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Evaluation of a Localized Correlation Based Predictive Metric as a Decision Making Tool in Online Image Guidance and Offline Adaptive Prostate Radiotherapy

Arun Gopal, Baoshe Zhang, Giovanni Lasio, Sung-Woo Lee, Byong Yong Yi

Department of Radiation Oncology, University of Maryland School of Medicine, Baltimore, MD

UNIVERSITY of MARYLAND SCHOOL OF MEDICINE

BACKGROUND

Prostate radiotherapy has benefitted greatly from the use of cone-beam CT (CBCT) based image guidance for accurate target localization. However, it is often challenging to accurately visualize the prostate due to poor soft-tissue contrast, especially in the absence of fiducial markers. In addition, bladder and rectal filling may be inconsistent from the treatment planning geometry, which can lead to target deformation as well as increased organ at risk (OAR) toxicities. The aim of this study is to extend CBCT imaging from mere target localization to more advanced quantitative imaging metrics that can allow better online 3D matching, as well as provide a predictive tool for offline treatment adaption based on observed deviations during treatments.

METHODS

A retrospective sample of 15 low to intermediate risk prostate cancer patients was selected that received a standard fractionation regimen (75 – 81 Gy to the prostate and proximal seminal vesicles at 1.8 – 2 Gy/fx) with daily CBCT image guidance (no fiducial markers). An automated scripting interface (figure 1) was developed in-house within the treatment planning system (Raystation 8A,RaySearch Laboratories, Stockholm, Sweden) to query and retrieve CBCT images from the record and verify (R&V) repository along with their online match registration vectors for automatic dose calculations[1]. A combination of rigid registration, deformable registration, and atlas based segmentation (ABS) was used to propagate contours for the clinical target volume (CTV), planning target volume (PTV), and the rectum from the treatment planning CT to each CBCT dataset. The contours were reviewed and manually adjusted as needed. A Pearson Correlation Coefficient (PCC) metric (see equation 1 below) was evaluated for voxels within the PTV between the first CBCT and all subsequent CBCT images to monitor inter-fraction variations in Hounsfield unit (HU) intensities in the PTV due to set-up errors or inconsistent rectal filling. For each patient, the observed trends in the PCC data was compared to inter-fraction variations in dosimetric parameters for the CTV and PTV (D90 and D95) and for the rectum (V70).

$$r_{ijk} = \frac{\sum_x \sum_y \sum_z [f(x+i,y+j,z+k)-\bar{f}][g(x,y,z)-\bar{g}]}{\sqrt{\sum_x \sum_y \sum_z [f(x,y,z)-\bar{f}]^2}\sqrt{\sum_x \sum_y \sum_z [g(x,y,z)-\bar{g}]^2}}$$

Where $r_{i,j,k}$ → sampled PCC between two distributions $f(x,y,z)$ and $g(x,y,z)$ with respective means of $\bar{f}$ and $\bar{g}$ and the denominator terms $\sqrt{\sum_x \sum_y \sum_z [f(x,y,z)-\bar{f}]^2}$ and $\sqrt{\sum_x \sum_y \sum_z [g(x,y,z)-g]^2}$ indicate their respective standard deviations (i.e. image noise)

Equation 1: Analytical expression for three-dimensional evaluation of the PCC expressed as $r_{i,j,k}$ between the sampled data distributions given by f(x,y,z) and g(x,y,z).

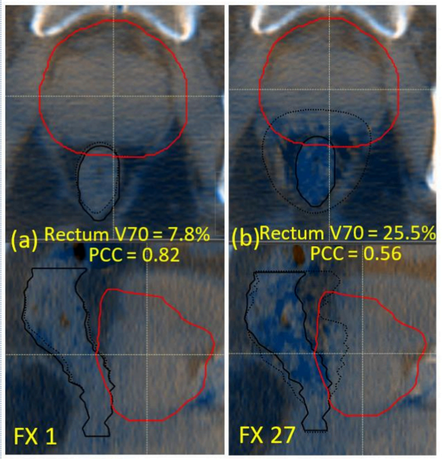

Figure 2: Sample PCC and rectum dose calculation showing reference PCC and rectum V70 metrics for fraction 1, and poor PCC and rectum V70 for fraction 27 with inconsistently large rectal filling.

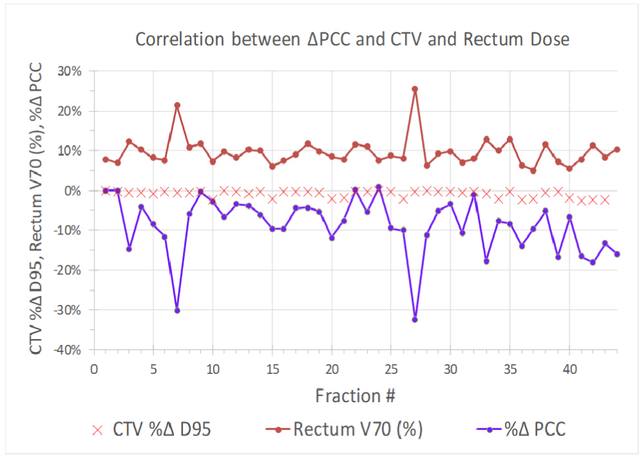

Figure 3: Inter-fraction variation in PCC is compared to the observed variation in the computed target dose (CTV D95) and the dose to the rectum (V70) for a representative patient. Variations in the CTV D95 were generally within 3%. PCC correlated well with rectum V70 as indicated in fractions 7 (set up error) and 27 (excessive rectal filling).

RESULTS

More than 500 CBCT datasets were analyzed for the 15 patients in the study (after attrition due to fractions when CBCT images were either not acquired or acquired incorrectly). The target dose metrics (D90 and D95 for CTV and PTV) showed very little inter-fraction variations for all patients in the study (ΔD90 and ΔD95 < 1% for > 50% of all fractions, and < 2% for > 90% of all fractions). In contrast, the rectum V70 showed significant inter-fraction variations (3 – 50%). The PCC calculated with the PTV for all patient fractions were found to vary greatly (0.4 – 0.9) with patient geometry and the CBCT imaging system. Therefore, the relative change in PCC was monitored and compared to inter-fraction dosimetric changes. The PCC was found to change by > 20% whenever the rectum V70 increased by > 15%. Figure 2 shows a typical case of an inconsistently large rectal filling for a patient (fraction 27) compared to the reference anatomic geometry in fraction 1. This results in increased dose to the anterior rectal wall as evidenced by a 22% increase in V70 and a 32% reduction in PCC. Figure 3 shows the overall trend in PCC compared to the CTV and rectal dose for the same representative case shown in figure 2.

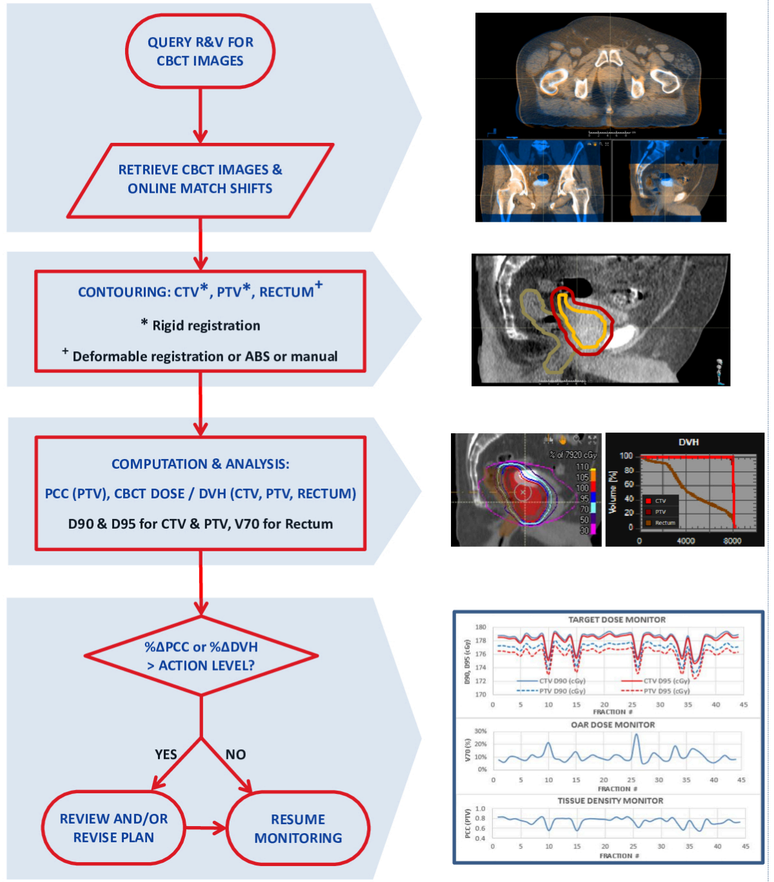

Figure 1: Flow chart describing the automated CBCT retrieval and dosimetric analysis program.

CONCLUSIONS

The minimal variation in target doses observed even in fractions where there was notable set up error or anatomic variations, can be attributed to the use of generous planning margins (8 – 10 mm) and the generally robust nature of photon dose calculations over typically observed changes in mass density in the pelvic area. However, the rectum dose was found to be quite sensitive to geometric misalignments and variable filling due to its proximity to steep dose gradients. While the PCC is desirable as a strong metric for anatomic changes, it is also easily influenced by large changes in the underlying variances in the image distributions (as indicated in equation 1). As a result, the PCC calculations were found to vary significantly between patients and between CBCT imaging systems. This is mainly due to the influence of image noise and its dependence on patient size and CBCT imaging hardware, image acquisition settings, and reconstruction parameters. Therefore, the relative change in PCC (corrected for baseline deviations across CBCT imaging systems) was monitored and compared to the target and rectum dose metrics. It was observed that a reference threshold of a 20% decrease in PCC was strongly descriptive of excessive rectum dose nominally set to ΔV70 > 15% from baseline (fraction 1). Therefore, monitoring the PCC can be highly effective as a dosimetric surrogate, both as an online metric for registration quality as well as an offline predictive metric for plan adaptation, wherein frequent incidences of low PCC can reflect the likelihood of the rectum V70 exceeding clinical tolerance.

REFERENCES

1. Baoshe Zhang, Sung-Woo Lee, Shifeng Chen, Jinghao Zhou, Karl Prado, Warren D'Souza, Byongyong Yi, Action Levels on Dose and Anatomic Variation for Adaptive Radiation Therapy Using Daily Offline Plan Evaluation: Preliminary Results. Practical Radiation Oncology, 2019 (9), pp 49 – 54