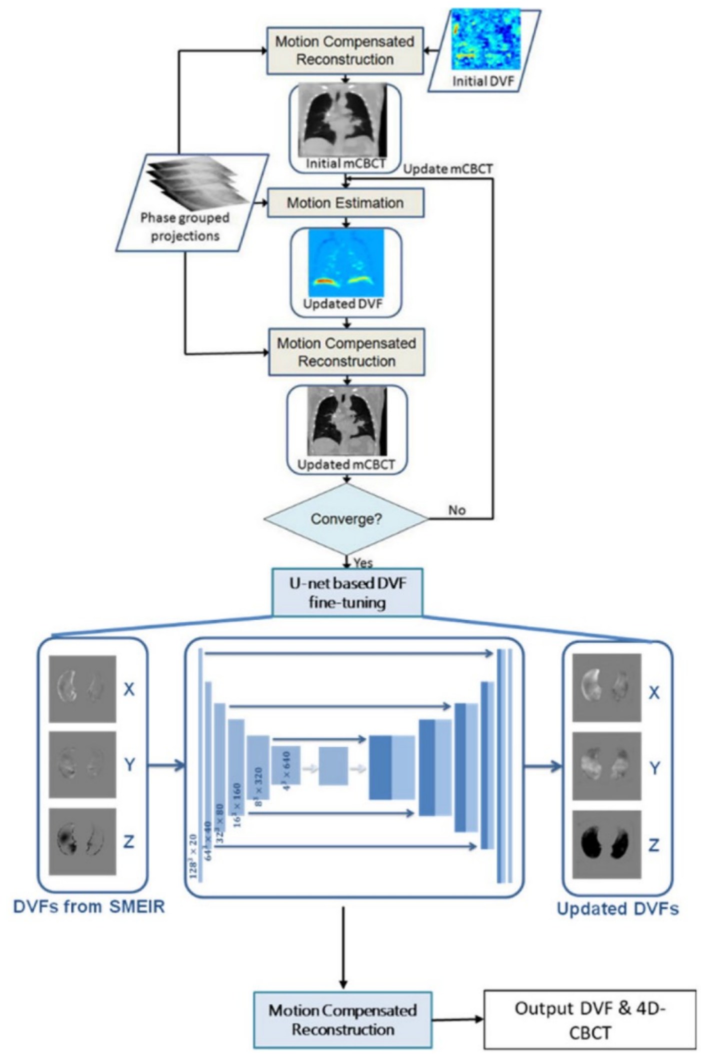

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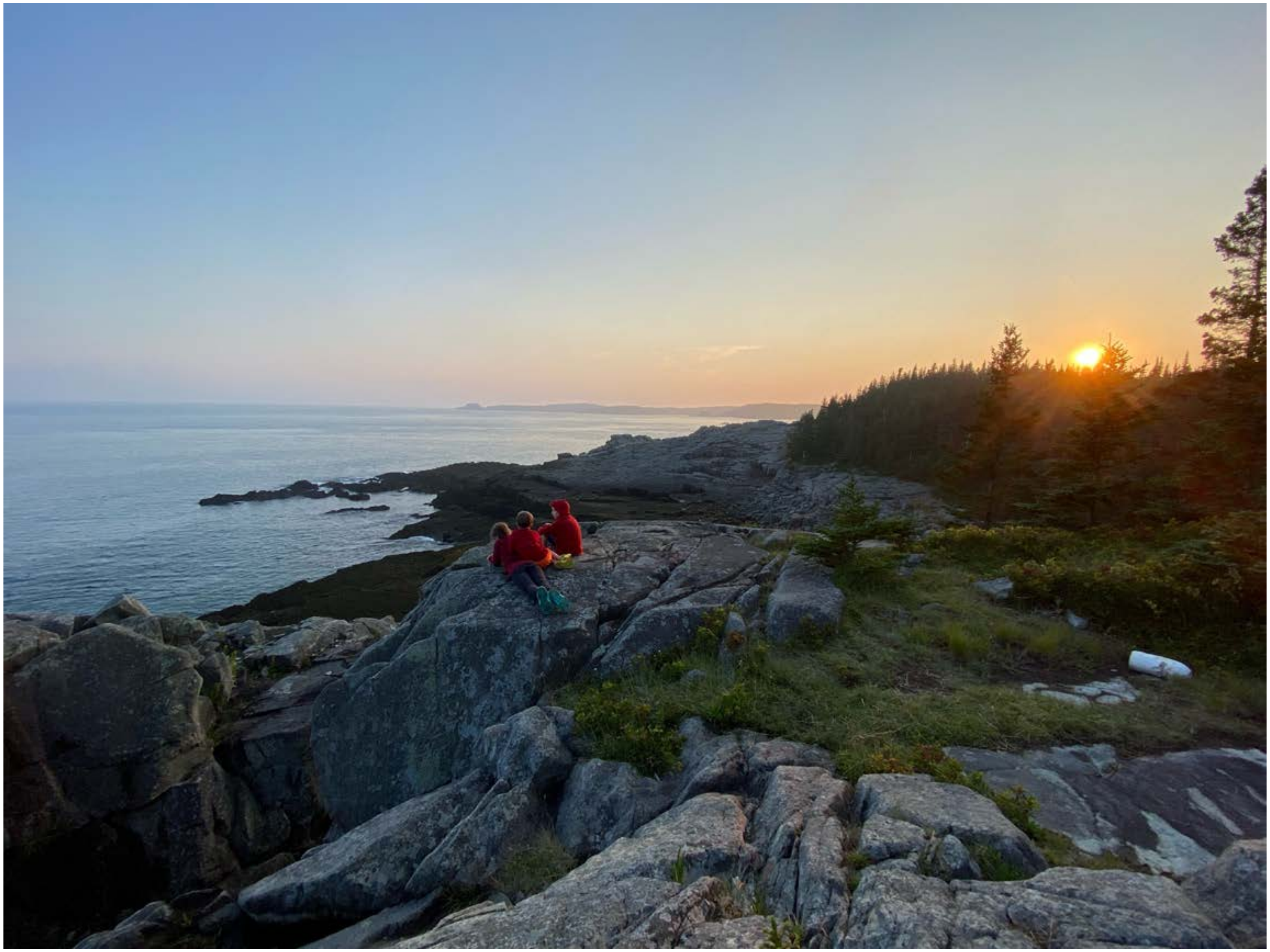

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