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Article

A Dosimetric Comparison of VMAT and IMRT for Head & Neck and Pelvis Cancers

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Abstract*— Cancer, which is the uncontrolled division of cells, is a leading fatal disease in the world with high mortality rates. It can be treated using several methods, including radiotherapy, which involves ionizing radiation. Radiotherapy on the basis of source placement has two types, i.e. brachytherapy and external beam radiotherapy. External beam radiotherapy has evolved from 2-D conventional therapy to 3-D Conformal radiotherapy (3D-CRT) and then intensity-modulated radiotherapy (IMRT). Modern radiation therapy techniques such as IMRT improve dose conformity and sparing of organs at risk. Volumetric modulated arc therapy (VMAT) is a newly developed technique that uses treatment in arcs. In this report, a dosimetry comparison was performed between IMRT and VMAT. This study was conducted in the Radiotherapy Department of the Institute of Nuclear Medicine and Oncology Lahore (INMOL). Two types of cancer patients were selected for this comparison, i.e., five patients with Nasopharyngeal Carcinoma and ten patients with Prostate Carcinoma. Simulation of these patients was done with the help of a CT Simulator. The oncologists delineated all target volumes and organs. Then suitable fields/arcs were applied, which cover volumes effectively. This was followed by the optimization of plans for both techniques for every patient. Finally, evaluating parameters were compared, including volume coverage, conformity index, homogeneity index, organ doses, and monitor units. We obtained better results of target conformity indices from VMAT (1.16 and 1.25) than IMRT (1.24 and 1.30). VMAT was better in organ sparing too. Also, VMAT shows very few monitor units (468 and 733) as compared to IMRT (2325 and 2149). On the basis of the results obtained, it was concluded that VMAT is better than IMRT. This technique will enhance treatment efficiency as it takes less time to obtain the required results. Also, a very less scatter dose will be delivered to the patient.

***Keywords*—** Radiotherapy; 2-D Conventional Radiotherapy; 3-D Conformal Radiotherapy; Intensity Modulated Radiotherapy; Volumetric Modulated Arc Therapy; Nasopharyngeal Carcinoma; Prostate Carcinoma.

I. INTRODUCTION

Cancer is one of the leading fatal diseases in the world. In this disease, cells of affected organs show uncontrolled division, eventually forming larger masses. It has a high mortality rate. In 2018, according to International Agency for Research on Cancer (IARC), more than 180 million new cases of cancer were observed worldwide, including 0.17 million cases in Pakistan. There are also nine million deaths due to cancer worldwide, including an estimated 0.12 million in Pakistan [1]. Cancer can be treated using several treatment

methods, including Surgery, Chemotherapy, Radiotherapy, Immune therapy, etc. In most cases, the patient is treated using a combination of these modalities [2].

Radiotherapy is employed in general for more than half of cancer patients alone or in combination with other modalities. In Radiotherapy, ionizing radiation is used to destroy cancer cells [3]. The basic aim of radiotherapy is radiation such that maximum interactions of radiation happen with cancer cells and the healthy tissues and organs at risk (OARs) are spared. Radiotherapy has two main branches, i.e., Brachytherapy and External Beam Radiotherapy (EBRT). In external beam radiotherapy, radiations are delivered externally, i.e., the radiation source is at a distance from cancer.

Two-Dimensional Radiotherapy (2D-RT) was initially used for treatment [4]. Lateral and anterior-posterior radiographs identified bony landmarks upon them. Then, rectangular fields were applied to the volumes containing cancer spread with a large number of normal tissues also included in irradiated volumes. For the sparing of these OARs, different shielding materials were used, e.g. cerrobend shielding and wedges [5].

After the development of computed tomography (CT) technology, target volumes for irradiation are obtained in three dimensions. Patients are scanned in the same position as of treatment. Then reconstruction of resultant axial images to desired planes, on which oncologists can draw the desired contouring, and the physicist creates a treatment plan using three-dimensional conformal radiation therapy (3D-CRT) [6]. Dose conformity is obtained by applying appropriate beams of beam's eye view (BEV) on images of targets. Each beam has a specific gantry angle, weight, and collimator angle. Beam modification can be obtained using different shielding blocks, wedges, and boluses. Planning is used, which accounts for tissue inhomogeneities present within the volume. Multi-leaf Collimators (MLCs) are being used to shape the sub-segments, increasing dose uniformity within the planning target volume (PTV).

After the advancement of MLCs and the development of inverse planning systems, Intensity Modulated Radiation Therapy (IMRT) was developed. This technique is based on two main steps, i.e., dose optimization and dose delivery [7].

Certain 'objective functions' are being assigned to target volumes and organs. There are some 'constraints' also present which should be fulfilled at every cost. A better plan will satisfy all the constraints and matches the objectives as well as possible with desired values. Multiple beams are applied at certain gantry angles. For every beam, optimized intensity levels are generated through Treatment Planning System (TPS). Every beam consists of many small beamlets that contain optimized intensity levels. MLC determines the width of these small beamlets, i.e., desired fluence map is obtained for every case.

The second step is the delivery of this map by leaf sequencing of MLCs to form desired apertures. There are two delivery methods, i.e., 'step and shoot' and 'dynamic' modes [8]. In the step-and-shoot technique, at all gantry angles, MLC leaves are arranged to certain desired patterns. All the desired fluences are delivered one after another. In dynamic mode, the beam is always on at a specific gantry angle. MLC leaves continually move during this time, and the desired fluence map is being delivered.

Amid getting better conformity, IMRT increases treatment time as a large number of monitor units were required to deliver its plans. Tomo-therapy was a technique in which the dose was delivered slice by slice in a spiral way as a CT mechanism. But again, treatment time and setup were inefficient in many circumstances. The Volumetric Modulated Arc Therapy (VMAT) technique was introduced, in which a rotational cone beam was used [9]. The gantry delivers dose by continuously moving in an arc. This technique showed a considerable reduction in treatment time and monitor units, providing the same conformity and other benefits of IMRT.

Delivery efficiency can be increased by carefully managing the speed of gantry rotation, MLC leaves speed and maximum amount of dose. VMAT has the ability to change the dose rate during the course of treatment. In optimizing the VMAT treatment plan, coarse sampling is applied at certain static gantry angles. Fluence maps or MLC aperture shapes are optimized at all angles in the same way as in IMRT. A method of progressive sampling is used for this procedure. In this method, optimization is started using a small number of samples and then adding new sample points. There should be enough samples available for the authentication of the dose models being used. For better delivery efficiency, the beam should be on throughout the arc. However, some relaxations must be provided due to limitations on speeds of gantry and MLCs and fluctuations of dose rate. MLCs are continually changing their position as they did in the dynamic mode of IMRT [10]. There should be an essential time given to them to re-orientate themselves before reaching the next sampling point. Less Monitor Units (MUs) and treatment time can benefit by delivering less scatter dose to the body of patients. This is also a key factor for the efficiency of the VMAT technique in clinical use [11].

This study evaluated IMRT and VMAT plans for Nasopharyngeal Carcinoma (NPC) and prostate carcinoma cases. Conformity Index (CI), Homogeneity Index (HI), and MUs were used as evaluating parameters. While comparing techniques, it was ensured that target coverage and doses to OARs were within limits imposed by the International Commission on Radiation Units and Measurements (ICRU) [12].

II. MATERIALS AND METHODS

A dosimetry comparison was performed between the two latest techniques of radiotherapy, i.e., IMRT and VMAT. This study was conducted in the Radiotherapy Department of the Institute of Nuclear Medicine and Oncology Lahore (INMOL).

Two types of cancer patients were selected for this comparison, i.e., five patients with nasopharyngeal carcinoma and 10 patients with prostate carcinoma. NPC patients were of stage 3/4 with the spread of cancer to near lymph nodal volume (T3/T4N2M0). Prostate patients of stage 3 or 4 were selected with diseases spread to the adjacent lymph nodes only(T3/T4N2M0).

CT Scanner was used to acquire initial data of patients. This procedure is called CT Simulation. Toshiba Aquillon CT scanner was used for CT simulation at INMOL. For defining the treatment field reference point, LAP Lasers were used. A slice thickness of 5 mm was used. Firstly, patients were set upon the CT scanner in the same position as of treatment

position. Different gadgets used in treatment, e.g., masks, pads, etc., were applied. Radiopaque markers (fiducial) were applied to laser cross-sections. Scout images were taken to set limits for the patient's CT scan. CT scan of that area was taken in the transverse plane, and other planes were reconstructed with the help of this data. In the end, all this data was transferred to TPS for further procedures.

For cases of nasopharyngeal carcinoma, oncologists drew the Gross Cancer Volume (GTV-High Risk) of primary cancer on each slice of data. 1.0 cm iso-centrical margins give us Clinical Target Volume (CTV-High Risk). CTV Intermediate Risk (CTV-IR) was drawn by giving margins of 0.5 cm to CTV-HR. This volume covers CTV-HR from all sides. As the disease is also present in lymph nodes, CTV Low Risk (CTV-LR) was also drawn by an oncologist. Then, a 0.5 cm margin in these CTVs for machine and delivery errors gave us Planning Target Volumes (PTV-HR, PTV-IR, and PTV-LR). All OARs were outlined by the oncologist, including brainstem, chiasma, parotids, lenses, and spinal canal. Figure 1 shows a delineation for one patient of NPC in this study. Doses to all targets/OARs were prescribed by the oncologist. PTV-HR was prescribed to deliver 69.96 Gy in 33 fractions. While in the same number of fractions, PTV-IR and PTV-LR were prescribed 61 Gy and 55.11 Gy, respectively. For the sparing of OARs, QUANTEC limits were followed.

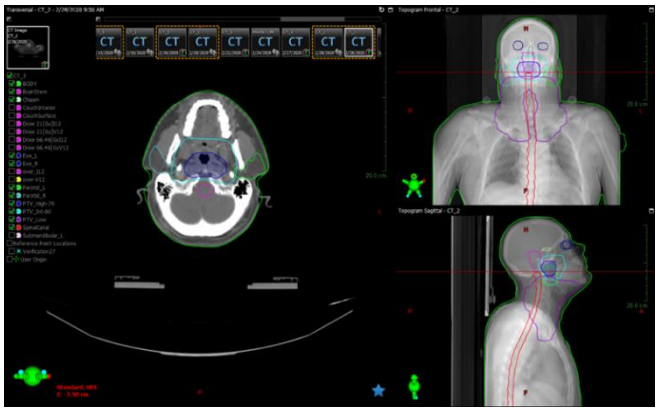

Figure 1. NPC case Delineation

For prostate carcinoma cases, GTV-HR, which contains primary cancer, was drawn. CTV-HR was obtained by giving iso-centrical margins of 1.0 cm to GTV-HR. Nodal Volumes were delineated by the oncologist as CTV-LR. After giving 0.5 cm margins, PTV-HR and PTV-LR were obtained. OARs like bladder, rectum, femoral heads, and small bowel were also drawn for each patient by an oncologist. Figure 2 shows targets/OARs delineation in one of the prostate carcinomas cases. Doses to all targets/OARs were prescribed by the oncologist. PTV-HR was prescribed to give 70 Gy in 28 fractions. While in the same number of fractions, PTV-LR was prescribed 50.4 Gy. For the sparing of OARs, QUANTEC limits (2.5Gy/fraction) were followed. These limits were obtained by modification limits of 2Gy/fraction by calculating equivalent doses (EQD2).

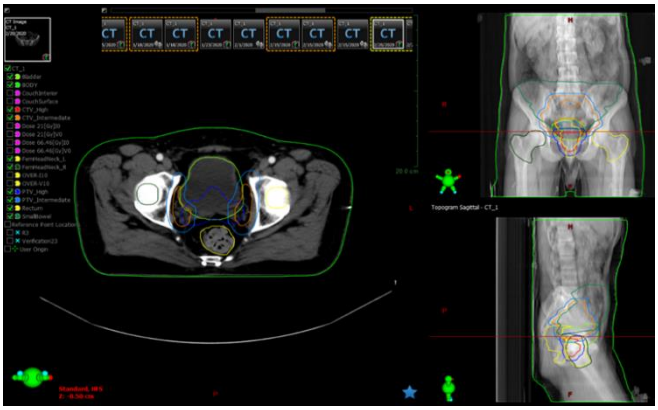

Figure 2. Prostate Carcinoma case delineation

For treatment planning, ECLIPSE Treatment Planning System (Version 15.6.04) was used. It uses an inverse planning technique. This system uses Photon Optimizer (PO) algorithm (version 15.6.04) for optimization. After optimization, the dose is calculated by Anisotropic Analytical Algorithm (AAA) (version 15.6.04). TPS provides resultant dose-volume histograms (DVHs) of all targets and organs to evaluate the required parameters.

For NPC VMAT planning, the 2.5 arcs technique was used. The Isocentre of these arcs was set upon the center of mass of PTV-LR. For prostate cases, the 1.5 arcs technique was used. The Isocentre of these arcs was set upon center of the mass of PTV-HR. A suitable collimator angle was given to the gantry head to effectively cover all target volumes. Figure demonstrates VMAT arcs upon both NPC and Prostate.

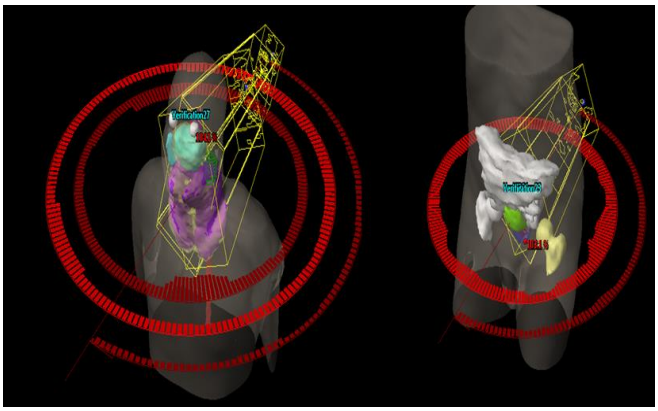

Figure 3. VMAT Planned Arcs

For NPC, 9 beams plan was generated for IMRT. These beams were applied on equally spaced angles (40 degrees apart). The Isocentre of these beams was set upon the center of mass of PTV-LR. In prostate carcinoma cases, 7 beams at equally spaced angles (50 degrees apart) were planned. The Isocentre of these beams was set upon the center of mass of PTV-HR. IMRT planned beams for both sites are given in Figure .

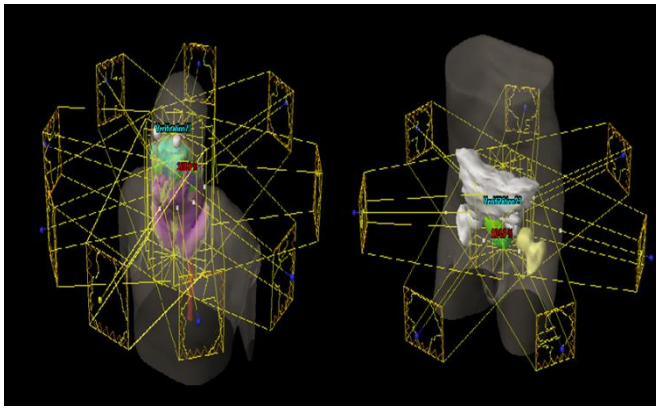

Figure 4. IMRT Planned beams.

For every case, a new treatment plan was generated. Firstly, the dose and number of fractions were set on our prescribed dose and fractions. Then arcs/beams were set. The target coverage was checked for each arc/beam. After this, the optimization of the plan was started. In optimization, the first step is to specify maximum/minimum dose limits for targets (according to ICRU 50) and set objectives/constraints for OARs. After that, different priority values were assigned to every target/organ. Different iterations were performed to reach our desired goal. After completion of optimization, the dose was calculated. Figure 5 demonstrates the optimization window.

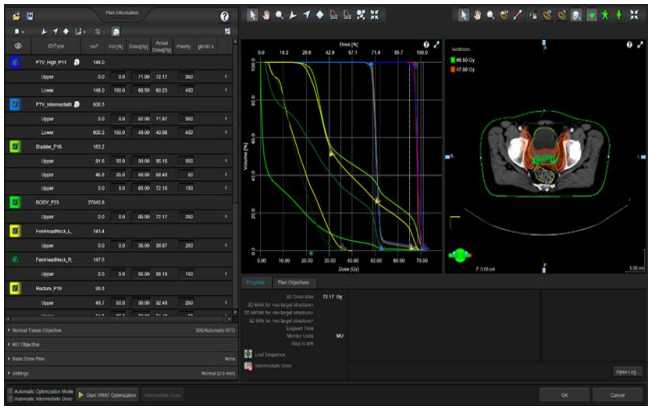

Figure 3. Optimization Window of Eclipse TPS (Version 15.6.04)

After that, all plans were evaluated on the basis of the following evaluation parameters.

1. In all plans, the same level of target volumes coverage was achieved, which fulfills ICRU 50 criteria. By achieving this criterion, the impact on other parameters was assessed for both techniques.
2. The conformity index (CI) was used to check the conformity of dose coverage of PTV-HR Volume. Its formula, as used in Lee et al. [13], is given as:

$$CI = \frac{D_{95} \times V_{PTV}}{OV^2}$$

Where:

D_{95} = Volume of 95% isodose curve.
V_{PTV} = Volume of PTV-HR
OV = Volume overlapped between PTV-HR and 95% isodose curve.

The value of CI should be close to 1 for a plan having better conformity.

3. Homogeneity Index (HI) accounts for homogeneity within the target volume. Its formula, as given by Wu et al. [14], is given by:

$$HI = \frac{D_2 - D_{98}}{D_p}$$

where:

D_2 = Maximum dose to 2% of PTV-HR volume.
D_{98} = Maximum dose to 98% of PTV-HR volume.
D_p = Prescribed dose to PTV-HR.

Ideally, its value should be close to 0 for better homogeneity in any plan.

4. The tumor coverage factor (TCF) determines the coverage of a reference dose in PTVPTV volume. It is defined as:

$$TCF = \frac{Volume\ of\ PTV\ recieving\ reference\ dose}{Total\ Volume\ of\ PTV}$$

As CI and HI well describe the characteristics of PTV-HR, we will evaluate this parameter on other planning volumes. Here reference dose is 95% of the prescribed dose to respective volumes.

5. It was ensured in every plan that doses don't exceed the limits assigned by QUANTEC. We noted every limit of every oar. Their DVHs were also plotted.
6. Monitor units for both plans were recorded and compared in each case. This parameter directly relates to treatment delivery time and dose to the patient.

III. RESULTS AND DISCUSSION

In the following section, all the results of this work are discussed.

A. Nasopharyngeal Carcinoma Results

The following results are obtained from work on nasopharyngeal carcinoma.

1) Targets Coverage:

During optimization, it was ensured that both techniques' plans achieved the same level of PTV Coverage. So, all of our plans achieved efficient coverage of the target volumes. Figure 6 shows the dose coverage of IMRT and VMAT on one of the NPC cases of this study.

In this study, the average D_{95} obtained for VMAT was 67.7 Gy, while for IMRT, it was 67.4 Gy. So, both modalities conform to the criteria imposed by ICRU 50. The average Maximum dose to PTV-HR was 74.5 Gy and 74.7 Gy for VMAT and IMRT, respectively. Therefore, both techniques fulfilled the ICRU 50 criteria of maximum doses.

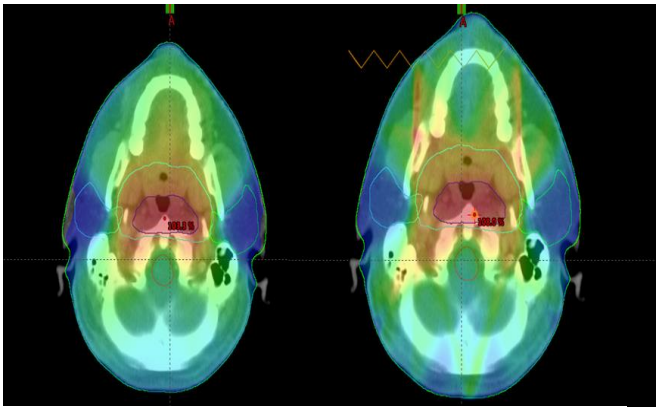

Figure 4. Dose coverage for IMRT (right) and VMAT (left)

The average value of CI was 1.25 and 1.30 for VMAT and IMRT, respectively. While on average, HI values were 0.08 (VMAT) and 0.07 (IMRT). VMAT shows a slightly better value of CI than IMRT because it delivers dose by optimization in an arc instead of beams at some angles, so better conformity of dose can be achieved. On the other hand, IMRT shows a slight improvement in HI, as less conformity will give better homogeneity.

Average TCF values for PTV-IR were 0.966 and 0.974 for VMAT and IMRT, respectively. While for PTV-LR, obtained values were 0.964 (VMAT) and 0.984 (IMRT). So, both techniques exhibit excellent coverage of PTV Intermediate risk and PTV low-risk volumes. However, in comparison, IMRT shows a slightly better result. One possible reason for this is optimization at suitable angles that effectively cover these volumes. The average DVHs of all PTVs can be seen in Figure 7.

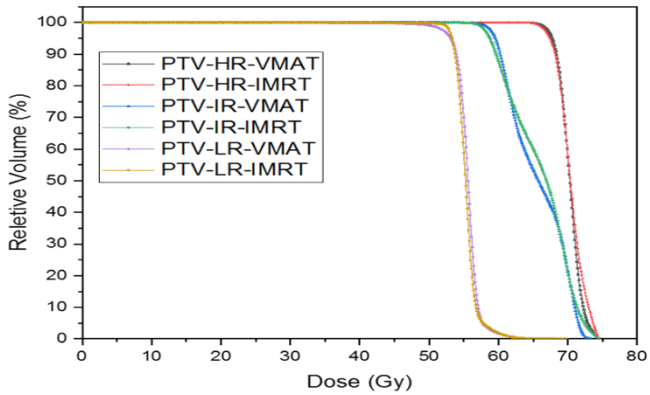

Figure 5. Average DVHs of PTV-HR, PTV-IR and PTV=LR in NPC cases.

2) Doses to OARs

In this study, the average maximum dose received to the brainstem was 48.42 Gy and 49.26 Gy from VMAT and IMRT, respectively. This shows that the results of both techniques are well within QUANTEC limits. However, VMAT shows a slightly low maximum dose than IMRT. The reason for this sparing is complete arc optimization, so fluence is adjusted in such a way that when the brainstem coincides with the field of view, low doses are delivered.

The average maximum dose to the right lenses of NPC patients was 6.74 Gy and 7.56 Gy from VMAT and IMRT. While to the left lenses, it was 6.59 Gy (VMAT) and 6.91 Gy (IMRT). This depicts that both techniques deliver doses that are within tolerance limits imposed by QUANTEC. However, IMRT delivers more doses in comparison with VMAT. One possible reason for this is that beams are angled at such points where they cover more lens volume delivering more doses to them.

The average mean doses to the right parotid were 18.54 Gy and 22.89 Gy from VMAT and IMRT, respectively. In comparison, left parotids received an average of 18.92 Gy from VMAT and 21.9 Gy from IMRT. Although mean doses of both parotids are within limits, VMAT demonstrates a slight superiority over IMRT in terms of parotid sparing. This is due to the complete arc rotation of VMAT, as it will efficiently control its fluence when the parotid's volume is in its way of radiating.

The average maximum doses of chiasma were 28.35 Gy and 30.99 Gy from VMAT and IMRT, respectively. These values show that the results of both techniques are within limits. However, VMAT shows a slightly lower maximum dose than IMRT. The reason for this sparing is complete arc optimization.

The spinal canal receives an average maximum dose of 40.46 Gy from VMAT and 41.32 Gy from IMRT. This shows that the results are within the tolerance limits of both techniques. However, VMAT shows a slightly low maximum dose than IMRT. The reason for this sparing is complete arc optimization. Figure 8 shows the Average DVHs of all OARs obtained in this study.

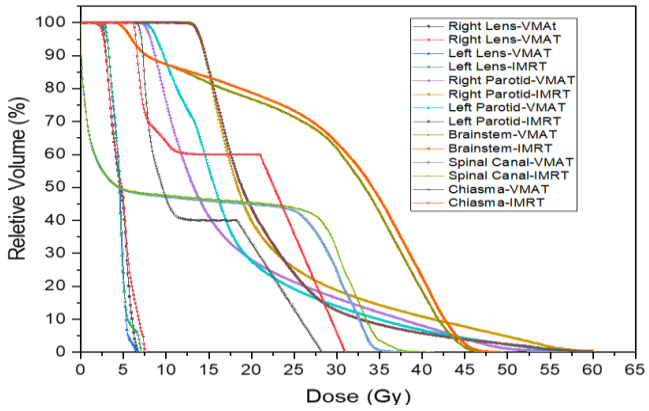

Figure 6. Average DVHs of Right Lens, Left Lens, Right Parotid, Left Parotid, Spinal Canal, Brainstem and Chiasma for IMRT and VMAT.

3) Monitor Units

The average monitor units obtained for VMAT were 468.4 and 2325.8 for IMRT. These values show a huge difference between monitor units that need to be delivered to implement our plans. IMRT shows a very large number of MUs than VMAT. This thing signifies the optimization in an arc over specific angles. Due to this, the treatment time will be significantly reduced for VMAT plans while delivering better results than IMRT.

B. Prostate Carcinoma Results

The following results are obtained from work on prostate carcinoma.

1) Target Coverage

During optimization, it was made sure that plans of both techniques achieved the same level of PTV Coverage. So, all of our plans achieved efficient coverage of target volumes. The average D95 for VMAT was 66.9 Gy and 66.5 Gy for IMRT. The average maximum dose in VMAT was 72.6 Gy and 73.6 Gy in IMRT. Figure 9 shows the dose coverage of IMRT (right) and VMAT (left) of one of the cases of this study.

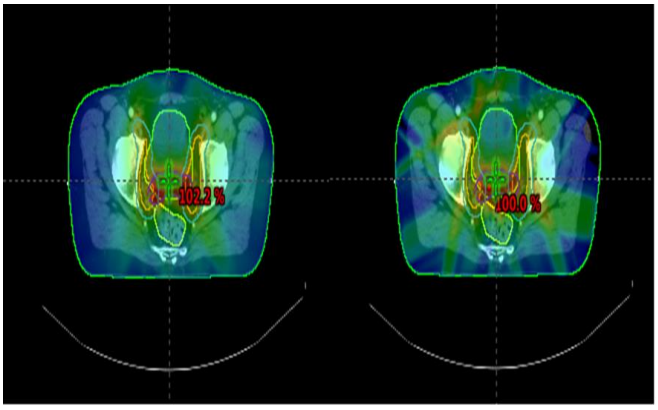

Figure 7. Dose coverage of VMAT and IMRT in prostate carcinoma

for IMRT plans. While average, HI values were 0.07 (VMAT) and 0.06 (IMRT). These values show that both techniques show excellent results in these parameters. VMAT shows a slightly better value of CI than IMRT because it delivers dose from an arc instead of beams at some angles, so better conformity of dose is achieved. On the other hand, IMRT shows a slight improvement in HI, as less conformity will give better homogeneity.

The average TCF values for PTV-LR were 0.971 for VMAT and 0.947 for IMRT. It shows that both techniques exhibit excellent coverage of PTV low-risk volume. However, in comparison, VMAT shows a slightly better result. One possible reason for this is complete arc rotation and effectively covering all volumes of PTV-LR. Figure 10 shows the average DVHs of all PTVs obtained in this study.

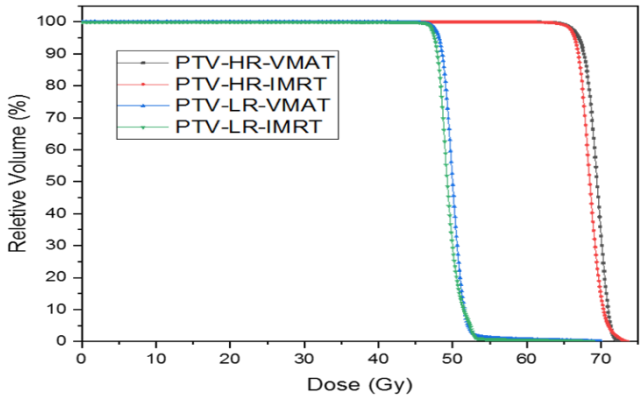

Figure 8. Average DVHs of PTV-HR and PTV-LR in prostate carcinoma cases.

2) Doses to OARs

For bladder, average values of QUANTEC limits (V59, V68, V72) were (20.93,11.66,0.24) for VMAT and (21.38,8.09,0.25) for IMRT. These values indicate that both techniques show excellent results as they are very much within limits. Although VMAT shows a slightly better bladder sparing as compared to IMRT. This sparing might be due to the presence of some IMRT beam which irradiates the bladder more than VMAT arc, which will reduce its fluence if the bladder comes in its way.

In this study, rectum parameters of QUANTEC limits (V45, V59, V68) were (29.07,12.26,2.55) for VMAT and (31.84,14.83,2.02) for IMRT. Although both are within QUANTEC limits, VMAT demonstrates a slight superiority over IMRT in terms of rectum sparing. This is due to the complete arc rotation of VMAT, as it will efficiently control its fluence when the rectum's volume is in its way of radiating. The average maximum dose to right femoral heads was 40.1 Gy and 39.77 Gy from VMAT and IMRT, respectively. While to the left femoral heads, it was 40.5 Gy (VMAT) and 40.52 Gy (IMRT). This data depicts that both techniques deliver doses that are within tolerance limits imposed by QUANTEC. However, IMRT delivers fewer doses in comparison with VMAT. One possible reason for this is that beams are angled at such points where they cover less volume of femoral heads, so less dose will be delivered to them.

Small bowel received an average mean dose of 25.79Gy from VMAT and 26.58Gy from IMRT. These values show that the results of both techniques are within limits. However, VMAT shows a slightly low mean dose than IMRT. The reason for this sparing is complete arc optimization. Figure 11 shows the average DVHs of all OARs of prostate carcinoma obtained in this study.

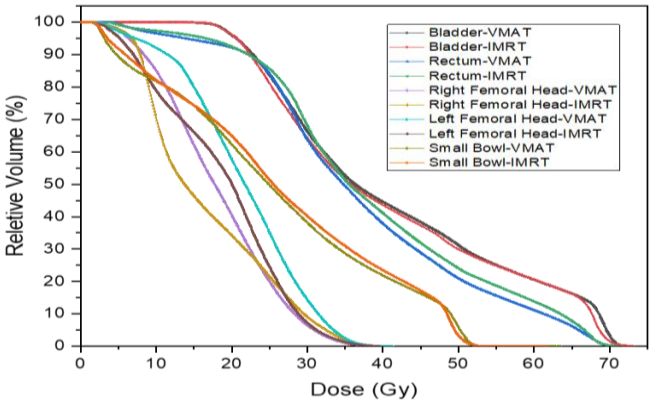

Figure 9. Average DVHs of Femoral Heads, Rectum, Small Bowl, and Bladder

3) Monitor Units

Obtained average monitor units for VMAT were 733.4 and 2149.1 for IMRT. This shows a huge difference between monitor units that need to deliver to impose our plans. IMRT requires a larger number of monitor units than VMAT, which reduces overall treatment time, keeping target coverage and OARs sparing the same.

IV. CONCLUSION

A dosimetric comparison was performed between IMRT and VMAT. Two patient cohorts, i.e., NPC and Prostate Carcinoma, were selected. After CT Simulation and Targets delineation, suitable arcs/beams were planned. Then all plans were optimized according to ICRU criteria. CI, HI, and the number of monitor units were compared for both techniques.

It was concluded in this study that VMAT proves to be a better technique than IMRT. While maintaining the same quality of plans, VMAT delivered fewer monitor units, leading to less treatment time and scatter dose. In developing countries like Pakistan, where the patient burden is one of the major concerns, VMAT will prove a more beneficial technique in treating a large number of patients.

CONSENT TO PARTICIPATE

Written informed consent was obtained from the patient for the anonymized information to be published in this article.

CONFLICT OF INTEREST

The authors declare that there is no conflict of interest regarding the publication of this paper.

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