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Solution for Processing Pelvic Bone Metastases with Halcyon ™ 2.0 on Lateral and Longitudinal Isocenters Treatment Plans Using the VMAT Technique: A Comparative Study

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ABSTRACT

Introduction: Treatment of pelvic bone metastases using a Halcyon machine, mostly presents some difficulties to plan, especially for big volumes because of the machine field size. The purpose of this study is to use two lateral isocenters in the treatment of pelvic bone metastases with the Halcyon machine, in order to overcome its limitations in treating large volumes.
Material and Methods: We report a retrospective study of 8 patients who received radiotherapy for pelvic bone metastases, all treated by two different VMAT techniques. The first technique was performed by two longitudinal isocenters (LONI) and the second by two lateral isocenters (LATI) respecting the authorized distance longitudinally between two isocenters which must be less than 8 cm. For each isocenter, two opposite arcs are used for all treated patients.
Results: The plans conformity index (CI) assessment shows no difference between the two used techniques for all the treated patients. Remarkable coverage of PTVs was obtained in lateral isocenter (LATI) with 96.2% compared to 94%.6% for LONI, as well as the maximum dose which was 109.4% for LATI versus 112.3% for LONI. However, the Conformation number (CN) that takes into account both healthy tissue and organ at risk protection was improved by 7.3% by using LATI.
Conclusion: A very satisfactory result has been obtained in the treatment of pelvic bone metastases with LATI. With this technique, we can exceed the limits of the Halcyon machine and process larger volumes.

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Introduction

Several technologies have been developed to provide faster treatment and optimal doses. The latest cancer radiotherapy treatment device, offered by Varian, is its modern, faster, and more ergonomic Halcyon ™ accelerator. It is mainly designed to revolutionize radiotherapy by delivering faster treatment time and reducing treatment errors compared to conventional linear accelerators. Its main advantage is the capability for rapid delivery at four rotations per minute (4 RPM), which reduces the time needed between fields.

Additionally, the rapid transit of multileaf collimator (MLC) allows treatment to be administered at a dose rate of 800 MU/min [1]. From 2017 to 2021, Varian (Varian Medical Systems, Palo Alto, CA, USA) developed and introduced three versions of the Halcyon machine. This treatment platform is specifically developed to deliver an easy-to-use, high-speed, and efficient workflow. It contains a single 6 MV photon beam with a flattening filter-free (FFF) configuration and a closed board with a 100 cm diameter aperture. [2-12]. Moreover, this machine has no optical distance or light field; for this reason, daily imaging is mandatory. Each treatment plans requires a kilo-voltage cone beam computed tomography (KV-CBCT) or megavoltage (MV) imaging field, either

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orthogonal pairs or CBCT. However, the MV imaging dose is calculated and added to the prescribed dose. [13].

Furthermore, the Halcyon™ features a dual-layer MLC system, unlike other single-layer Varian MLC systems. This design ensures rapid beam modulation and considerably reduces leakage between MLC leaves. Additionally, Halcyon™ does not include beam-shaping jaws; instead, the MLC is used as the sole beam-shaping component. Moreover, the Halcyon commissioning process is much simplified and streamlined, resulting in short times between installation and the start of treatment. Though the beam output of the Halcyon™ has been published, the offset-stacked double-layer MLC has not been independently characterized [14]. A comprehensive characterization of the MLC system can provide detailed information on system constraints, guiding the establishment of quality assurance protocols to ensure accurate radiation delivery. It should be noted that a reference beam model integrated with the Eclipse treatment planning system was used to preconfigure the Halcyon LINAC. In addition, beam model parameters relating to small fields and MLC dosimetry can benefit significantly from a close agreement between planned and delivered doses.

Halcyon machine was upgraded from version one to three; each improvement aimed to accomplish the previous limitations. Only one isocenter per plan is allowed with a maximum field size of 28 × 28 cm^2 for Halcyon 1.0, though in Halcyon 2.0 this geometry can be extended 8 cm longitudinally through two isocenter per plan, while in Halcyon 3.0 also two isocenter per plan can be used but with a maximum additional distance of 10 cm; hence the length (longitudinal direction) will up to 38 cm.

Following the spine, which is the most common site of bone metastases, the pelvis is the second most frequent site, causing pain and significantly reducing function and weight-bearing capacity.

The most frequent type of malignant tumor that affects bone is metastatic bone disease (MBD), accounting for around 70% of all malignant bone tumors [15]. Following the spine, which is the most common site of bone metastases, the pelvis is the second most frequent site, causing pain and significantly reducing function and weight-bearing capacity. The pelvis is recognized by (a) the wide size of its cavity, (b) the stretchy structure of its organs, and (c) the muscles that surround it. As a result, tumors in this region typically attain a significant volume before causing symptoms.

Bone metastasis mostly originates from the carcinoma of the breast, renal, lung, thyroid, and prostate. In addition, bone metastasis is the third most frequent site, following lung and liver. Moreover, the detailed incidence of bone metastasis is not completely understood [16]. Furthermore, as many as 70% of bone metastasis are caused by prostate and breast cancer and are associated with intense pain, reduced mobility, pathological fractures, spinal cord compression, bone marrow aplasia, and hypercalcemia [17]. The percentage of metastasis that affects the bone can be caused mostly by 65-75% of breast cancer, 65-75% of prostate cancer, 60% of thyroid cancer, 30-40% of lung cancer, 40% of bladder cancer, 20-25% of renal cell carcinoma and 14-45% of melanoma. Patients with bone metastasis can survive, on average: 6 months for melanoma, 6-7 months for lung cancer, 6-9 months for bladder cancer, 12 months for renal cell carcinoma, 12-53 months for prostate cancer, 19-25 months for breast cancer and 48 months for thyroid cancer [18].

Radiation therapy is most often used for pain relief for the palliative treatment of bone metastases and is reported in many doses per fraction of randomized studies [19, 20]. Many authors reported clinical characteristics and radiotherapeutic strategies in hepatocellular (HCC) patients with bone metastasis, as well as stereotactic body radiotherapy for spine metastasis [21-24]. Contrary to vertebral metastases, a handful of studies have evaluated HCC patients with pelvic bone metastasis.

Recently Uehara et al. described the use of a Halcyon machine for total body irradiation (TBI) [25]. Moreover, many authors have described the treatment of bigger volumes as the TBI and the total marrow irradiation (TMI) using C-ARM linear accelerator and Tomo-therapy [26–32]. However, this requires more time in the treatment, about 1.5 hours or more depending on the group experience [33]. The optimal solution to this problem could be the Halcyon or Tomo-therapy machine [7, 16, 24–28]. In addition, the use of these techniques, performed by Hui et al, allowed to obtain a dose reduction to organs at risk (OARs) by 34–70% between TMI and TBI plans [26]. In this study, we will focus only on the treatment of Pelvic bone metastases to solve the problem of irradiating the largest part of the bone.

Our center installed Halcyon 2.0 in December 2020 combined with Eclipse™ treatment planning software (v16.1.0) using a 6 X FFF energy and 600 MU/min dose rate. In this study, we reported our clinical experience of treating patients with volumes bigger than the authorized field size (Pelvic bone metastases). However, this presents a challenge for planners and more time to achieve clinically acceptable results.

Materials and Methods

Patient's Selection and prescriptions

Since we installed only Halcyon 2.0 in our center to treat all patients with different localizations, some difficulties as recommended and allowed field size of 36 cm using two isocenter, single energy of 6 MV flattening filter free (FFF), and closed bore system that limits the table movement laterally are the main factors that restrict planners in treating larger volumes. A CT image dataset of 8 patients diagnosed with Pelvic bone metastases, who received radiotherapy in our department, were selected. The pelvis is first of all a bony framework limited dorsally by the sacrum and below the coccyx, laterally and ventrally by the two coxal bones which meet in front at the level of the pubic symphysis. Due to lumbar lordosis, the axis of the pelvis, in the anatomical position of reference, is oblique dorsally and caudally at an angle of approximately 60° with respect to the horizontal.

CT simulation for all patients was performed in 2 mm slices with head-first supine using Siemens Somatom Sensation Open CT (Siemens, Erlangen, Germany). Target volumes and OARs were delineated using Varian SOMAVISION Focal workstations v.16.1.0 (Varian, Palo Alto, CA, USA). The primary clinical target volume was delineated according to the clinical protocol in use. The bony pelvic and OARs were delineated according to published guidelines [34, 35]. The clinical target volume (CTV) was contoured by radiation oncologists afterward; a uniform margin of 5mm was added to define Planning Target Volume (PTV). The prescription dose was 30 Gy in 10 fractions.

Planning Technique

Treatment plans for all patients are generated in Eclipse TPS (v16.1.0) using VMAT technique with 6 MVP photon flattening filter-free (FFF) energy and 600 MU/min dose rate. Two different planning techniques were applied to all patients. The first technique is performed by two longitudinal isocenters technique (LONI) at a maximum distance of 8 cm from each other, it is the allowed distance by Halcyon version 2.0; however, the choice of the convenient distance between isocenters depends on the treatment region length, Figure 1 to irradiate the whole volume of the PTV.

Despite this, some limitations are still present, more precisely if the treated PTV is larger than 28 cm, a part of the volume laterally is not irradiated from all gantry angles direction. Mostly, the shape of the irradiated volume is larger than the treatment field size from the anterior and posterior directions.

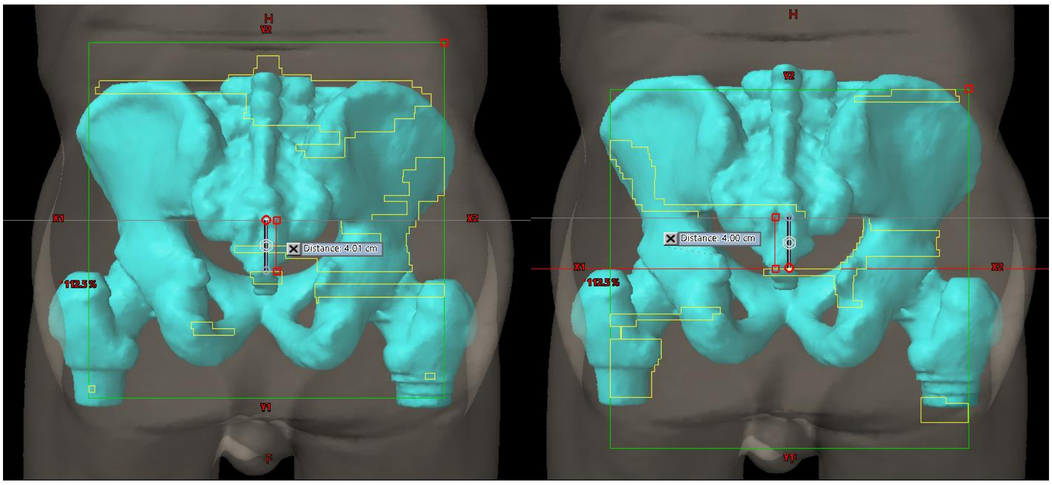


Figure 1. Pelvic treatment using two longitudinal (LONI) with a distance under 8cm between isocenters: The upper isocenter refers to the field that irradiates the upper part of the volume (left side), while the lower isocenter is used for the irradiation of the lower part of the volume (right side)

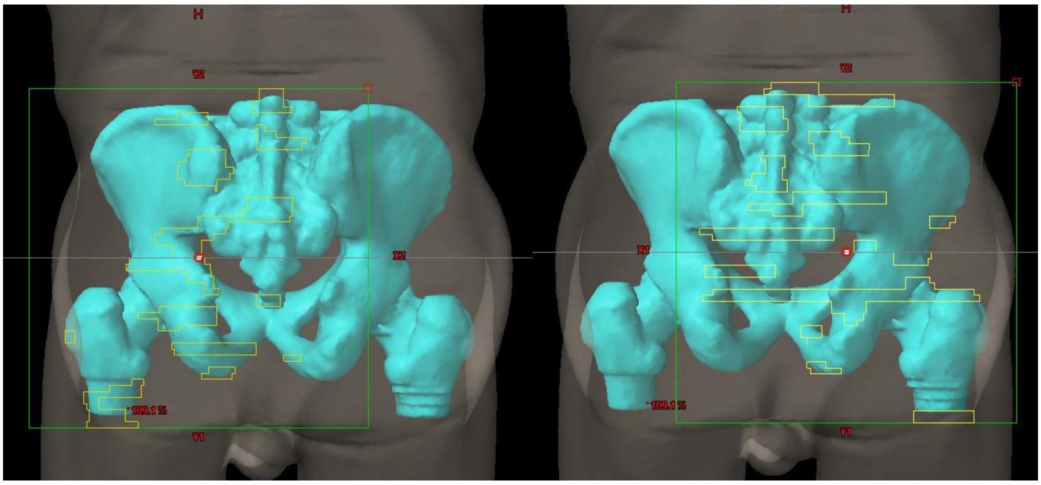


Figure 2. Pelvic treatment using two lateral isocetenters (LATI) with a distance under 8cm between isocenters: The left image shows the setup for the left isocenter, while the right image shows the setup for the right isocenter, both used to irradiate the entire volume.

From the oblique to the lateral directions, depending on the “beam’s eye view”, the width of the PTV decreases while the depth increases, and the whole volume will be included in the irradiated field size. The missing regions will be in the irradiated field only from the lateral directions when the gantry rotates far from the anterior and posterior angles. Consequently, this results in a complex plan with the production more MUs, hot spot, and time-consuming for the user to achieve the desired objectives. Likewise, to overcome this constraint the second technique is based on two lateral isocenters technique (LATI) Figure 2.

Using this technique makes it possible to irradiate the total volume from all gantry angle directions. Thus, no messing region during irradiation, no leaf sequencing complexity that may increase errors in the delivery, no hot spot, and more dose homogeneity are obtained. The distance between the two isocenters was kept to be less than 8cm for both techniques; two full opposite arcs per isocenter are created for all plans. After the plan’s calculation, the lateral technique is not allowed in the treatment machine; for this reason, we split each plan into two separate plans with one isocenter; Right Lateral and Left Lateral (RL, LL) Figure 2. More precision in positioning using CBCT imaging is mandatory in this technique since the delivery is performed by two separate plans with an overlap region.

Planning Objectives

For PTV coverage in pelvic treatments, the planning objective was to ensure that at least 95% of the prescribed dose covered 95% of the target volume (quasi-minimal dose D95% > 95%). Additionally, for the maximum dose, no more than 2% of the volume should receive over 107% of the prescribed dose (D2% < 107%). Moreover, the dose to healthy tissue was considered, prioritizing increased conformity and homogeneity to the PTV.

To compare the effectiveness of each technique, we evaluated the following indices: Homogeneity Index (HI), Conformity Index (CI), Healthy Tissue Conformity Index (HTCI), and Confirmation Number (CN), which take into account both PTV coverage and healthy tissue protection.

We used the following formula to assess dose homogeneity in each PTV:

$$HI = (D_{2\%} - D_{98\%}) / D_P \qquad (1)$$

Where D_P is the prescribed dose to the PTV [36, 37], the HI ideal value is 0. In addition, the conformity index (CI) was calculated to estimate the degree of conformity of the dose to the PTV volume [38,39]:

$$CI = V_{RI} / V_{TV} \qquad (2)$$

Where V_{RI} represents 95% of the prescribed dose volume and V_{TV} the PTV volume. The ideal conformity index is 1, and any increase from this value indicates increased irradiation of healthy tissue by the reference isodose. If the CI is less than 1, it indicates that the target volume is only partially irradiated. to simultaneously account for the irradiation of both the target volume and the healthy tissue; van’t Riet et al. proposed an index called confirmation number that is defined as [40]:

$$CN = \frac{TV_{RI}}{TV} \times \frac{TV_{RI}}{V_{RI}} \qquad (3)$$

Where: CN is the confirmation number, TV_{RI} is the target volume covered by the reference isodose, TV is the target volume, and V_{RI} is the volume of the reference isodose.

The first fraction of this equation proposed by SALT-Lomax [41, 42] and defines the quality of coverage of the target; the second fraction proposed by Lomax [42] and defines the volume of healthy tissue receiving a dose greater than or equal to the prescribed reference isodose. For plan efficiency and treatment time, the number of monitor units in each using technique was considered.

Results

The mean results of the used dosimetric parameters of our study for the upper and lower part of pelvic bone metastases for both, LATI and LONI are outlined in Table 1 No difference between the two techniques in terms of dose conformity is achieved, though a better homogeneity index (HI) is obtained in the laIT. The HI values were 0.36 and 0.45 for LONI and LATI. PTV coverage was clearly better in LATI with 96.2% against 94.6% as well as the maximum dose was 109.4% for LATI against 112.3% for LONI. CN evaluation also showed an improvement of 7.3% for LATI compared to that of LONI. However, MUs also was taken into account to compare the treatment time differences between the two techniques, and only 21 MUs of difference were obtained with the advantage of LATI.

Conformity index (CI), Homogeneity index (HI), near maximum (D2%), maximum point (DMAX), Conformation number (CN), and monitor units (MUs).

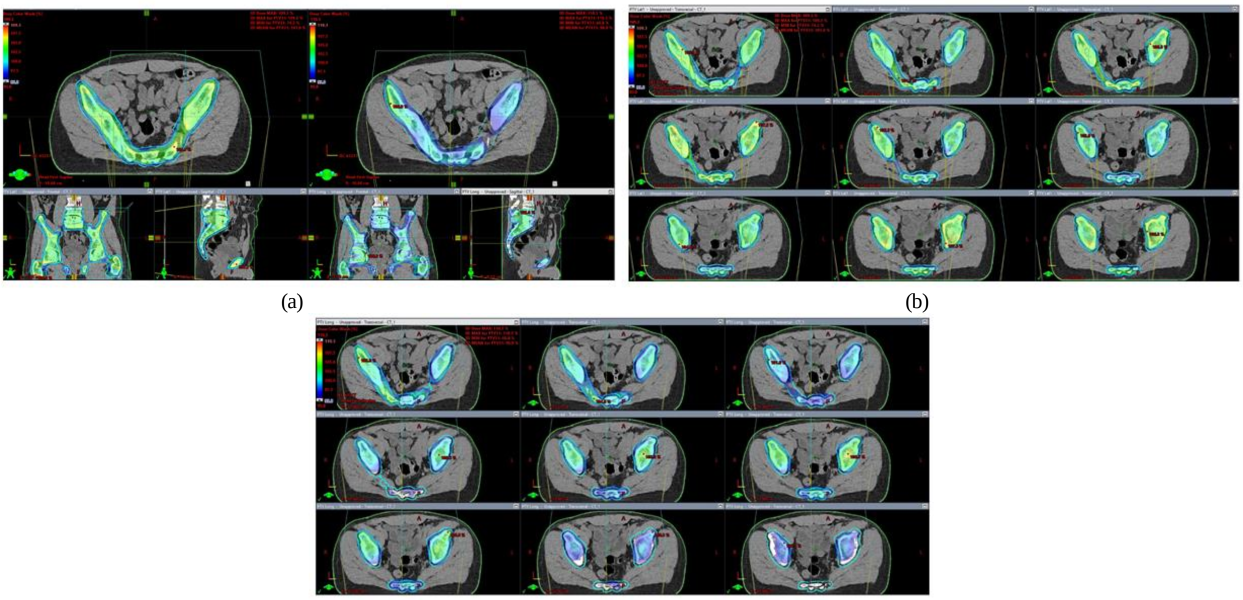
Figure 3 a, b, and c show, with respect to PTV coverage and dose homogeneity, the advantage of using LATI for large-volume treatment. Table 1 demonstrates the benefit of the previously mentioned technique by examining dosimetric parameters. The same CI is obtained for both techniques and the HI was better with 20% for LATI compared to LONI, as well as the PTV coverage was 2% favored to LATI and 3% in terms of maximum dose. We also used CN which takes into account both; PTV coverage and healthy tissue irradiation, which can give an expectation of organs at risk protection. The ideal value of this index is 1 when 100% of the PTV is covered by reference isodose and 0% of reference isodose irradiates healthy tissue. Our results on the calculated CN for the studied patients were 0.82 for LATI and 0.76 for LONI Table 1.

In pelvic treatment, when the size of the PTV is small and covered by the treatment field size; acceptable clinical objectives can be reached by using LONI, and the results are not significantly different from that of LATI as shown in Figure 4 for patient 5 (P5), where all dosimetric parameters are almost the same for both techniques with an advantage to LONI except for CI. On the other hand, for P6 and P7 where the PTV is big, LATI was clearly better in all the studied dosimetric parameters.

Dose distribution differences for a patient with a small pelvic size treated by LATI and LONI are shown in Figure 5. Conformation numbers for all patients are calculated and plotted in Figure 6 (CN, LATI and LONI) to display the gain and quality of each technique.

Table 1. Dosimetric parameters for Lateral and Longitudinal techniques in the pelvic treatment

	CI	HI	D2%	D95%	DMAX	CN	MUs
LATI	1.09	0.36	105.4	96.2	109.4	0.82	1036
LONI	1.1	0.45	105.78	94.6	112.3	0.76	1057



(a) (b) (c)

Figure 3. a) Comparison of dose distribution in axial, coronal, and sagittal slices for a patient treated with LONI (left) and LATI (right); b) Dose distribution comparison in multi-axial slices, for a patient treated by LATI. C) Dose distribution comparison in multi-axial slices, for a patient treated by LONI

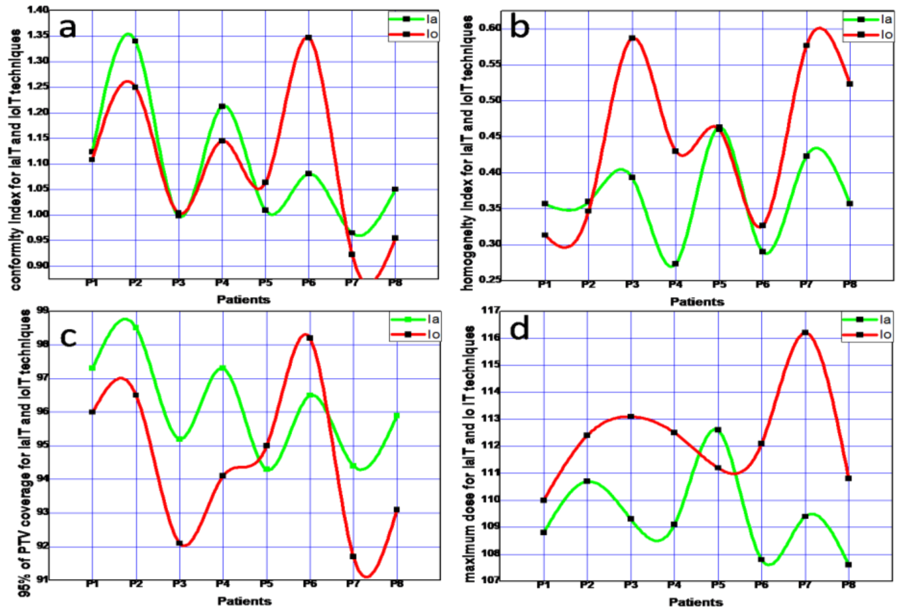


Figure 4. Dosimetric parameter curves for each individual patient treated with both, LATI and LONI techniques: a) represent the conformity index, b) represent the homogeneity index, c) represent the PTV coverage by reference isodose (D95%), and d) represent the maximum dose (DMAX)

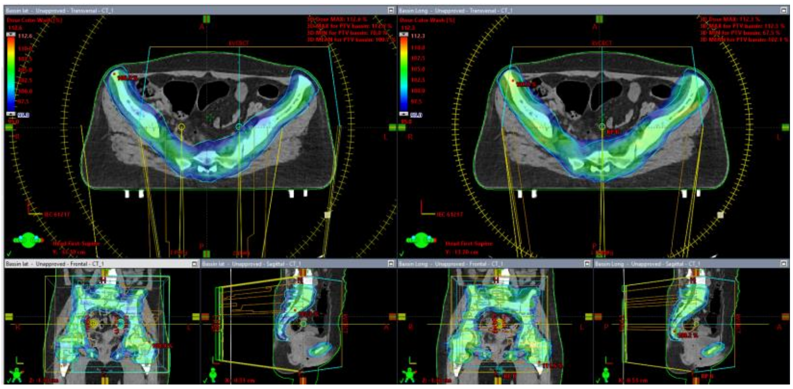


Figure 5. Dose distribution comparison, for a patient treated with LATI (right side) and LONI (left side)

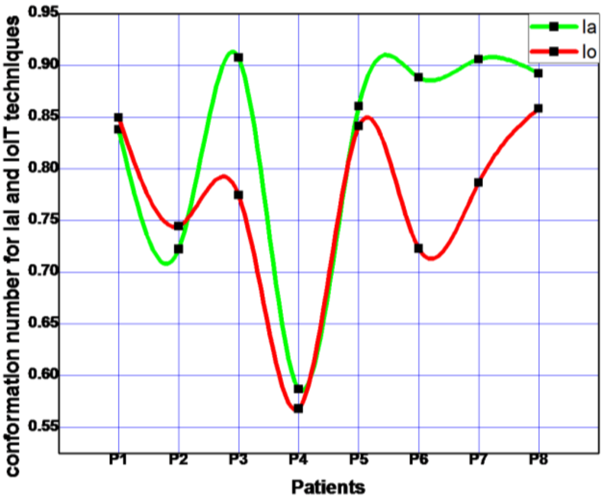


Figure 6. Conformation number for each individual patient treated by LONI and LATI

Discussion

The pelvic skeleton provides essential support for maintaining trunk balance and comprises a complex bone structure. Numerous organs, including the intestines, bladder, and internal reproductive organs, are located in or near the pelvis, which typically exceeds the size of the Halcyon machine field in both dimensions. With these considerations, radiotherapy (RT) planning for pelvic bone metastases presents some difficulties to irradiate the whole volume and healthy tissue sparing. Shahid et al used more than two isocenters in the treatment of total body irradiation but only a longitudinal shift was allowed between the first and subsequent isocenters [43]. However, this study investigated longitudinal and lateral isocenter techniques to treat only pelvic bone metastases and compare their performance by identifying dose coverage, Homogeneity, and conformity as well as healthy tissue sparing. There is convincing evidence in favor of using a single dose of low-fraction radiotherapy to treat pain due to bone metastases in adults, when necessary and accessible. It is essential to evaluate all patients with bone metastases for external beam radiotherapy (EBRT) or radioisotope therapy.[44]. Practically, the EBRT of localized pain is used with various doses per fraction. Therefore, the efficacy of a unique fraction of 8 Gy is equal to that of 20 Gy in 5 fractions as well as 30 Gy in 10 fractions for pain relief [44, 45]. This study is administered to 8 patients with pelvic bone metastases with 30 Gy in 10 fractions through two techniques loIT and laIT Figure.1 and Figure.2. These two techniques are reviewed based on Dosimetric parameters to investigate the advantage of each technique and go beyond the limit of the machine to treat large volumes. For Halcyon.2, two isocenters with an additional length of 8 cm mostly are sufficient to cover the PTV longitudinally. Unfortunately, lateral isocenters are not allowed in Halcyon machines. However, this presents a problem in treating patients with the large pelvis. Therefore, loIT remains restricted if the treated volume is larger than 28 cm because a part of the volume will not be in the radiation field from all directions. Hence, a complicated plan will be acquired with the need for more optimization time to respond to user demands, also MUs calculation for loIT was bigger with 21 MUs compared to laIT Table 1. More heterogeneities will be obtained for such plans and messing dose coverage to target volume as shown in Figure 3-a (right side) and Figure 3-c. To conquer these difficulties, laIT is based on two isocenters but in lateral directions. Though this isocenters arrangement is not allowed in the treatment machine. It was necessary to split each laIT plan before loading it to the treatment machine into two plans with one isocenter per plan. In addition, this technique needs accurate positioning since the two plans will overlap during the, which may produce a hot spot or missing dose in the edge of the plans, also the number of CBCTs is twice that of loIt. However, according to our experience, the overlapping problem can be solved by contouring structures on the edge of each imaging setup field. Consequently, using laIT requires more time in the treatment machine. For patient treatment, the studied Dosimetric parameters achieved better coverage; the mean value of D95% was 96% for LATI against 94% for LONI Table1, also a dose distribution for a studied patient in Figure 3-b showed better coverage in all slices for LATI compared to LONI Figure 3-c where some slices are not covered with the reference isodose. Figure 4-c demonstrated the benefit of LATI in terms of dose coverage for each patient and no gain is obtained for patients 5. However, this disadvantage can be explained by the small size of the treated volume and this was clearly noticed in all the studied dosimetric parameters Figure 4. In addition, 95% of the dose distribution for this patient with a small size of the treated volume Fig 5, shows no differences between the two techniques. At last, the advantage of LATI increases with the size of the treated volume. Organs at risk are not considered in this study because the delivered dose is only 30 Gy which is tolerable for Rectum, Bladder, and small bowel. Nevertheless, the conformation number is calculated in both techniques for each patient to take into account healthy tissue sparing; and the superiority favored LATI Fig 6.

This study was performed to surmount the difficulties of treating big volumes with the permitted technique in the treatment machine which is time-consuming to achieve the desired objectives whenever the size of the PTV is larger than 28 cm However, both techniques are still limited if the PTV is longer than 36 cm. In this situation, a part of the PTV will not be covered by the treatment field. However, a further study will focus on treating volumes larger than 28 cm and longer than 36 cm.

Conclusion

This study demonstrates that using two lateral isocenters (LATI) with the Halcyon machine considerably improves the treatment of pelvic bone metastases compared to the traditional two longitudinal isocenters (LONI) technique. LATI provides better planning target volume (PTV) coverage, improved dose homogeneity, and decreased maximum dose, enabling for more precise radiation targeting and sparing of healthy tissues. Despite requiring increased precision in patient positioning and additional imaging, LATI overcomes the Halcyon machine's field size limitations, enabling the treatment of larger volumes and expanding its capability for complex radiotherapy cases. Overall, LATI is a more effective technique for treating large pelvic bone metastases.

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