Evaluation of deep-learning based sCT derived from CBCT images with several network dimensionalities for clinical use in online adaptive radiotherapy

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PURPOSE

- Cone-beam CT (CBCT) has been widely adopted to facilitate image-guided radiotherapy (IGRT), but low image quality limits the ability to perform online adaptive radiotherapy (ART) treatment planning.
- Deep-learning networks can be used to transform CBCT images into synthetic CT-like (sCT) images with improved image quality
- sCT networks can be classified by the dimensionality of the image used to infer the output image: either 2D (slice-by-slice), 3D (volume-by-volume) or 2.5D (slice-by-slice, but incorporating information from neighboring slices)
- This study compares the performance of 2D and 2.5D models for sCT generation to be used in performing online dose recalculation. Due to the substantially increased data needs for training and assessing 3D models, they were not assessed as part of this study.

MATERIAL & METHODS

- CycleGAN networks with both 2D and 2.5D dimensionality were trained to convert CBCT images into sCT images.
  - Each network employed a unique loss function to better produce CT-like image quality without compromising unique structures.[1]
- To evaluate the performance of the two networks, CBCT images from 20 pelvic patients were retrospectively analyzed. Performance of the sCT networks was assessed qualitatively and along three quantitative metrics:
  - **Contourability**
    - Auto-segmenting software (Contour ProtégéAI, MIM Software) was used to contour pelvic structures on both sCT and corresponding planning CT (refCT) images.
    - Reference contours for the sCT images were created by a physician who corrected the auto-segmented contours on the sCT 2D image.
    - RefCT reference contours were based on the clinically-approved contours.
    - Auto-segmentation accuracy was assessed using mean distance-to-agreement (MDA) and dice similarity coefficient (DSC).
  - **HU value accuracy**
    - Mean HU values for each contoured structure were compared between each sCT image and the corresponding refCT image.
  - **Dose calculation accuracy**
    - A Monte-Carlo algorithm (SciMoCa, Radiologica) was used to recalculate the treatment plan on each refCT and sCT image.
    - Calculated sCT doses were compared to recalculated refCT doses using 3D global gamma analysis with 3%/2mm and 1%/2mm criteria.

RESULTS

- The 2D sCT model shows blurring and streaks caused by inconsistent soft tissue boundaries between adjacent slices. The 2.5D improves the organ boundary consistency (**Figure 1a**) which helps reduce the severity of extreme contouring outliers (**Figure 1b**).
- **Contourability**
  - Both sCT models showed generally excellent auto-segmentation accuracy. Average MDAs and DSCs were each comparable or higher for sCT contours than the corresponding refCT contours (**Figure 2**).
- **HU value accuracy**
  - Differences in mean HU values between the refCT and each sCT were generally within 30 HU for soft tissues and 50 HU for bony structures, as specified by TG-179 (**Figure 3**). Exceptions were the small bowel, colon, and rectum, which showed highly variable gas content.
- **Dose calculation accuracy**
  - Gamma analysis of treatment doses calculated on the sCT images showed overall high agreement with the recalculated refCT doses (**Figure 4**). Mean gamma pass rates for the sCT doses were 99.5±0.5% for the 3%/2mm criterion and 97±2% for 1%/2mm, comparing favorably with previous results.[2]

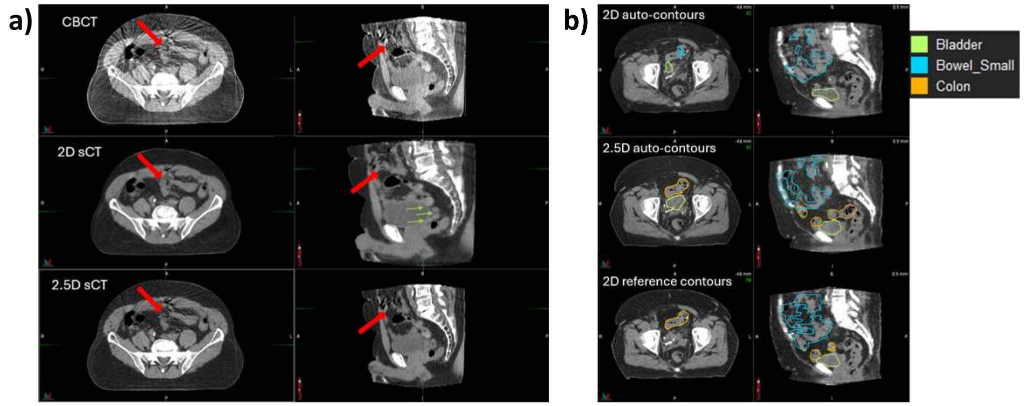

Figure 1. Axial and sagittal views of two example patients. **(a)** The 2D sCT model (middle row) hallucinated a one-slice loop of bowel (red arrows) and showed slice-by-slice inconsistencies in the bladder/rectum boundary (green arrows). The 2.5D model (bottom row) improved these slice-based anatomical inconsistencies to more accurately reflect the clinical CBCT (top row). **(b)** Auto-segmentation on the 2D sCT (top row) is hindered by slice-based inconsistencies that blur the bladder-colon boundary and obscure the small bowel. The 2.5D model (middle row) mitigates against these extreme segmentation failures by correcting these slice-based inconsistencies. W/L: 350/-50 HU (CBCT), 400/40 HU (sCT)

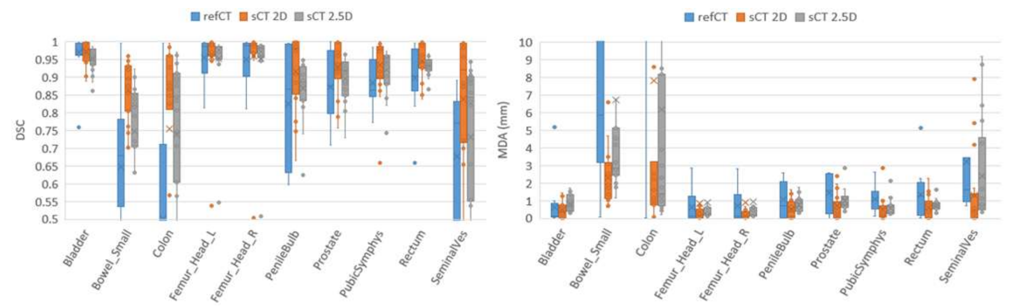

Figure 2: DSC and MDA distributions for refCT and sCT auto-segmented contours. Colon and Small bowel, both mobile structures with variable gas content, required the most physician contour adjustment.

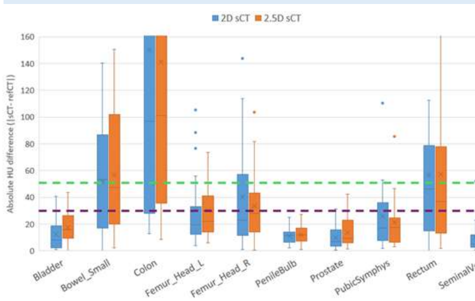

Figure 3: Absolute deviations in mean CT number between sCT structures and corresponding refCT structures for 2D and 2.5D models. The bowel, colon, and rectum, have highly variable gas content, leading to day-to-day inconsistency in mean CT numbers. Dashed lines show the AAPM TG-179 tolerances for soft tissue (purple) and bone (green). sCT models were statistically similar (p > 0.25)

Figure 4: Gamma analysis results for doses calculated on sCT images compared to refCT images. Per AAPM TG-132, a 95% gamma pass rate is considered ideal for the 3%/2mm criterion. For the tighter 1%/2mm criterion, the action limit of 90% is used as an acceptability threshold. sCT models were statistically similar (p > 0.74).

CONCLUSIONS

The 2.5D sCT model produced notable qualitative improvements over the image quality of the 2D sCT model. The reduction of streaks and boundary inconsistencies reduced the extreme failures of the sCT images, which would contribute to improved consistency in online ART workflows.

REFERENCES

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