



Technical note

Using the iterative kV CBCT reconstruction on the Varian Halcyon linear accelerator for radiation therapy planning for pelvis patients

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ABSTRACT

Purpose: The ability to utilise a linear accelerators kV cone beam CT, for treatment planning and dosimetry calculation, has a number of potential uses including adaptive planning and daily dose analysis. This work validates the use of the iterative reconstruction of the Varian Halcyon cone beam CT (iCBCT) as datasets for radiation therapy planning of pelvis patients.

Methods: A CT to electron density (ED) curve was created in the Varian Eclipse treatment planning system (TPS) using scans of a CIRS ED phantom under a variety of scattering conditions. A pelvis phantom was imaged using a diagnostic CT scanner and Halcyon iCBCT. Ten pelvis patient plans were copied onto each dataset and compared using a global 3D gamma analysis. Each patient being treated on Halcyon has a daily iCBCT, and each plan was also recalculated on their respective day 1 iCBCT dataset.

Results: 3D Gamma analysis results for the patients planned on the pelvis phantom were analysed using a 1%/1mm and 2%/2mm, 10% low dose threshold criteria. The average pass rate was $99.4\% \pm 0.2\%$. The same metrics were used to analyse the patient plans recalculated on day 1 iCBCTs. The average result for the 1%/1mm gamma analysis was $94.4\% \pm 6.1\%$, and $98.6\% \pm 2.0\%$ for 2%/2mm. A comparison of typical patient volumes showed average mean dose volume differences of $0.0\% \pm 1.4\%$, $0.0\% \pm 0.9\%$ and $1.0\% \pm 4.0\%$ for the PTV, Bladder and Rectum volumes respectively.

Conclusions: Halcyon iCBCT datasets can be used for dose calculation in radiation therapy treatment planning for pelvis patients.

1. Introduction

Utilising the on-board patient image guidance system on a linear accelerator (linac) as a substitute for a CT scan for RT planning has many potential applications in the clinic, including adaptive radiation therapy or daily dose analysis. Version 2 of the Varian Halcyon Linear Accelerator (Halcyon) (Varian Medical Systems, Palo Alto, CA, USA) is capable of image guidance using a kV cone beam CT (CBCT) that can be constructed using an iterative algorithm (iCBCT). This iCBCT is obtained using a set of pre-configured parameters [1]. There is presently no literature on the feasibility or use of this system as a substitute for conventional radiation therapy CT datasets for treatment planning purposes. However, the use of other CBCT systems has been assessed in various studies, including Varian Clinacs [2–4].

One of the main differences between the Halcyon iCBCT and a standard diagnostic CT scanner, as used for RT planning datasets is the collimation of the kV source. Most modern diagnostic CT scanners, used for radiation therapy planning, use a kV fan beam in combination and a

couch with a known pitch [5], resulting in limited scattering throughout the imaged volume. Conversely, a CBCT is, by definition, a cone beam and is known to be affected by changes in scattering conditions [6–7]. The Halcyon iCBCT is acquired with a stationary couch and is designed for pre-treatment image guidance, meaning that the consistency of Hounsfield units (HU) throughout the imaged volume needs to be assessed in varying scatter conditions.

In this study, work was carried out to determine the feasibility of the use of Halcyon iCBCT for dose calculation in radiation therapy planning, by determining the consistency of the CT number or Hounsfield units (HU) throughout the scanning volume under varying scatter conditions, and confirming the dose calculation accuracy of patient plans, using both phantom and patient datasets in the Varian Eclipse treatment planning system (TPS).

2. Materials and methods

This work comprised of three parts. The first was to establish a CT

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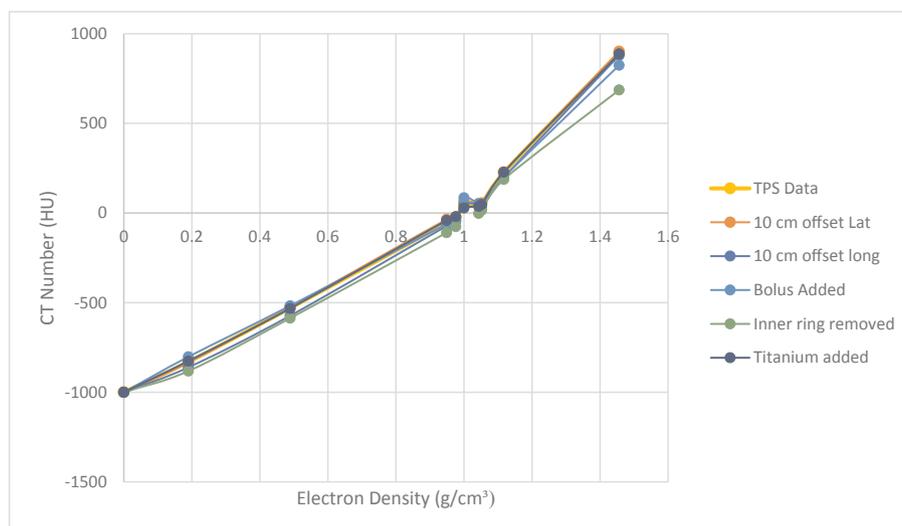


Fig. 1. CT-ED curves based on varying scatter conditions.

number to electron density (CT-ED) curve for the iCBCT ($CT-ED_{iCBCT}$) in the Varian Eclipse TPS (version 15.6.03). The second was to compare plans based on a clinical CT and iCBCT of the same phantom for comparison, and the third part was to compare clinical patient plans on their clinical, planning CT to the same plans calculated on their day 1 iCBCT.

The CT-ED curve was established using a Model 062 M CIRS electron density phantom (CIRS Tissue Simulation & Phantom Technology, Norfolk, VA, USA). From this, limitations of the application of the CT-ED curve based on changes to scatter conditions were determined. The electron density phantom consisted of two rings containing 2 cm diameter inserts representing adipose, breast, lung inhale, lung exhale, trabecular bone, dense Bone, liver, and muscle. The dense bone insert contained a 5 mm diameter insert of dense bone, surrounded by water equivalent material.

The phantom was set up on the central axis of the Halcyon, and 7 cm of solid water was added to either end of the phantom to ensure full scatter conditions were maintained for the iCBCT, and more closely simulated the patient environment. The pre-configured “pelvis” protocol (125 kV, 30 mA, 10 ms) was used in conjunction with the largest scan length possible (28 cm) for all phantom iCBCTs taken.

Changing scatter conditions consisted of shifting the phantom both longitudinally and laterally to the limits of the scanning field of view (2 cm, 5 cm and 10 cm in each direction), introducing a 16 cm air cavity within the phantom by removing the inner portion of the electron density phantom, simulating various patient sizes by first using the inner portion of the phantom only followed by adding 7 cm of superflab bolus (NL-Tec, Willetton, Australia) to the top of the standard phantom, and finally, by adding titanium inserts to simulate prostheses into the scans.

The $CT-ED_{iCBCT}$ curve was established in Eclipse by taking the average of all scans with a complete phantom. That is, excluding the scans with the inner portion of the phantom removed. A planning CT scan was taken of a Model 002PRA CIRS IMRT Pelvic 3D Phantom (CIRS Tissue Simulation & Phantom Technology, Norfolk, VA, USA), using a clinically commissioned Phillips Brilliance CT (Koninklijke Phillips N.V. Amsterdam, Netherlands) with 2 mm slice thickness and x-ray tube voltage of 140 kV.

Several iCBCT scans were taken of the pelvis phantom on the Halcyon using the pre-defined pelvis protocol, consisting of 2 mm slice thickness and an x-ray tube voltage of 125 kV, including scans taken up to 10 cm offset longitudinally and laterally and centred on axis. The $CT-ED_{iCBCT}$ curve was applied to these scans within the Eclipse TPS.

The ED changes in the offset scans of the central slice of the pelvis

phantom were compared to that with the phantom centred on the imaging axis to determine the potential dosimetric effect of offsetting a patient within the scanner. This was completed by taking 5 scans, the first with the phantom centred on the imaging axis, followed by scans offsetting the phantom by ± 10 cm in longitudinal and lateral directions. The regions selected for this comparison were representative of the prostate, rectum and femurs. The images were matched in the TPS and the regions of interest copied onto each dataset for consistency.

Ten patient plans, representing a variety of pelvis based disease types and PTV sizes were copied onto the two datasets, and the dose recalculated using the Analytical Anisotropic Algorithm (AAA, version 15.6.03) within the Eclipse TPS. Patients with a body contour extending beyond the field of view of the iCBCT and patients with treatment volumes larger than 25 cm were excluded. A 1%/1mm and 2%/2 mm global 3D Gamma analysis (using an absolute dose comparison, and a 10% low dose threshold) was completed using PTW verisoft software, version 7.1 (PTW, Freiburg, Germany). The ten patient plans consisted of three prostate, three prostate and nodes, three Rectum, and one Gynaecological plan.

As all pelvis patients within our clinic have daily image verification using a pelvis iCBCT, the same ten patient plans were copied onto their respective day 1 verification scans. This was completed after the day 1 iCBCT was matched to the corresponding planning CT using a manual rigid registration, and the contours, including Body, PTV, Rectum and Bladder copied onto the matched image. The resultant match was checked using departmental protocols, as were the resulting placement of the copied planning volumes. The $CT-ED_{iCBCT}$ curve was applied to each of the iCBCT datasets prior to dose calculation. A 3D Gamma analysis was conducted to assess the difference between the plan calculated on the planning CT and the iCBCT using PTW Verisoft software.

3. Results

Within the Eclipse TPS, CT data was compared for the various ED inserts for the different conditions. The most predominant effects were seen in the high-density region of the curve. While offsetting the phantom in any one direction did not greatly contribute to changes in the CT-ED curve, with the introduction of a large air cavity of 16 cm diameter proved to result in the largest change to the curve. The maximum difference in CT number was 84 HU for the dense bone in this scenario compared to the $CT-ED_{iCBCT}$ data created in Eclipse. The changes in scattering conditions are shown in Fig. 1.

Although the introduction of stainless steel into the phantom did not affect the $CT-ED_{iCBCT}$ curve as significantly as the introduction of a

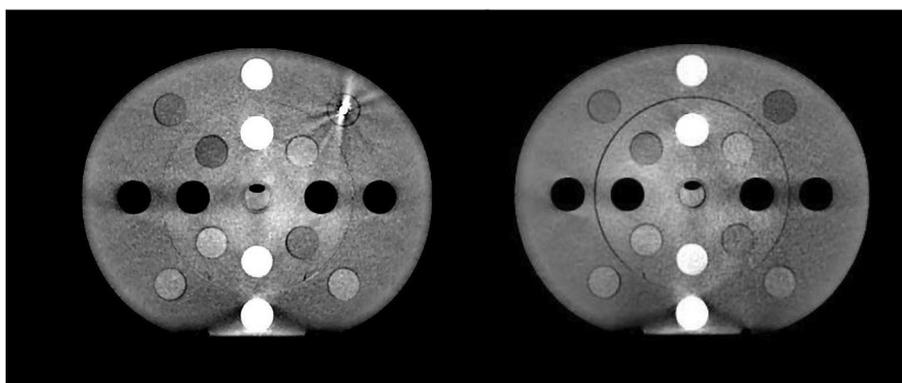


Fig. 2. Image quality with the introduction of titanium into the phantom (left) compared to without (right).

Table 1
Differences in HU and ED when a Pelvis phantom is offset within the scanner.

Phantom Offset	Mean HU				Mean ED (g/cm ³)			
	Prostate	Rectum	L Femur	R Femur	Prostate	Rectum	L Femur	R Femur
No Offset	-6.5	-81.9	710.4	726.3	0.99	0.91	1.37	1.38
+10 cm Long	-0.4	-103.2	796.0	740.6	0.99	0.89	1.41	1.39
-10 cm Long	-29.6	-118.3	755.7	719.1	0.96	0.88	1.39	1.38
+10 cm Lat	-60.3	-119.8	837.3	524.0	0.93	0.88	1.44	1.28
-10 cm Lat	-39.8	-129.5	558.8	900.9	0.95	0.87	1.29	1.47

cavity to the phantom, it did significantly impact the image quality, as shown in Fig. 2.

The differences in ED observed on offset Pelvis phantom scans are shown in Table 1. The largest differences in electron density are seen in the femurs in the laterally offset scans- up to 0.1 g/cm³.

The 3D Gamma analysis results, using a 1%/1 mm and 2%/2 mm, 10% low dose threshold criteria from patient plans calculated on the CT and iCBCT images of the pelvis phantom are shown in Table 2. The average pass rate was 99.4% ± 0.2% for the 1%/1mm analysis, with the worst result being 99.1%.

Similarly, the 3D Gamma analysis results for patient plans calculated on the patient planning CT and the iCBCT taken on day 1 of treatment are shown in Table 3. The average result for the 1%/1 mm gamma analysis was 94.4% ± 6.1%, and for 2%/2 mm is 98.6% ± 2.0%. The worst agreement is patient 10, with a Gamma analysis of 99.1%, which may be attributed to the patient contour, as patient 10 exhibited the greatest change in body contour between planning CT and day 1 CBCT.

Although the change in body contour was somewhat offset by copying the body structure from the planning CT onto the day 1 iCBCT prior to dose calculation, the changes still heavily impact the dose calculation due to the change in patient shape and tissue location, as the body contour regions without tissue were not accounted for (e.g. air

Table 2
Gamma Analysis Results from Verisoft using a 1%/1mm and 2%/2mm 3D Gamma Analysis with a 10% low dose threshold for plans calculated on a pelvis phantom scanned with a planning CT and iCBCT.

Patient	Site	Length of treatment field (cm)	1%/1mm gamma pass rates	2%/2mm gamma pass rates
1	Prostate and SVs	8.2	99.5	99.9
2	Prostate and SVs	10.0	99.6	99.9
3	Prostate and SVs	11.1	99.6	99.9
4	Prostate Bed	10.7	99.5	99.9
5	Prostate Bed	10.1	99.5	99.9
6	Prostate Bed	12.2	99.4	99.9
7	Rectum	20.7	99.2	99.9
8	Rectum	7.2	99.8	99.9
9	Rectum	20.4	99.2	99.9
10	Uterus	17.6	99.1	99.9

Table 3
Gamma Analysis from Verisoft for patient plans calculated on their planning CT compared to day 1 iCBCT. A 10% low dose threshold was used for both the 1%/1 mm and 2%/2 mm analysis.

Patient	Site	1%/1mm gamma pass rates	2%/2mm gamma pass rates
1	Prostate and SVs	99.5	100
2	Prostate and SVs	99.3	99.8
3	Prostate and SVs	92.2	98.8
4	Prostate Bed	99.5	99.9
5	Prostate Bed	99.7	100
6	Prostate Bed	98.8	99.8
7	Rectum	89.7	99.2
8	Rectum	82.9	94.1
9	Rectum	87.4	95.7
10	Uterus	95.1	98.7

within the body contour). The air gaps were not accounted for, so that overridden tissue was not introduced into the datasets, although it is acknowledged that this is a limitation of this work. The change in contour for the patient with the worst agreement is shown in Fig. 3.

The difference in the mean dose to the PTV, Bladder and Rectum was determined for each of the patients between their planning CT and



Fig. 3. Day 1 iCBCT of patient 8 with the body contour from the planning CT overlaid to demonstrate the change in patient contour.

Table 4

Dose differences between doses to volumes calculated on patient planning CTs and iCBCTs.

Patient	Site	PTV Mean Dose Difference (%)	Bladder Mean Dose Difference (%)	Rectum Mean Dose Difference (%)
1	Prostate and SVs	−1.2	−0.9	−2.5
2	Prostate and SVs	−0.2	0.1	−1.1
3	Prostate and SVs	−1.7	−1.0	−2.6
4	Prostate Bed	0.1	−0.4	0.5
5	Prostate Bed	0.2	0.4	0.0
6	Prostate Bed	0.5	1.2	1.2
7	Rectum	−1.5	−1.3	N/A
8	Rectum	3.0	7.9	28.1
9	Rectum	2.6	1.1	2.8
10	Uterus	0.9	0.4	9.7

day 1 kV CBCT. These results are shown in Table 4. The worst case for all three of these parameters was patient 8 with differences of 3.0%, 7.9% and 28.1% for the PTV, Bladder and Rectum respectively. Excluding the data from patient 8 gave average mean dose volume differences of 0.0%, 0.0% and 1.0%, and standard deviations of 1.4%, 0.9% and 4.0% for the PTV, Bladder and Rectum volumes respectively.

Excluding the outlier in the data, patient 8, the maximum mean dose difference observed in the PTV was 2.6%, where the PTV was a rectum and therefore may have changed in composition (i.e. gas or filling) between the planning CT and day 1 iCBCT. The maximum mean dose in the Bladder and Rectum were −1.3% and 9.7% respectively.

4. Discussion

The results from the CT-ED_{iCBCT} curve show that for pelvis treatments, the CT-ED_{iCBCT} curve is suitable for RT planning. However, there is a limitation in the utilisation of the iCBCT module in its current form for all patient planning datasets.

Although beyond the scope of this paper, continued work on the use of the Halcyon for other treatment sites is ongoing and will investigate scanning volumes that include lung and smaller patient diameters, such as head and neck. The current work shows that, if the target volume within the patient is in a region with a large volume of lung such as the thorax, or if the patient has a prosthesis, it may be necessary for the patient to be scanned on a diagnostic CT scanner commissioned for RT planning.

Offsetting the pelvis phantom for iCBCT images shows that electron density does not vary as much in the longitudinal portion of the scan as it does when patients are shifted laterally. Patients having iCBCT

images acquired for planning purposes should be centred on the imaging axis. Tissue that is not captured in the image can influence the electron density and therefore the dose calculation. As such, patient size is a limitation of this scanning procedure.

Recalculating patient plans on the iCBCT of the Pelvis phantom resulted in excellent agreement between scans when no additional patient-specific uncertainties such as interfraction motion and contour changes were introduced into the analysis. The plan with the worst agreement contained a 15 cm long PTV, which extended to the end of the phantom, which may have affected the results.

Although there was a larger difference seen in calculating the 3D Gamma pass rate on the patient day 1 verification iCBCTs, there are a number of patient specific factors that contribute to this change that cannot easily be accounted for within this study. The first, and most common effect is any small change in body contour and shape that had occurred between the planning CT and day 1 of treatment, the effect of which is frequently reported in literature [8–9], and is clearly seen in the patient datasets with the worst agreement. Although the body contour from the planning CT was copied onto the day 1 iCBCT, no overrides to density were included as this would have artificially added tissue that was not captured in the scan. As a rigid registration was used, air and other changes to the body at the edge of the patient body contribute significantly.

Other changes that have occurred between the planning CT and day 1 of treatment that are believed to have an effect on the calculations are bladder and bowel filling. Although patients are expected to follow a rectum and bladder preparation protocol when on treatment, there are instances where patients are non-compliant, which is well documented published literature [10–11]. As such, random, patient specific errors

are introduced into the datasets that cannot be accounted for without the use of deformable registration.

Another issue encountered with the patient day 1 images was that the dose to the patient for a daily CBCT is considered and as such, the region which is imaged daily is often reduced in such a way that scattering material in the superior and inferior of the PTV is reduced to less than that generally accepted for a planning CT. This is considered a limitation of the current work, and is considered in the scanning workflow.

Some other limitations in the workflow of using the Halcyon include the lack of a scout image to determine scan levels. Cases to be scanned on the Halcyon will require setup to external anatomy, and the tumour size to be smaller than the maximum scan length of 28 cm.

5. Conclusion

The use of the Halcyon Pelvis iCBCT for radiation therapy planning datasets was found to be accurate for dose calculation when taken with adequate scattering conditions in treatment centres where immediate access to a CT scanner is unavailable. For Pelvis patients, the dose calculation on a dataset obtained using the Halcyon iCBCT was found to be accurate within the aforementioned limitations, with the main variations in treatment coming from expected daily changes in patient anatomy such as bladder and rectum filling, as well as external contour changes.

In future, the use of the iCBCT for RT planning datasets will be investigated for other regions of the body, including H&N, thorax and abdominal treatments, widening the applications of this work. However, due to the changed scattering conditions, this will require overcoming the inherent uncertainty that occurs due to the use of a cone beam compared to a fan beam, as well as changes in patient

anatomy due to breathing.

Conflict of interest statement

The authors have no relevant conflicts of interest to disclose

Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.ejmp.2019.11.015>.

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