Deep Learning-based Synthetic CTs for CBCT-based Adaptive Proton Therapy of Lung Cancer Patients

Adrian Thummerer, PhD Candidate, University Medical Center Groningen; Paolo Zaffino, PhD; Arturs Meijers, PhD; Gabriel Guterres Marmitt, PhD; Joao Seco, Prof. Dr.; Johannes Langendijk, Prof. Dr.; Antje Knopf, Dr. rer. nat.; Maria Francesca Spadea, PhD; Stefan Both, Prof.

Introduction
Cone beam computed tomography (CBCT) images are routinely used for daily patient alignment in radiotherapy, but lack accurate CT-numbers required for proton dose calculations. CBCT images however provide daily information on patient anatomy. This is essential for adaptive proton therapy workflows, which aim at detecting anatomical changes and modifying treatment plans accordingly. Deep learning has shown to be effective in generating synthetic CT images based on CBCTs. In this study a deep convolutional neural network (DCNN) was trained to correct thoracic CBCTs. The resulting sCT was compared to a conventional CT in terms of image quality and dose calculation performance.

Hypothesis
Deep convolutional neural networks can generate CBCT-based synthetic CTs with sufficiently accurate Hounsfield-units for proton dose calculations.

Methods
The dataset used for training, validation and testing consisted of 33 lung cancer patients treated with pencil beam scanning (PBS) proton therapy. For each patient CBCT images, same-day CT scans (rCT) and clinical proton treatment plans were available. For training and evaluation, deformable image registration was used to further reduce anatomical differences between CBCT and CT. The deformed CT image was also used as reference image to evaluate image quality and dosimetric accuracy. For image quality analysis we calculated global mean absolute error (MAE), MAE for lung, heart, and target volume (GTV), and contrast-to-noise ratio (CNR) between fat and muscle tissue. For dosimetric evaluation we recalculated clinical treatment plans, performed gamma analysis, using a 3%/3mm criteria, and compared Hounsfield-unit and dose profiles.

Results
Figure 1 shows CBCT, rCT, sCT and a difference map between sCT and rCT. An average global MAE of 34.1 ± 5.5 HU was measured between sCTs and rCTs. For heart, lung and GTV, an average MAE of respectively 41.3 ± 6.6 HU, 27.51 ± 11.2 HU and 13.8 ± 2.4 HU was observed. Due to noise reduction and image smoothing, the average CNR increased from 24.1 for rCTs to 44.4 for sCTs. An average gamma pass ratio (3%/3mm) of 93.7 ± 4.8% was observed. Figure 2 shows Hounsfield unit and dose profiles for sCT and rCT along one of the beam directions.

Conclusion
Our results indicated that DCNNs can generate accurate synthetic CTs with sufficient accuracy for application in adaptive proton therapy workflows.

Statement of Impact
Deep learning based synthetic CTs are an important step towards CBCT based adaptive proton therapy and can thereby potentially benefit lung cancer patients in the future.
Figure 1: Overview of CBCT, reference rCT, synthetic CT (sCT) and HU-difference between sCT and rCT. A HU-window of 2000/0 (window/level) was used. The difference image shows HU differences between -250 and 250 HUs.
Figure 2: HU-profile of rCT and sCT (solid lines) with complementary dose profile (dashed lines) along the direction of the posterior beam. Image on the right shows the dose distribution of the posterior beam and not the entire plan. Profile location and direction is indicated by the yellow arrow.

**Keywords**
Adaptive Proton Therapy; CBCT; Synthetic CT; Deep Convolutional Neural Network