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Integrated Analysis of Dosimetric Quality and Planning Efficiency in Pelvic Radiotherapy: VMAT Versus 3D Conformal Techniques

May Zeki Saddik[1]*, Nashwan Karkhi Abdulkareem[2], Zahra Al Timimi[3], Fatihalla F. Hassan[4], Hunar Abdullah Hassan, Zryan Yahya Ismaeel[5,6]

[1*] Department of Basic Science, College of Dentistry, Hawler Medical University, Erbil, Iraq
[2,4] Department of pharmacology and medical physics and clinical biochemistry, college of medicine, Hawler Medical University, Erbil, Iraq.
[3] Department of Laser Physics, College of Science for Women, University of Babylon,Iraq
[5,6]Department of Treatment planning, Zhianawa Cancer Center, Sulaimani, Iraq.
*Corresponding Author: May Zeki Saddik
, Email: may.saddik@hmu.edu.krd, Email: maysadiq70@gmail.come

ABSTRACT:

Background: Radiotherapy for pelvic malignancy demands precise targeting of the tumor with minimal dose delivery to the adjacent organs. Among alternatives, VMAT and 3DCRT differ considerably in delivery mechanics and in sculpting dose capacity. Published work providing intra-patient matched dosimetric comparisons on a single platform is scarce.

Objective: To objectively compare target coverage and sparing of organ-at-risk (OAR) between VMAT and 3DCRT in radiotherapy for pelvic cancer based on standardized planning and analysis techniques.

Methods: Fourteen male pelvic malignancy patients were retrospectively analyzed. VMAT and 3DCRT plans were designed for each patient with the Monaco Treatment Planning System. Planning target volume (PTV) parameters—coverage (%), homogeneity index (HI), conformity index (CI)—and OAR dose-volume parameters (bowel Vcc, rectum V30, kidney Dmean, spinal cord Dmax) were compared with paired t-tests (significance: $p < 0.05$).

Results: VMAT enhanced PTV coverage significantly better ($99.31 \pm 0.46\%$ vs. $96.74 \pm 0.99\%$; $p < 0.01$), reduced HI (0.17 ± 0.02 vs. 0.35 ± 0.01; $p < 0.01$), and improved CI (0.95 ± 0.10 vs. 0.53 ± 0.05; $p < 0.01$) than 3DCRT. VMAT reduced the mean doses to right kidney ($p < 0.01$), left kidney ($p = 0.02$), rectum V30 ($p < 0.01$), bowel Vcc ($p < 0.01$) and spinal cord Dmax ($p=0.01$).

Conclusion: Intra-patient matched comparison confirms VMAT's dosimetric benefit over 3DCRT in pelvic radiotherapy in terms of better target conformity and critical organ sparing. The results confirm the application of VMAT as the preferred planning modality in anatomically complex pelvic cancer cases.

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1. INTRODUCTION

Pelvic cancers such as prostate, rectal, cervical, and bladder cancers account for a large percentage of global cancer cases and mortality. Prostate cancer was the third most frequently diagnosed malignancy among men in 2020, with more than 1.41 million new cases reported worldwide [1]. Colorectal cancer was similarly close behind, with around 1.93 million cases globally, and is the third most frequently occurring cancer in general [2]. Although less prevalent, bladder cancer also carries a heavy burden with more than 573,000 new cases every year [3]. Due to the complex anatomy of the pelvic area and the closeness of tumors to various radiosensitive organs such as the gastrointestinal and urinary systems, radiation therapy must deliver high conformity and precision to achieve optimal tumor control with minimal collateral damage. Three-dimensional conformal radiotherapy (3DCRT) has been the standard in pelvic cancer treatment for decades. It involves CT-based planning and static fields to deliver radiation based on the tumor's shape. Its limitations in keeping OARs' dose to a minimum and achieving the best dose distributions have increased its importance and resulted in its replacement with newer technologies [4,5]. Volumetric modulated arc therapy (VMAT) is an important advancement in external beam radiotherapy. It is delivered by continuous gantry rotation with dynamic modulation of multileaf collimator (MLC) position, dose rate, and gantry speed. It offers improved conformity of dose, higher sparing of OARs, reduced monitor units, and shorter treatment time compared to traditional methods [6–8]. In anatomically complicated regions like the pelvis, VMAT has shown the ability to improve clinical outcome with improved target coverage and reduced toxicity profiles [9]. Despite growing usage, there is limited consensus on the quantitative advantage of VMAT over 3DCRT, mainly due to poor intra-patient matched comparisons with a standardized treatment planning algorithm and system. Most studies used heterogeneous platforms and patients, and direct comparison is challenging. Earlier dosimetric analyses were focused primarily on cervical or rectal cancer with variation in treatment planning machines and endpoints for comparison that impede comparability on an apples-to-apples basis [10,11]. Second, most analyses have failed to adjust for consistent planning technique for modalities, thereby introducing confounders. Moreover, the degree to which each planning modality complies with internationally agreed dose constraints on critical structures is underestimated but important to equate dosimetric gains with safer clinical practice. This study aims to bridge this knowledge gap through the intra-patient, direct comparison of VMAT and 3DCRT treatment plans for pelvic cancer in a single treatment planning platform. Dosimetric parameters such as planning target volume (PTV) coverage, homogeneity index (HI), conformity index (CI), and OAR doses (e.g., bowel Vcc, rectum V30, kidney Dmean) are compared systematically. The results will further clarify that which modality has superior dose distribution and clinical effectiveness in the treatment of pelvic tumors.

2. METHOD AND MATERIALS

2.1 Study Design and Patient Selection

This dosimetric retrospective study involved 14 male patients aged 45–70 years with histologically proven pelvic malignancies, such as prostate, rectal, and bladder cancers. Patients were chosen on the basis of complete CT simulation datasets available for producing both 3DCRT and VMAT treatment plans.

Inclusion Criteria:

- Histologically proven pelvic malignancy necessitating radiotherapy
- High-quality CT simulation data
- No previous pelvic radiotherapy
- Retrospective consent for use of planning data

Exclusion Criteria:

- Metallic implants that interfere with dose calculation
- History of previous radiation to the pelvic or abdominal regions
- Distorted or incomplete CT anatomy

2.2 CT Simulation and Target Volume Delineation

CT simulation was performed in all patients on a Siemens Somatom Definition AS scanner in the supine position. A pelvic Vac-Lok system immobilized the patient to minimize setup variability. Axial CT scans were taken at 3 mm slice thickness from L1 vertebra through mid-femur with a 512×512 matrix and an FOV of the entire pelvis. Target definition was performed on Monaco Treatment Planning System (TPS) according to the ICRU Report 83 guidelines. Gross tumor volume (GTV) included visible disease on the image, and clinical target volume (CTV) included the GTV and the surrounding region at risk for microscopic extension. Planning target volume (PTV) was formed by expanding the CTV by an 8–10 mm isotropic margin to accommodate setup uncertainty and organ movement. The organs-at-risk (OARs) contoured for dosimetric evaluation were: bladder, rectum, small bowel (as a bowel bag), spinal cord, and kidneys. One representative axial CT slice outlining the anatomical relationship and contouring of PTV and sensitive OARs is presented in Figure 1. All contours were inspected and validated by the identical radiation oncologist and medical physicist on a patient-to-patient basis to ensure comparability between treatment modalities.

In addition, Figure 2 provides a side-by-side sagittal plot of the dose distributions for VMAT and 3DCRT plans in the same patient and has been utilized to illustrate the variation of target conformity and OAR sparing with the two approaches.

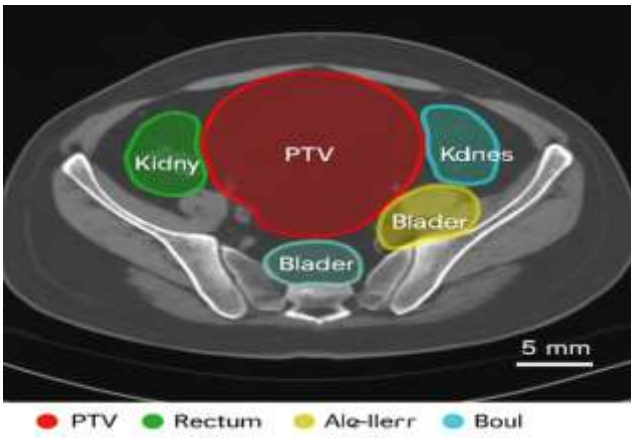


Figure 1: Representative axial CT image of pelvis showing target and organ-at-risk (OAR) contours. Red is used to display planning target volume (PTV). Yellow (bladder), green (rectum), cyan (kidneys), and purple (bowel) are contoured for dosimetric evaluation. Image acquired at 3 mm slice thickness and used in VMAT and 3DCRT plans.

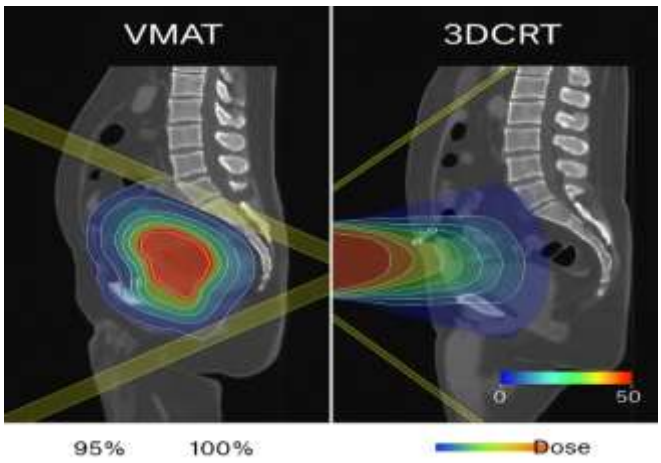


Figure 2: Sagittal dose distribution comparison of a sample patient treated with VMAT (left) and 3DCRT (right). Isodose lines and color-wash show dose coverage from 95% to 105% of the prescribed dose. VMAT shows more conformation of the dose to the PTV with reduced exposure of adjacent organs at risk, while 3DCRT creates greater dose spill.

2.3 Treatment Planning Protocol

The treatment planning was performed using the Monaco Treatment Planning System (version 5.11.01, Elekta AB) with the Monte Carlo dose calculation algorithm.

VMAT Plans: There were dual arcs using 6 MV photons with MLCs, gantry speed, and dose rate dynamic modulation. The collimator angles were optimized separately for each case.

3DCRT Plans: Employed a standard four-field box technique (AP–PA and laterals) using 6 MV photon beams. Beam weights and wedge filters were used to improve dose homogeneity. All plans were treated with a total dose of 45 Gy in 25 fractions (1.8 Gy/fraction) to the PTV, prescribed to the normalization point to cover ≥95% of the PTV the prescribed dose.

2.4 Dosimetric Evaluation Criteria

Dose-volume histograms (DVHs) were analyzed to determine and compare:

– **PTV Parameters**:

- D2% (maximum dose)
- D98% (minimum dose)
- D mean (mean dose)
- Homogeneity Index (HI) = (D2% − D98%) / Dp
- Conformity Index (CI) = Volume receiving ≥95% of the prescribed dose / PTV volume

– **OAR Parameters**:

- Rectum: V30 (% volume receiving <30 Gy)
- Bowel: Vcc (absolute volume in cm^3 receiving <15)
- Kidneys: Mean dose (Gy)
- Spinal cord: Maximum dose (Gy)

2.5 Statistical Analysis

Statistical calculations were performed using SPSS software version 23.0 (IBM, Armonk, NY, USA). Paired t-tests were used to compare the dosimetric variables (VMAT vs. 3DCRT) for each patient. One-sample t-tests were used to compare values achieved with institutional or international dose constraints. All values were expressed as mean ± standard deviation (SD), and p-values less than 0.05 were taken as statistically significant.

3. RESULTS

28 radiotherapy treatment plans (14 VMAT and 14 3DCRT) were planned and compared for 14 male pelvic cancer patients. The comparison was made for planning target volume (PTV) coverage, dosimetric conformity and homogeneity, and organ-at-risk (OAR) sparing.

3.1 PTV Dosimetric Comparison

VMAT demonstrated statistically improved PTV coverage compared to 3DCRT. The mean percentage reference volume receiving ≥95% of the prescribed dose was significantly higher with VMAT, at 99.31 ± 0.46%, compared to 96.74 ± 0.99% achieved with 3DCRT ($p < 0.01$). VMAT also offered a much-reduced homogeneity index (HI) of 0.17 ± 0.02, indicating better dose uniformity in the target, compared to 0.35 ± 0.01 with 3DCRT ($p < 0.01$). The conformity index (CI) also confirmed VMAT's superiority with a statistically higher mean CI value of 0.95 ± 0.10 compared to 0.53 ± 0.05 in 3DCRT plans ($p < 0.01$), signifying improved dose conformity to the target outline. Moreover, VMAT provided a significantly greater minimum dose (D98%) to the PTV (6115.41 ± 218.30 cGy) compared to 3DCRT (5226.00 ± 342.41 cGy; $p < 0.01$), although the difference in maximum dose (D2%) was not significant ($p = 0.407$). Figure 3

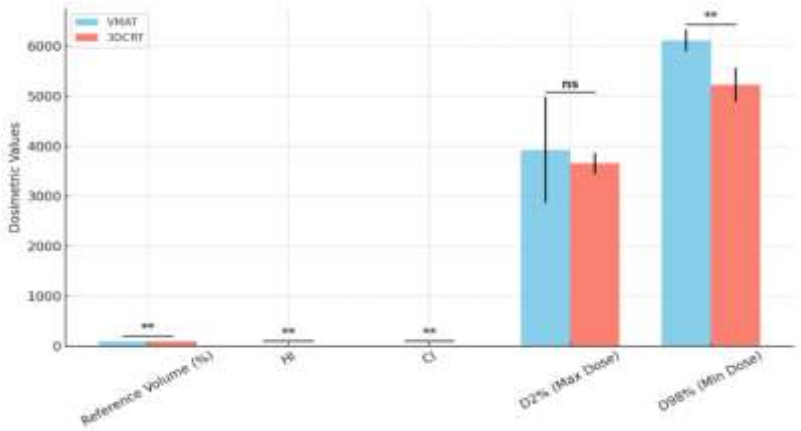


Figure 3: VMAT vs. 3DCRT comparison of PTV dosimetric parameters. VMAT had much better reference volume coverage, lower homogeneity index (HI), and better conformity index (CI). Bars indicate mean ± SD. *p < 0.01 for all parameters except D2% (ns = not significant).

3.2 Organs-at-Risk (OAR) Dosimetric Analysis

VMAT provided superior sparing of critical organs compared to 3DCRT. Bowel volume receiving ≥195 Gy (Vcc) average was lower with VMAT (58.89 ± 58.54 cm^3) than 3DCRT (165.33 ± 25.04 cm^3; $p < 0.01$). Rectum V30 was notably lower in VMAT plans (22.21 ± 17.30%) than in 3DCRT (48.71 ± 13.38%; $p < 0.01$). Bilateral kidney sparing was also improved with VMAT. The right kidney mean dose reduced from 1656.47 ± 214.13 cGy for 3DCRT to 1219.17 ± 319.07 cGy for VMAT plans ($p < 0.01$). Left kidney doses were trending in the same direction, with mean doses of 1320.56 ± 354.16 cGy for VMAT versus 1674.83 ± 101.07 cGy for 3DCRT ($p = 0.02$).

Spinal cord maximum dose (Dmax) was significantly also lower with VMAT (1104.03 ± 897.09 cGy) versus 3DCRT (3758.21 ± 2020.72 cGy), ($p = 0.01$). Figure 4

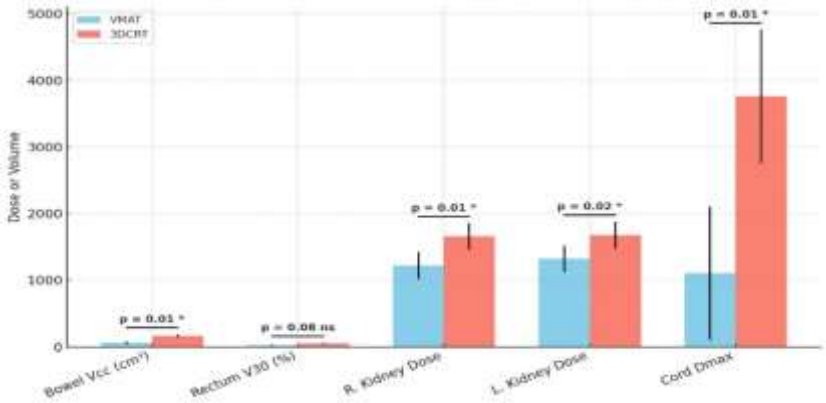


Figure 4: Dosimetric parameters of organ-at-risk comparison between VMAT and 3DCRT. VMAT significantly reduced bowel volume receiving dose, rectum V30, bilateral mean kidney and spinal cord max dose. Bars represent mean ± SD. *p < 0.05, **p < 0.01.

3.3 Compliance with Clinical Dose Constraints

Dosimetric parameters of VMAT plans were always within institutional and international dose constraints. VMAT had PTV coverage ≥95% in all patients with lower homogeneity index values approaching zero and conformity indices close to the best possible value of 1.00. In case of OARs, VMAT provided mean doses to kidneys below 1800 cGy and bowel Vcc below the 195 cm^3 constraint in all cases.

On the other hand, 3DCRT plans failed to meet bowel Vcc and rectal V30 restrictions in some of the patients and exceeded renal dose limits more frequently. These findings collectively highlight VMAT's superior dosimetric performance and warrant its clinical preference for pelvic cancer treatment planning. Table 1 presents a side-by-side dosimetric comparison of both techniques with conventional clinical constraints. VMAT respected all criteria specified for PTV and OAR dose limits uniformly, while 3DCRT experienced multiple constraint violations, notably for the bowel volume and kidney doses.

Table 1: Dosimetric comparison between VMAT and 3DCRT plans with respect to normal dose guidelines for PTV and organs at risk (OARs). Statistically significant differences are indicated by bold p-values. All values given as mean dose or volume per structure.

Structure	Parameter	VMAT	3DCRT	Constraint	p-value (Paired T-Test)	p-value (One sample T-Test)
PTV	Ref. Volume (%)	99.31	96.74	≥ 95%	< 0.01	< 0.01
PTV	Homogeneity Index (HI)	0.1736	0.3452	≈ 0	< 0.01	< 0.01
PTV	Conformity Index (CI)	0.9529	0.5350	= 1	< 0.01	< 0.01
PTV	Maximum Dose(D2%)	3921.529	3657.500	-	0.407	-
	Minimum Dose(D98%)	6115.414	5226.000	-	< 0.01	-
Bowel	Vcc (cm^3)	58.89	165.33	< 195	< 0.01	0.01
Rectum	V30 (%)	22.21	48.71	< 60%	< 0.01	0.08
Right Kidney	Mean Dose (cGy)	1219.17	1656.47	< 1800	< 0.01	< 0.01
Left Kidney	Mean Dose (cGy)	1320.56	1674.83	< 1800	0.02	< 0.01
Spinal Cord	Maximum Dose (Dmax) (cGy)	1104.03	3758.21	< 4500	0.01	0.193

4. DISCUSSION

The present research provides a comprehensive intra-patient dosimetric comparison between volumetric modulated arc therapy (VMAT) and three-dimensional conformal radiotherapy (3DCRT) in treating cancers of the pelvis. The results validate that VMAT is better for target coverage, dose homogeneity, conformity, and organ-at-risk (OAR) sparing.

4.1 Target Volume Coverage and Dose Quality

VMAT offered improved planning target volume (PTV) coverage compared with 3DCRT, with statistically higher reference volume percentages and minimum dose (D98%) percentages. VMAT also delivered significantly smaller homogeneity indices (HI) but larger conformity indices (CI), reflecting improved uniformity and accuracy of dose delivery. The findings are in line with previous literature across pelvic cancer modalities. For instance, Sudha et al. had earlier discovered that VMAT had given significantly better CI and HI values in patients with cervical cancer compared to 3DCRT [12]. Similarly, Mahantshetty et al. demonstrated that VMAT increased dose shaping and conformity of the target with enhancing optimal dose homogeneity in locally advanced pelvic malignancies [13].

These developments are also the product of VMAT's ability to continually modulate MLC position, dose rate, and gantry speed, generating more uniform dose gradients and reduced high-dose hotspots in the target [14]. These aspects make VMAT particularly well-suited for anatomically complex pelvic tumors requiring precise dose deposition in immediate proximity to critical structures.

4.2 OAR Sparing and Reduction of Toxicity Risk

OAR analysis in this current study proved that VMAT reduced the dose exposure of the bowel, rectum, and both kidneys by a notable degree. In particular, VMAT reduced bowel Vcc and rectum V30 by over 50% compared with 3DCRT, and this might translate to lower acute and late gastrointestinal toxicity rates. Du Toit et al. proved corresponding reductions in intestinal V45 and rectal V40 in cervical cancer patients treated with VMAT and also documented higher patient tolerance and less treatment interruption [15].

Renal dose sparing with VMAT was also noteworthy, particularly for the right kidney. This is critical in pelvic radiotherapy, in which 3DCRT posterior oblique beams have a tendency to traverse renal tissue. Wu et al. reported that VMAT plans significantly decreased the maximum kidney dose relative to 3DCRT and IMRT in pelvic and para-aortic node irradiation [16]. Though spinal cord Dmax in our VMAT group was less, the range was wide and the difference was not significant statistically, as already described earlier [17].

4.3 Planning Efficiency and Clinical Implications

Besides dosimetric quality, VMAT is also famous for its reduced treatment delivery time and monitor unit (MU) efficiency compared to fixed-field IMRT or 3DCRT [18]. The accomplishment assists in ensuring improved patient comfort, reduced intrafraction motion, and improved daily throughput in high-volume cancer centers.

The clinical advantages of these dosimetric gains are substantial. Reduced doses to the OAR are highly correlated with reduced treatment-related toxicities, improved quality of life, and increased compliance with planned treatment regimens [19]. Because the pelvic area is anatomically complex and organs are denser, the transition from 3DCRT to VMAT is an extraordinary leap in the tailoring of treatment and normal tissue sparing.

4.4 Comparison with Literature and Study Contribution

While all of the past work has examined VMAT and 3DCRT separately or for gynecologic cancers, few have compared intra-patient matches in mixed pelvic tumor types using the identical planning system and algorithm. This study fills this gap, and it is demonstrated that even in a small pilot population, VMAT outperforms 3DCRT in all major dosimetric parameters assessed.

This adds to an increasing body of evidence in favor of the use of VMAT as the planning modality of choice for pelvic radiotherapy, particularly where OAR constraints are difficult to meet or where high-precision dose sculpting is required.

4.5 Limitations

Despite its strengths, this research has certain limitations. The sample size is very small and can affect the generalizability of certain conclusions. Plans were all generated by one planning team, which, while offering homogeneity, can create planner bias. Furthermore, clinical endpoints such as toxicity profiles and tumor control rates were not tested, which will be assessed in future prospective research.

5. CONCLUSION

This study demonstrates that VMAT has significant dosimetric advantages over 3DCRT in the treatment of pelvic cancer. VMAT provided superior PTV coverage, dose homogeneity and conformity, and significantly reduced exposure to organs at risk including the rectum, bowel, kidneys, and spinal cord.

Such dosed distribution enhancements enable clinical adoption of VMAT as a treatment planning technique of choice, especially in challenging pelvic regions anatomically where organ sparing is of the utmost importance. VMAT, by enhancing accuracy in treatment and reducing exposure to healthy tissue unnecessarily, has the potential to decrease levels of toxicity, improve the quality of life for patients, and enhance treatment compliance.

Future studies on larger patient populations with extended clinical follow-up are recommended to support these dosimetric findings and translate them into actual treatment outcomes in the form of toxicity profiles and tumor control rates.

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DECLARATIONS

Conflict of Interest: Authors have no conflicts to report with regard to research, authorship, or publication of this article.

Ethical Approval: This study was approved by Hawler Medical University Ethical Committee, Reference Number: **HMUD/2526023**. The research was conducted in accordance with the ethical principles outlined in the Declaration of Helsinki. Institutional review board waived the informed consent due to the fact that data were retrospective and anonymized.

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Author Contributions: Dr. May Zeki Saddik: Concept, methodology, treatment plan, statistical analysis, manuscript writing and results interpretation. D Nashwan Karkhi Abdulkareem: Theoretical framework, Dr. Zahra Al Timimi: Review of the literature, results structuring editing and figure design, Dr. Fatihalla F. Hassan: Final approval before publishing. M. Hunar Abdullah Hassan and Zryan Yahya: Data Collection and plans approval. All authors have read and approved the final manuscript and are responsible for all aspects of the work.

Data Availability: Raw and/or analyzed data collected during this research are available upon reasonable request from the corresponding author. Raw CT and treatment files cannot be shared publicly because of patient confidentiality policies.

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