IMPACT OF SEGMENTS NUMBER REDUCTION IN IMRT PLANNING

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Purpose: *To investigate the planning and dosimetric advantages of direct aperture optimization (DAO) over beamlet optimization in IMRT treatment of head and neck (H/N) and prostate cancers.*

Materials and methods: *a brain metastatic case with multiple lesions, five head and neck, as well as five prostate patients were planned using the beamlet optimizer in Elekta-Xio© ver 4.6 IMRT treatment planning system. Based on our experience in beamlet IMRT optimization, PTVs in brain were prescribed to 66Gy using 5 fields, PTVs in H/N plans were prescribed to 70 Gy delivered by 7 fields, and prostate PTVs were prescribed to 76 Gy using nine fields. In all plans, fields were set to be equally spaced. All cases were re-planed using Direct Aperture optimizer (DAO) in Prowess Panther© ver 5.01 IMRT planning system at same configurations and dose constraints. Plans were evaluated according to ICRU criteria, number of segments, number of monitor units and planning time.*

Results: *In brain case, beamlet optimization was better than DAO for both GTVs and PTVs in 95% isodose coverage, and the hot area was about 7% more in beamlet plan than DAO plan. For OAR, results showed an improvement in OAR sparing up to more than 35% in rt. eye, lt. eye, rt. optic nerve and lt. optic nerve when using DAO for planning, while optic chiasma sparing was about 20% also in beamlet optimizer plan.*

For H/N plans, the near maximum dose (D_2) and the dose that covers 95% (D_{95}) of PTV has improved by 4% in DAO. For organs at risk (OAR), DAO reduced the volume covered by 30% (V_{30}) inspinal cord, right parotid, and left parotid by 60%, 54%, and 53% respectively. This considerable dosimetric quality improvement achieved using 25% less planning time and lower number of segments and monitor units by 46% and 51% respectively.

In DAO prostate plans, Both D_2 and D_{95} for the PTV wereimproved by only 2%. The V30 of right femur, left femur and bladder were improved by 35%, 15% and 3% respectively. On the contrary, the rectum V_{30} got even worse by 9%. However, number of monitor units, and number of segments decreased by 20% and 25% respectively. Moreover the planning time reduced significantly too.

Conclusion*: DAO introduces considerable advantages over beamlet optimization for different sites of cancer, in regards to organ at risk sparing. While no significant improvement occurred in the PTV ICRU reporting dose.*

Keywords:-*DAO, IMRT, Optimization, Prostate, head and neck*

INTRODUCTION

Intensity-modulated radiotherapy (IMRT) can achieve conformal dose distributions to concave tumor shape while sparing nearby normal tissues. Step-and-shoot IMRT plans can be created using a fluence-based optimization (beam-let optimization) involving two steps: a fluence optimization and a delivery optimization (or a leaf-sequencing process).

Beamlet intensity modulated radiation treatment (IMRT) methods rely on optimizing dose distributions using intensity maps; subsequent to optimization, the maps are converted into sequences of deliverable MLC apertures. Converting the ideal intensity map into a deliverable one can require modification of the ideal map; this can result in a suboptimal plan being delivered Another type of optimization is one-step optimization (direct aperture optimization), where the step of fluence optimization in two-step optimization algorithms is eliminated.[1-9] There is renewed interest in rotational radiotherapy techniques to achieve improvement of dose distribution, MU efficiency and treatment throughput for IMRT delivery.[10]

The main idea of Direct Aperture Optimization (DAO) can be described that the shapes of the multileaf collimator (MLC) apertures and their beam weighting are optimized, so, the treatment plan is optimized using a deliverable treatment solution and thereforethe optimized distribution is the one that will be delivered.

Shepard et al.[2] introduced the concept of DAO and showed that when applied to several patient cases, it resulted in highly conformal dose distributions with significantly fewer segments and monitor units (MUs) than conventional optimization methods. The DAO plans were generated using a noncommercial planning system with a Monte Carlo-based dose calculation.

Bergman et al.[7] introduced a Monte Carlo-based DAO algorithm. For a nasopharynx case, they found approximately 33% improvement in MU efficiency when the optimization engine was changed from two-step optimization to one-step optimization.

From a study of 11 head-and-neck plans, Jones and Williams[13] found that fewer segments were used in DMPO plans than corresponding IM plans. Ludlum and Xia[11] showed that a significant MU reduction was achieved when changing from IM to DMPO for five prostate cases, but no significant MU reduction for five nasopharynx cases. DMPO and IM IMRT plans were also compared by van Asselen et al.[12] for twelve breast cancer patients. They found no significant reduction in MUs, but a reduction in the number of segments. As well, Ahunbay et al.[13] compared the DAO method in the Panther TPS and the two-step optimization in the XiO CMS TPS for ten cases of whole breast treatment. They observed that the total number of MUs for DAO plans were approximately 60% less than those of two-step optimization IMRT plans.

II. MATERIALS AND METHODS

Intensity modulated treatment plans were generated for a brain metastatic case with multiple lesions, 5 head-and-neck, and 5 prostate cancer patients using XiO Planning system (CMS, Elekta Inc.) and Prowess Panther Planning system (Prowess Inc.). For each patient, 2 plans were constructed, 1 using beamlet optimization and the other re-optimized using DAO. The adaptive convolution algorithm was used for all calculations.

Treatment plans were designed for delivery on a Siemens Oncor linear accelerator equipped with a80-leaf double focused MLC (Siemens Healthcare USA, Inc) using 6-MV photons delivered at 400 MU/min with a step-and-shoot IMRT method. At our institution, all brain and head-andneck patients are positioned during treatment using a thermoplastic immobilization system, and prostate cases are positioned using vacuum cautions with daily online corrections performed using an amorphous silicon electronic portal imager and a 3-mm positional tolerance.

For each patient, a plan was generated firstly using the beamlet optimization method and then using DAO, wherever possible, identical parameters were used. These parameters included the number and direction of beams; which was determined experimentally by making plans for each patient on Xio TPS with different beam numbers and directions, then select the optimum plan (results not shown here). Also, the dose objectives and their relative weights were kept constant. The convolution dose calculation took place between the 5th and the 8th iteration.

For the segmentation, a minimum segment size of 1 cm^2 and minimum MUs of 2 MU were specified. These parameters had been derived from previously published values and independently confirmed for use at our institution.[14]

7 intensity levels per beam were used for the beamlet intensity based optimization. This was consistent with the findings of Keller-Reichenbecheret al.,[15] which established that using between 5 to 7 intensity levels was sufficient for most IMRT treatments. For the plans using DAO value of segments per beam was determined experimentally (results not shown) by the repeated optimization of multiple plans with different numbers of segments and observing the convergence of the COV to a stable minimum.[16,17] In DAO, the convolution dose iteration is also the point at which the optimized intensity map is converted into MLC segments for the first time.

Plans were evaluated based on ICRU 83[18] criteria (D98, D95,D50, D2, and V30), number of segments, number of monitor units and planning time. The results for 5 headandneck 5 prostate cases have been summarized.

Results

For all cases; the optimum plans done using beamlet optimizer was compared with those done using DAO based on criteria defined by ICRU 83, where doses delivered to target volumes and OAR were measured, and also comparing the number of segments and total number of monitor units should be delivered from clinical linear accelerator.

Results showed that; in brain case beamlet optimization shows better 98% coverage than DAO for both GTV1 and PTV1 by 1% and 6% respectively. The hot area was 5% and 6% more in beamlet plan than DAO plan. For GTV2 and PTV2 there was no difference in 95% isodose coverage between plans done using beamlet and done using DAO, and the hot area was 6% and 4% more in beamlet plan than DAO plan. For GTV3 and PTV3 the percentage difference in 95% isodose coverage was 2% and 7% in plan done using beamlet more than that done using DAO, and the hot area was 7% and 6% more in beamlet plan than DAO plan. Figure (1) showed GTVs and PTVs dose difference between DAO and beamlet optimizer.
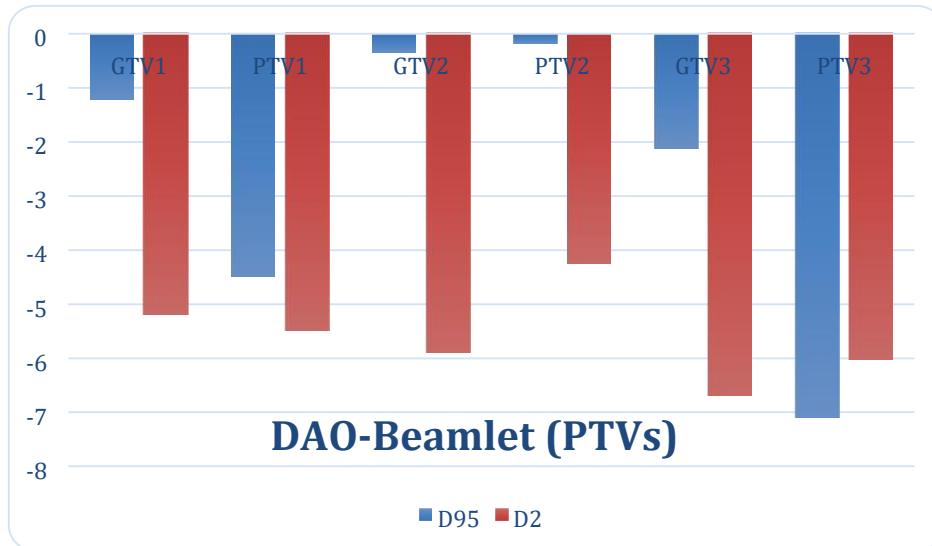

Fig. 1 Graph of GTVs and PTVs dose coverage difference between DAO and beamlet optimizer plans.

For OAR, results showed an improvement in OAR sparing up to more than 35% in rt. eye, lt. eye, rt. optic nerve and lt. optic nerve when using DAO for planning, while optic chiasma sparing was about 20% also in beamlet optimizer plan. Figure (2) showed the dose difference between DAO and beamlet plans for OAR.
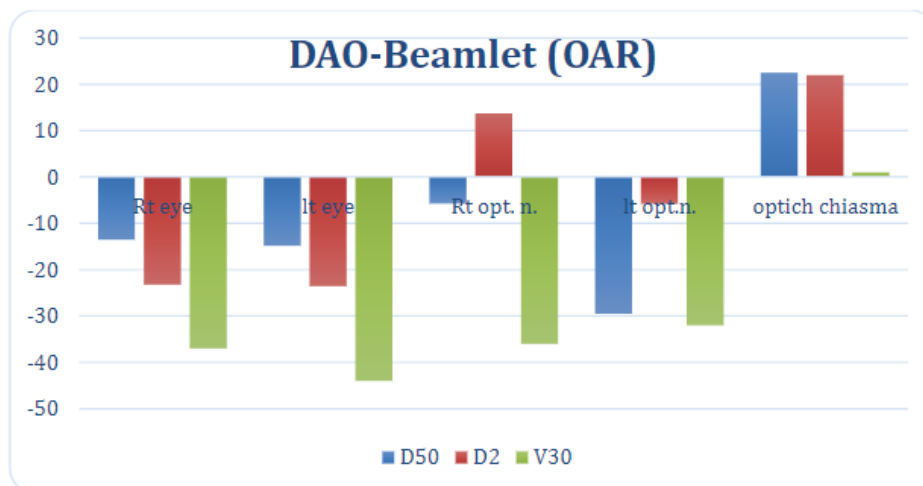

Fig. 2 Graph of OAR dose coverage difference between DAO and beamlet optimizer plans.

The number of segments in plan using DAO was 35, while it was 97 segments in plan using beamlet optimizer as shown in figure (3). And number of total monitor units should be delivered from linear accelerator was 8236 in DAO plan, while it was 28095 monitor units in beamlet plans as shown in figure (4).
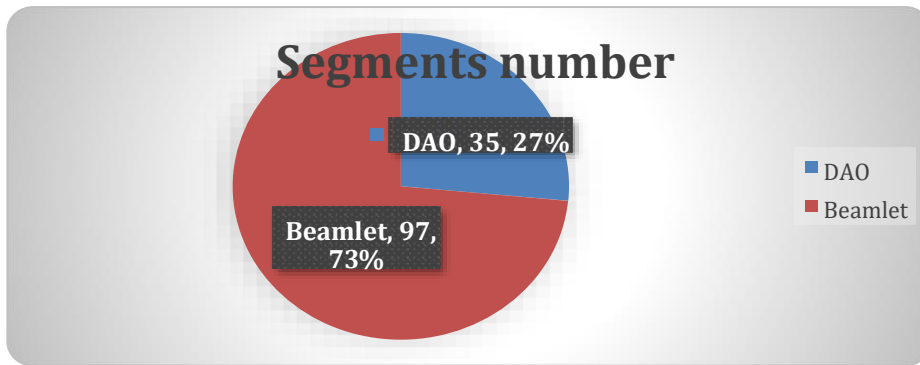
Fig. 3 Graph of segments number for DAO and beamlet optimizer plans.
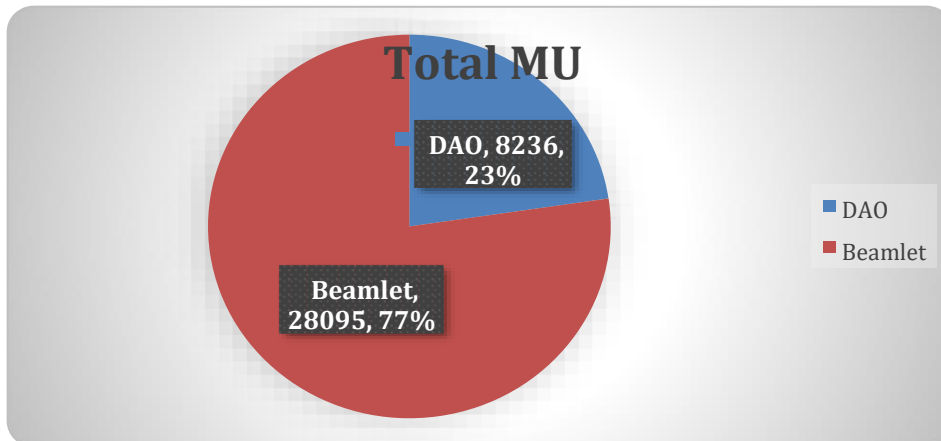

Fig. 4 showing the graph of total monitor units for DAO and beamlet optimizer plans.

The results of head-and-neck plans were, for GTV the average percentage difference for all cases in 95% isodose coverage was 1% plans done using DAO more than that done using beamlet optimizer, the average difference in volume which was covered by the prescribed dose was 12% in plans done using DAO more than those done using beamlet optimizer, and the hot area was 4% more in beamlet plan than DAO plan. For PTV the average difference in 95% isodose coverage was 3% plans done using beamlet optimizer more than that done using DAO, the average difference in volume which was covered by the prescribed dose was 4% in plans done using beam optimizer more than those done using DAO, and the hot area was 4% more in beamlet plan than DAO plan. Figure (5) showed GTV and PTV average dose difference between DAO and beamlet optimizer.
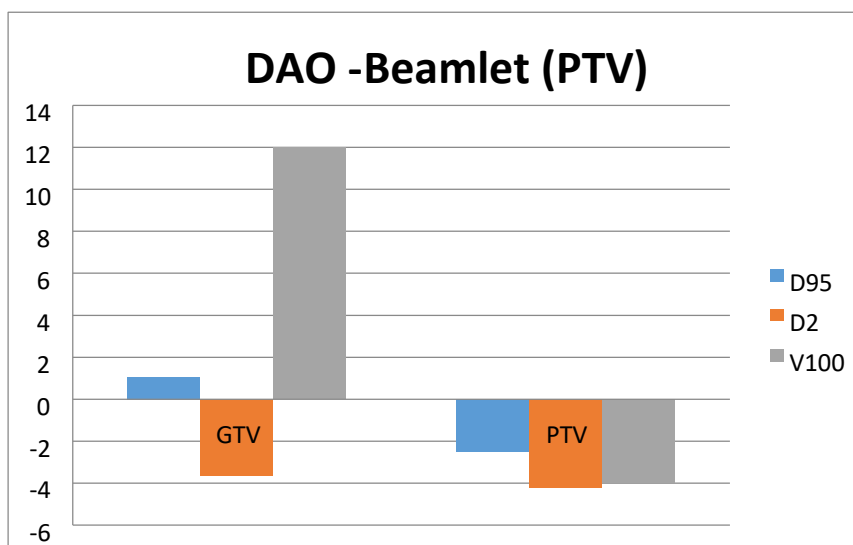

Fig. 5. The graph of GTVs and PTVs dose coverage difference between DAO and beamlet optimizer plans.

For OAR, results showed an improvement in OAR sparing up to more than 27%, 22%, and 29% on average in rt. Parotid and lt. parotid and spinal cord respectively in plans done using DAO, Figure (6) showed the dose difference between DAO and beamlet plans for OAR.
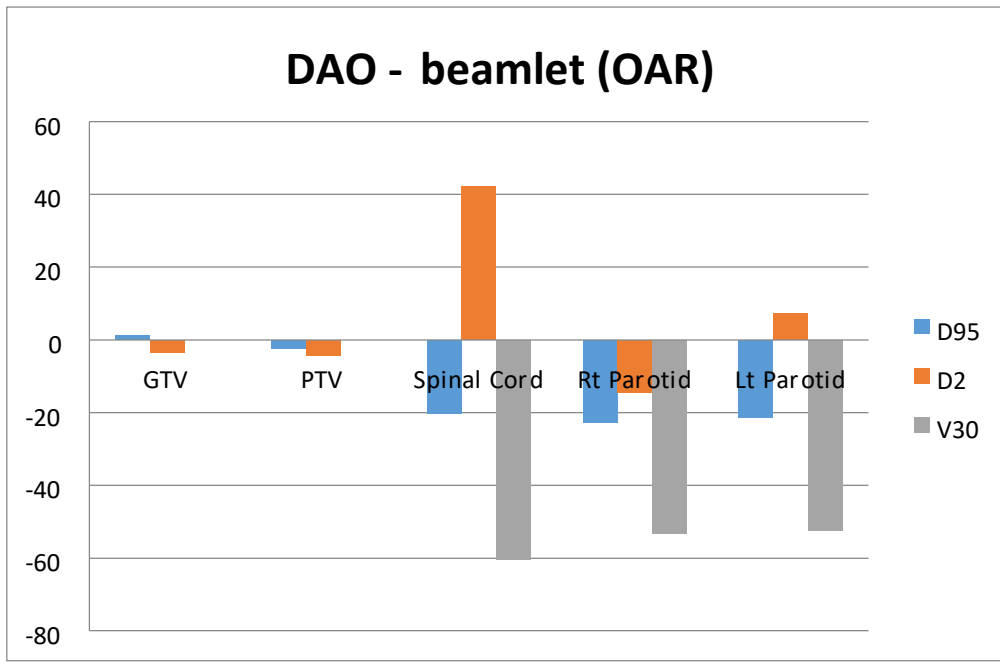
Fig. 6. The graph of OAR dose coverage difference between DAO and beamlet optimizer plans.

The number of segments in plan using DAO was constant at 49 because the planner determine it by himself, while it was varies from 71 up to 129 segments in plan using beamlet optimizer as shown in figure (7). And the number of total monitor units should be delivered from linear accelerator was lower in DAO plans than those for beamlet plans by about 55% on average as shown in figure (8).
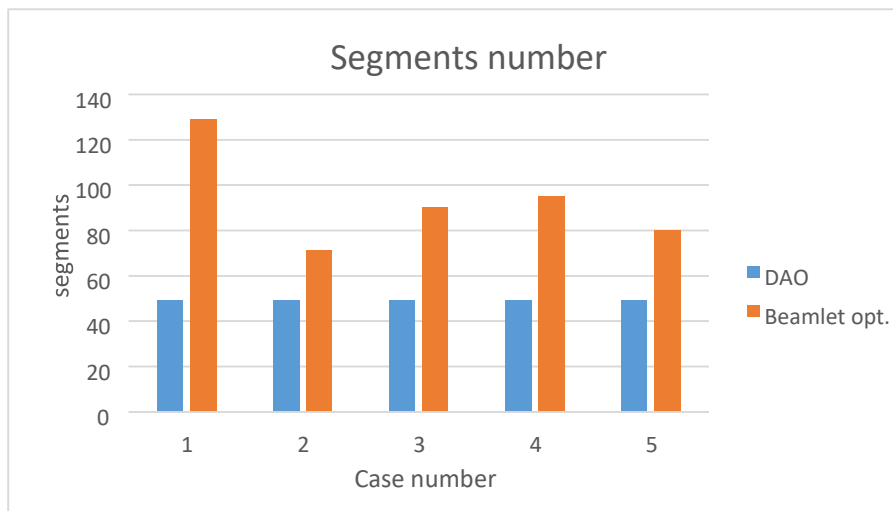

Fig. 7. The graph of segments number for DAO and beamlet optimizer plans.
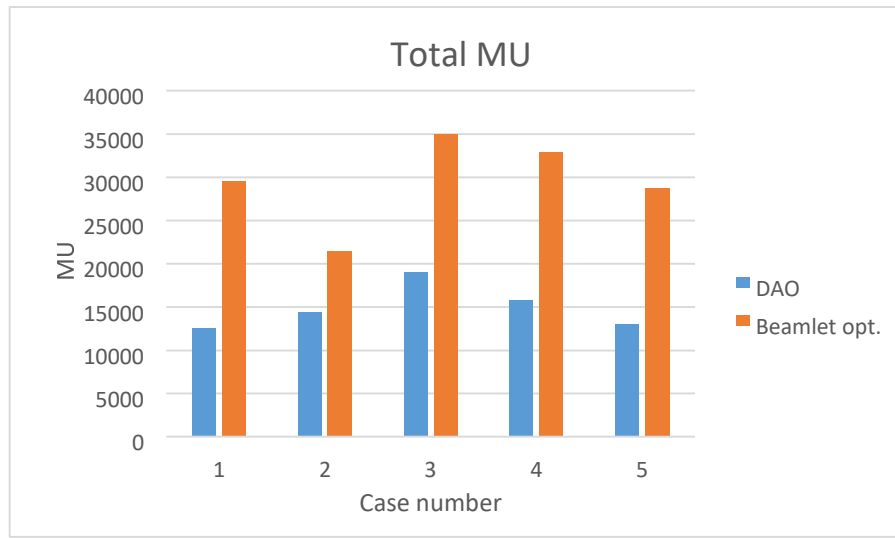
Fig. 8. The graph of total monitor units' number for DAO and beamlet optimizer plans.

For prostate plans, results showed, for GTV, there was no significant differences between DAO and beamlet in all plans in 95% isodose coverage, while for the same isodose line in PTV, and seminal vesicles, the difference was 6.3% and 2.6% on average for plans done using beamlet optimizer more than that done using DAO. The average difference in GTV, PTV, and seminal vesicles volume which was covered by the prescribed dose was 15%, 34%, and 37% respectively in plans done using beamlet optimizer more than those done using DAO, and also D2% was higher in beamlet optimizer plans than in DAO optimizer by about 2.5%, 2.6%, and 3.4 % respectively. Figure (9) showed GTV, PTV, seminal vesicles average dose differences between DAO and beamlet optimizer.
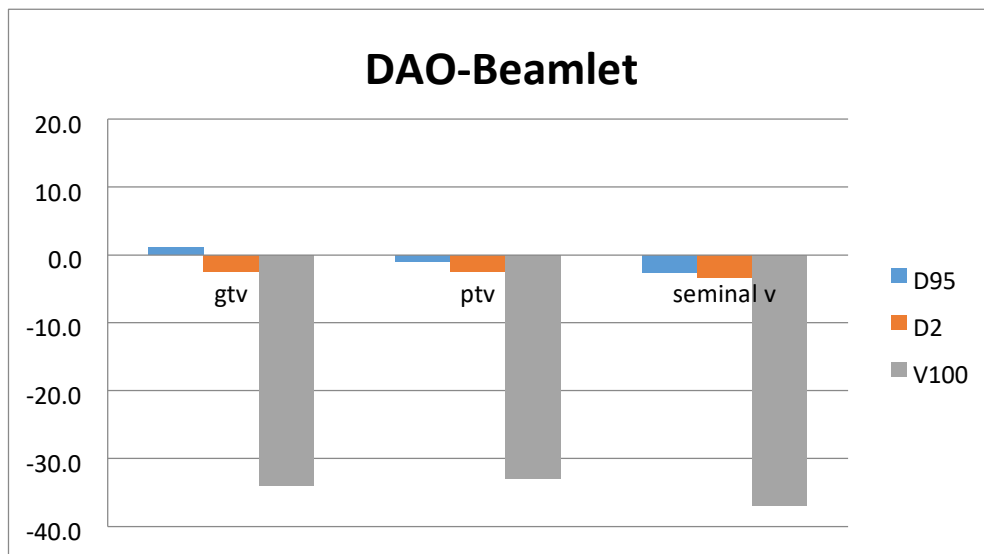

Fig. 9. The graph of GTV, PTV, and seminal vesicles dose coverage difference between DAO and beamlet optimizer plans.

For OAR, results showed an improvement in rectum and bladder sparing in plans done using beamlet optimizer where D50%, D2%, and V30 were lower by 9.5%, 2.8%, and 12.4% respectively in rectum and were 4.6%, 1.3%, and 4.5% respectively in bladder. While DAO improved lt. femur and rt. femur sparing than beamlet optimizer as D50%, D2%, and V20 were lower by 3.6%, 5.9%, and 14% respectively in lt. femur, and were 18.4%, 13.6%, and 35% respectively in rt. femur. Figure (10) showed the dose difference between DAO and beamlet plans for OAR.

In beamlet optimization when converting the plan from the computer generated solution to deliverable segments, the dose distribution will degrade from that originally decided upon. DAO differs from beamlet optimization in that it does not rely on the use of a segmentation routine (sequencing step) to select the initial leaf sequence as this step is incorporated into the original optimization resulting in avoidance of the plan degradation which can occur.

Brain results showed that no significant difference in target coverage while DAO improved OAR sparing by about 35% better. The number of segments for DAO was approximately 65% segments less than those for beamlet optimizer. And number of total monitor units should be delivered from linear accelerator was 60% less in DAO plan, than in beamlet plans.

Head and neck the dose coverage has improved by 4% in DAO. For organs at risk (OAR), DAO reduced the volume covered by 30% (V_{30}) in spinal cord, right parotid, and left parotid by 60%, 54%, and 53% respectively. DAO required lower number of segments and monitor units by 46% and 51% respectively. In another study of 10 hypopharyngeal patients, no statistically significant difference was found for compliance to the dose volume constraints although the mean dose to the parotid was lower with the beamlet based plans compared to the DAO plans. Dose homogeneity within the PTV was superior for the DAO plans and they also required significantly less MU to deliver[19].

In prostate plans, PTV dose coverage was improved by only 2% when planned using DAO. The right femur, left femur and bladder were improved by 35%, 15% and 3% respectively also. On the contrary, the rectum V_{30} got even worse by 9%. However, number of monitor units, and number of segments decreased by 20% and 25% respectively. Ludlum et al[11] compared DAO to beamlet based optimization in 5 prostate. Their results showed that DAO could create plans of similar quality yet with a significant reduction in the number of segments, requiring 3–5 times fewer segments reducing the delivery time for MLC. With DAO, clinical requirements could be met for prostate patients with as fewer segments compared to beamlet based optimization.

Calculation time for all cases were also calculated in this study and it was found that the DAO IMRT treatments would easily fit into the about 18 - 25 min but the beamlet based IMRT treatments would require slightly longer treatment slots of 30 - 40 min depending on target volume and the complexity of plan. the difference in calculation time arises from that beamlet perform calculations twice as it calculates the map intensity first and then recalculate to translate the map to deliverable segments while DAO perform the calculation once as discussed earlier.

Conclusion:
 DAO introduces considerable advantages over beamlet optimization in regards to organ at risk sparing. While no significant improvement occurred in the PTV ICRU reporting dose. The main advantage for using DAO was decreasing the number of segments to be used during treatment as well as decreasing the total number of monitor units should be delivered from linear accelerator which is reflecting on the treatment time and scattered radiation to the patients.

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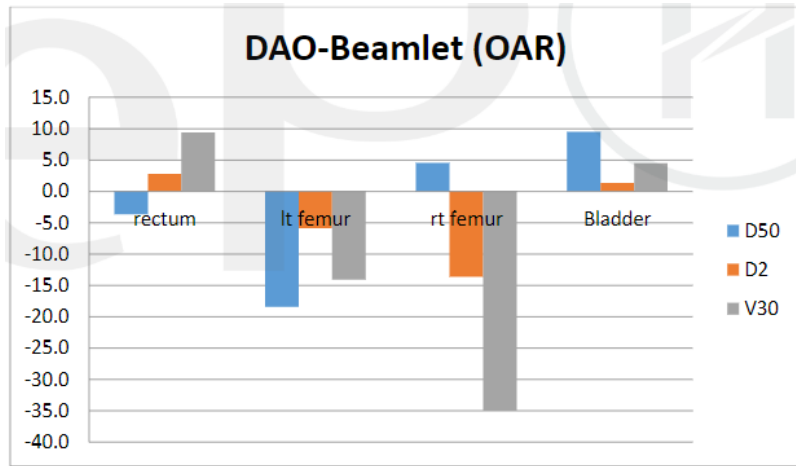
Fig. 10. The graph of OAR dose coverage difference between DAO and beamlet optimizer plans.

The number of segments in plan using DAO was constant at 81 because the planner determine it by himself, while it was varies from 100 up to 130 segments in plans using beamlet optimizer as shown in figure (11).
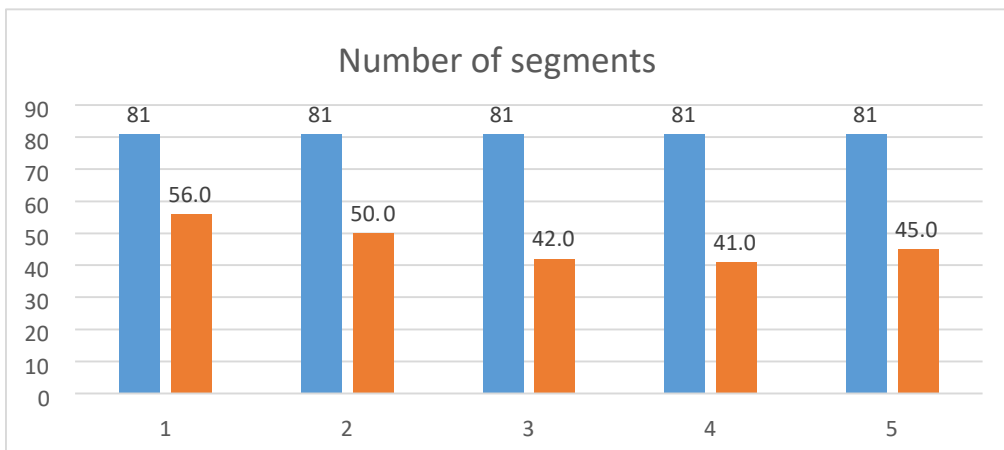

Fig. 11. The graph of segments number for prostate cases planned using DAO and beamlet optimizer plans.

Total monitor units should be delivered from linear accelerator was lower in DAO plans than those for beamlet plans by about 15% on average as shown in figure (12).
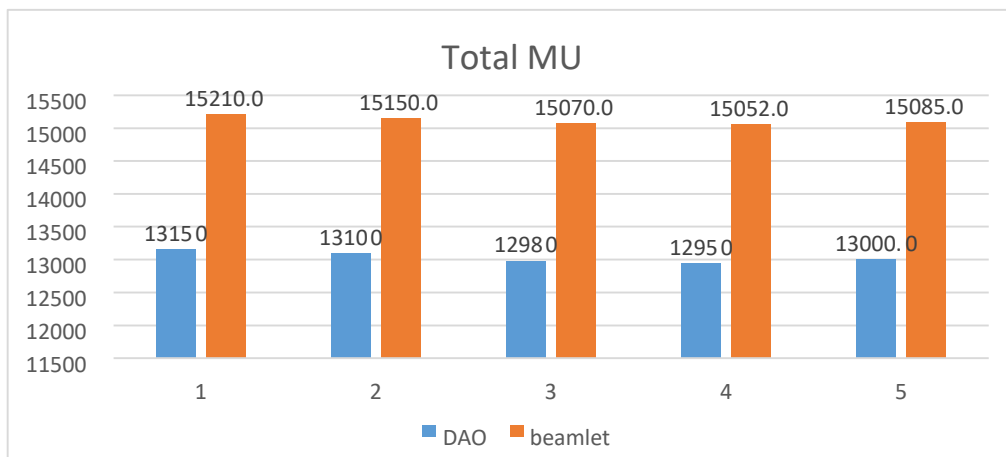

Fig. 12. The graph of total number of monitor units for prostate cases planned using DAO and beamlet optimizer plans.

IV. DISCUSSION

Direct Aperture optimization (DAO), sometime termed Direct Machine Parameter Optimization, is an inverse planning where the apertures are identified during the planning process, however the apertures are not selected by considering the anatomical relationship between the target and critical structures. The planner inputs the dose constraints, beam angles, energies and number of apertures. With DAO, the planner can also put a constraint on the minimum size of each aperture and place a lower bound on the weight[2]. The apertures are selected based on a few initial iterations and then the dose distribution is calculated for all fields. A large number of candidate apertures are sampled and either accepted or rejected depending on whether the plan is improved by adding the new aperture.

In beamlet based optimization a large beam is divided into many small beamlets of about 1 cm^2, then dose constraints are assigned to the targets and sensitive structures. Computerized inverse optimization must be performed to find the individual weights of this large number of beamlets. The computer adjusts the intensities of these beamlets according to the required planning dose objectives. Plans frequently fail to achieve the desired dose constraints and so clinical decisions have to be made as to which are most important and which can be relaxed. Once the optimal fluence map is decided upon, there is a further leaf sequencing step. The optimized intensity patterns are decomposed into a series of deliverable MLC shapes made up of a number of basic beamlets with mathematically related weights/intensities[11].

There are many dosimetric concerns associated with IMRT such as low MU per segment, high overall MU, and dosimetric uncertainties can be improved by controlling plan complexity. Direct aperture optimization is a method of controlling complexity that provides a significant reduction in the number of beam segments and MU required.

In beamlet optimization when converting the plan from the computer generated solution to deliverable segments, the dose distribution will degrade from that originally decided upon. DAO differs from beamlet optimization in that it does not rely on the use of a segmentation routine (sequencing step) to select the initial leaf sequence as this step is incorporated into the original optimization resulting in avoidance of the plan degradation which can occur.

Brain results showed that no significant difference in target coverage while DAO improved OAR sparing by about 35% better. The number of segments for DAO was approximately 65% segments less than those for beamlet optimizer. And number of total monitor units should be delivered from linear accelerator was 60% less in DAO plan, than in beamlet plans.

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