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Comparison of Dose Distribution with Graphical Optimization and Inverse Planning Techniques in Cervical Cancer Brachytherapy

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Abstract: Cervical cancer is the leading cause of death among women in Indonesia, with 36,964 new cases reported in 2022. Brachytherapy is a key component in treating advanced-stage cervical cancer, where dose optimization is critical to maximize the target dose (HRCTV) and minimize exposure to organs at risk. Graphical Optimization (GrO) and Inverse Planning (IP) techniques are commonly used, but comparative studies using Co-60 sources remain limited. Previous studies have largely used Ir-192, so this study explores the comparison of GrO versus IP using Co-60, which has not been widely studied in Indonesia. Co-60 was chosen because it provides a dose distribution comparable to Ir-192, has a longer half-life reducing the frequency of source replacements and maintenance costs and has been reported to shorten patient treatment time by approximately 10%. This study compared the dose distribution of both techniques in 30 brachytherapy patients treated with a Co-60 source at Prof. Dr. I.G.N.G. Ngoerah Hospital. Data were analyzed using the Sagiplan 2.2.1 Treatment Planning System (TPS) following the TG-43 protocol. Evaluations included D90 HRCTV, COIN, DHI, bladder D2cc, and rectum D2cc based on ICRU Report 89 recommendations. MANOVA results (SPSS 29.0; significance < 0.05) showed that GrO's D90 HRCTV (7.239 Gy ± 0.134 Gy) was significantly higher (sig = 0.006) than IP (7.155 Gy ± 0.093 Gy). GrO's DHI (0.352 ± 0.043) was also superior (sig = 0.030), while COIN, bladder D2cc, and rectum D2cc showed no significant differences. Overall dose distribution for GrO differed significantly from IP (p = 0.011), though all parameters met ICRU standards. Conclusion: GrO excels in target coverage and homogeneity, while IP is equivalent in OAR protection. Both techniques are dosimetrically feasible, but GrO is more adaptive for complex anatomies despite requiring longer planning time.

Keywords: Brachytherapy; Cervical cancer; Dose distribution; Graphical optimization (GrO); Inverse planning (IP)

Introduction

Cervical cancer remains a major contributor to female mortality globally, with Indonesia being no exception. The primary cause of this condition is infection by the Human Papilloma Virus (HPV), notably the high-risk strains HPV 16 and 18, which spreads through sexual contact(Dewi et al., 2024; Puteri, 2020). According to the Global Burden of Cancer Study (Globocan) 2022, Indonesia rank s third in Asia for cervical cancer cases, with 36,964 new cases and 20,708 deaths(Utami et al., 2025; Winarno et al., 2021). One of the most effective treatment methods for cervical cancer is radiotherapy, which uses high-dose radiation to kill cancer cells while preserving surrounding healthy tissues(Abdel et al., 2021; Sharma et al., 2023). Radiotherapy techniques include external therapy and brachytherapy. Brachytherapy involves inserting a radiation source into the patient's body to achieve precise dose distribution(Pathak et al., 2024). This

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technique is often combined with external radiotherapy or chemotherapy, especially for advanced-stage cervical cancer(Doudoo et al., 2023; Jayakody et al., 2022; Suharmono et al., 2021). However, its success depends significantly on the accuracy of dose distribution planning, which is managed through the Treatment Planning System (TPS). Treatment Planning Systems (TPS) are designed to precisely deliver radiation doses to the High-Risk Clinical Target Volume (HRCTV) while maintaining safe exposure levels for adjacent organs at risk (OARs), such as the bladder and rectum, in compliance with the International Commission on Radiation Units and Measurements (ICRU) Report 89 guidelines(ICRU, 2013; Petric et al., 2008; Petrič et al., 2011). The main challenge lies in optimizing parameters such as dwell time and dwell position to achieve a balance between treatment effectiveness and patient safety(Aldelaijan et al., 2018; Gul et al., 2021; Johansen et al., 2019).

In clinical practice, two commonly used dose optimization techniques in brachytherapy Treatment Planning Systems (TPS) are Graphical Optimization (GrO) and Inverse Planning (IP). GrO relies on manual adjustments of isodose lines by medical physicists to cover the HRCTV while avoiding the OAR, whereas IP utilizes computer algorithms to calculate dose distribution based on predefined constraints (e.g., D_{90} HRCTV at 100%Rx-107%Rx of the prescription dose, D_{2cc} bladder ≤80%Rx, and D_{2cc} rectum ≤75%Rx)(Gül et al., 2024; Roy et al., 2021). According to a study by Roy et al. (2020), treatment planning using the IP technique resulted in lower OAR dose values than the GrO technique(Roy et al., 2021). Meanwhile, a study by Gul et al. (2024) found no difference between treatment planning results using GrO and IP in terms of the dose received by the target (HRCTV). However, for the dose received by the OAR, the IP technique delivered a lower dose than the GrO technique (Gül et al., 2024). These studies were conducted exclusively using Ir-192 brachytherapy sources, therefore this study further explores the results of treatment planning using GrO and IP with Co-60 brachytherapy sources which have not been widely studied in Indonesia(Gül et al., 2024; Palled et al., 2020; Tang et al., 2019; Vijande et al., 2021). The use of the Co-60 radioisotope is based on previous research, which found no significant difference in dose distribution between brachytherapy using the Ir-192 and Co-60 radioisotopes(Tamihardja et al., 2022; Wen et al., 2022). In addition, the use of the Co-60 radioisotope also minimizes maintenance costs, because its half-life is longer (5 years) compared to Ir-192 (74 days) which means that the replacement of the radioisotope source is carried out less frequently and reduces accuracy errors due to decreased radioactive activity(Sadeghi et al., 2021; Tamihardja et al., 2022; Wen et al., 2022). The use of radioactive Co-60 also provides a reduction in patient treatment time approximately 10%(Fotina et al., 2018; Sadeghi et al., 2021; Shukla et al., 2019; Srivastava et al., 2022). Therefore, further research is conducted to evaluate the differences in dose distribution results between these two techniques when using the Co-60 radiation source in cervical cancer brachytherapy.

Method

Treatment planning

This study used data from 30 patient treatment plans who underwent brachytherapy at the Radiotherapy Sub-Installation of Prof. Dr. I. G. N. G. Ngoerah Central General Hospital as research samples. All patients received external radiotherapy with a total dose of 50 Gy administered in 25 fractions, followed by brachytherapy. For brachytherapy, a dose of 7 Gy per fraction was delivered in 3 fractions. The Sagiplan 2.2.1 Treatment Planning System (TPS) was utilized, which calculates doses based on the latest TG-43 protocol from the American Association of Physicists in Medicine (AAPM). The brachytherapy planning was designed for treatment using the BEBIG Saginova HDR afterloader machine, which employs a Cobalt-60 (Co0.A86) radiation source. All patients were treated with the BEBIG Fletcher tandem and ovoid applicators, inserted without interstitial needles. A Canon Aquilion LB CT simulator was used to obtain 3D images for treatment planning.

The High-Risk Clinical Target Volume (HRCTV), Intermediate-Risk Clinical Target Volume (IRCTV), bladder, and rectum were contoured by radiation oncology specialists, adhering to the GYN GEC ESTRO recommendations (Beyzadeoglu et al., 2010). Virtual applicators in the TPS were aligned based on the positions observed in the 3D CT simulator images. The process was followed by dose optimization using the Graphical Optimization (GrO) and Inverse Planning (IP) techniques.

Figure 1. BEBIG Saginova HDR afterloader in Prof. Dr. I. G. N. G. Ngoerah Central General Hospital

Graphical optimization

After contouring and virtual applicator placement, dose optimization was performed using the Graphical Optimization (GrO) technique. In this method, the medical physicist manually adjusted dwell time and position(Roy et al., 2021). The isodose lines were manually adjusted to achieve uniform dose distribution throughout the implant, administer the prescribed radiation to the target area, and limit radiation exposure to adjacent organs at risk, following the recommendations of ICRU Report 89 (Tang et al., 2019). Specifically, the high-risk clinical target volume (HRCTV D_{90}) was maintained within 100%–107% of the prescription dose. The bladder (D_{2cc}) was kept below 80% of the prescription dose, and the rectum (D_{2cc}) dose was kept below 75% of the prescription dose(Bentzen et al., 2016). This adjustment is repeated until the desired dose distribution is achieved.

Inverse planning

In Inverse Planning (IP), after contouring and virtual applicator placement, dose optimization was performed by inputting dose constraints and weighting factors into the inverse planning objectives setup by the medical physicist(Gül et al., 2024). The specific dose constraints and weighting factors used are detailed in Table 1.

Table 1. Dose constraints and weighting factors in IP technique

Organ	Dose Min (%Rx)	Weighting	Dose Max (%Rx)	Weighting
HRCTV (D_{90})	100	5	107	5
Bladder (D_{2cc})	-	-	80	3
Rectum (D_{2cc})	-	-	75	3

The Treatment Planning System (TPS) automatically calculated the dwell time, position, and dose distribution based on these constraints and weighting factors until the desired dose distribution was achieved(Tang et al., 2019).

Plan evaluation

To evaluate the quality of the treatment plans, we adopted the criteria outlined in ICRU Report 89 as our primary reference. This included maintaining the High-Risk Clinical Target Volume (HRCTV D_{90}) dose within 100%–107% of the prescription dose, limiting the bladder (D_{2cc}) dose to below 80%, and restricting the rectum (D_{2cc}) dose to below 75% of the prescription dose. In addition to these constraints, we assessed plan quality using the Conformity Index (COIN) and the Dose Homogeneity Index (DHI).

The COIN evaluates how precisely the prescription dose covers the target volume while minimizing exposure to surrounding organs. It is calculated by multiplying two components: c_1, which represents the fraction of the target volume (HRCTV) covered by the prescription dose (V_{100}/V_{HRCTV})(Baltas et al., 1998; Krishna et al., 2025; Palled et al., 2020), and c_2, the fraction of the total irradiated volume receiving the prescription dose ($V_{100}/V_{100total}$)(Mosleh-Shirazi et al., 2019). An ideal COIN value of 1 indicates perfect conformity(Mosleh-Shirazi et al., 2019; Palled et al., 2020).

$$COIN = c_1 \times c_2 \quad (1)$$

The DHI, defined as the ratio of the volume receiving 100% of the prescription dose (V_{100}) to the volume receiving 150% (V_{150}), quantifies dose uniformity within the treatment volume(Palled et al., 2020; Wu et al., 2024). A higher DHI (closer to 1) signifies a more homogeneous dose distribution(Palled et al., 2020).

$$DHI = \frac{V_{100} - V_{150}}{V_{100}} \quad (2)$$

To statistically compare the dose distributions achieved by Graphical Optimization (GrO) and Inverse Planning (IP) techniques, we conducted a Multivariate Analysis of Variance (MANOVA) using SPSS 29.0. A significance threshold (Sig.) < 0.05 was applied, with results below this threshold indicating a statistically significant difference between the two planning methods.

Result and Discussion

Result

In the study conducted on 30 cervical cancer brachytherapy patients, dose distributions resulting from the Graphical Optimization (GrO) and Inverse Planning (IP) techniques are displayed in Figure 2.

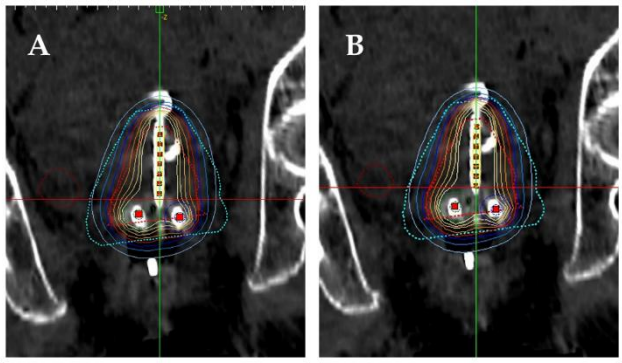

Figure 2. Distribution of doses from the GrO technique (A) and the IP technique (B).

The D_{90} HRCTV, COIN, and DHI values for the target volume and the D_{2cc} values for organs at risk (OARs) are presented in Table 2.

Table 2. Dose constraints and weighting factors in IP technique

Parameters	GrO (Mean±SD)	IP (Mean±SD)	Sig.
D_{90} HRCTV (Gy)	7.239 ± 0.134	7.155 ± 0.093	0.006
COIN	0.581 ± 0.081	0.589 ± 0.059	0.686
DHI	0.352 ± 0.043	0.330 ± 0.035	0.030
D_{2cc} bladder (Gy)	4.689 ± 0.591	4.771 ± 0.704	0.627
D_{2cc} rectum (Gy)	3.639 ± 0.693	3.561 ± 0.786	0.685

The analysis revealed that the D_{90} and DHI variables had significance values < 0.05, indicating a statistically significant difference between the D_{90} and DHI values obtained with the Graphical Optimization (GrO) and Inverse Planning (IP) techniques. Conversely, the D_{2cc} bladder, D_{2cc} rectum, and COIN variables showed significance values > 0.05, meaning no significant differences were observed in these parameters between the GrO and IP techniques. Additionally, overall dose distributions from the Graphical Optimization (GrO) technique showed a significant difference compared to those from the Inverse Planning (IP) technique, with a significance value of 0.011. According to the standards established in ICRU Report 89, the dose distribution values for HRCTV (D_{90}), bladder D_{2cc}, and rectum D_{2cc} remained within the recommended limits, as illustrated in Figure 3, Figure 4, and Figure 5.

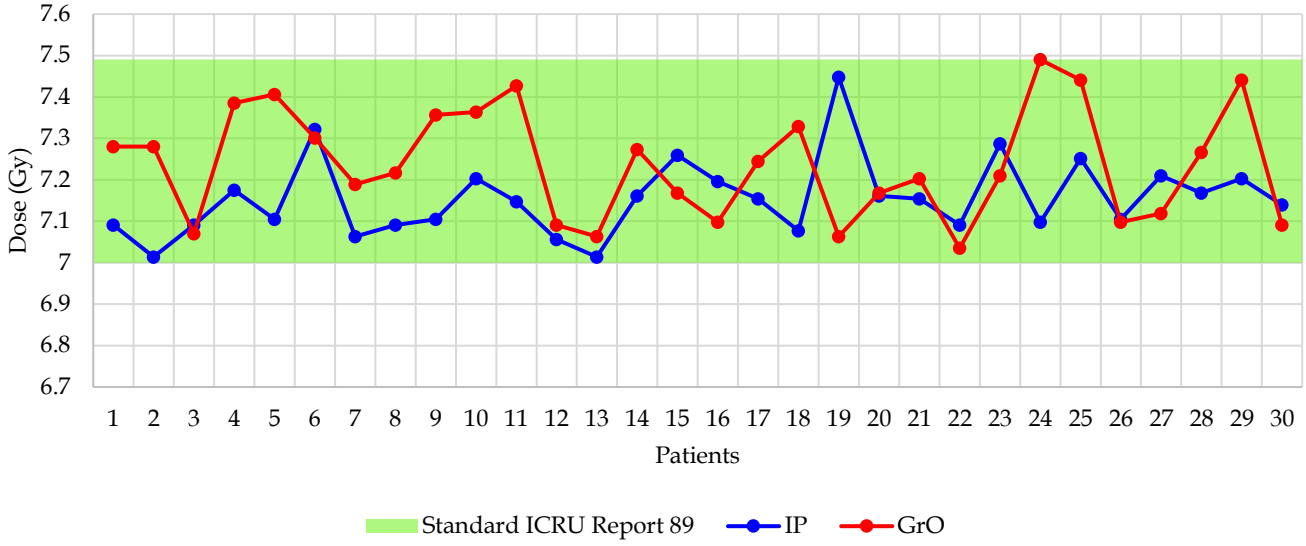

Figure 3. Comparison chart of D_{90} values with ICRU Report 89 standards

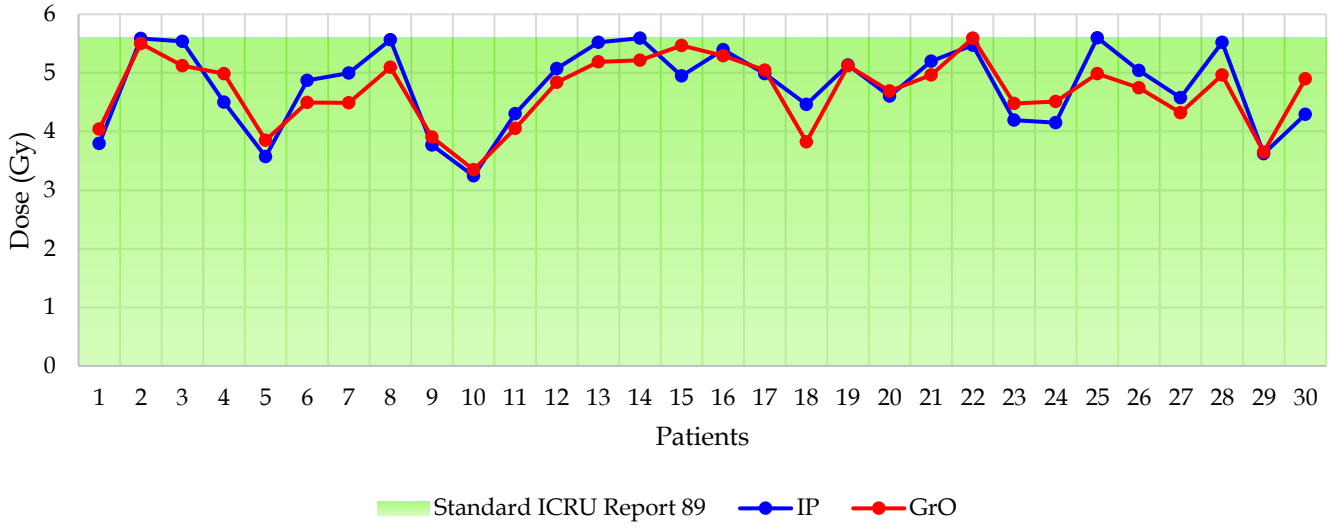

Figure 4. Comparison chart of D_{2cc} bladder values with ICRU Report 89 standards

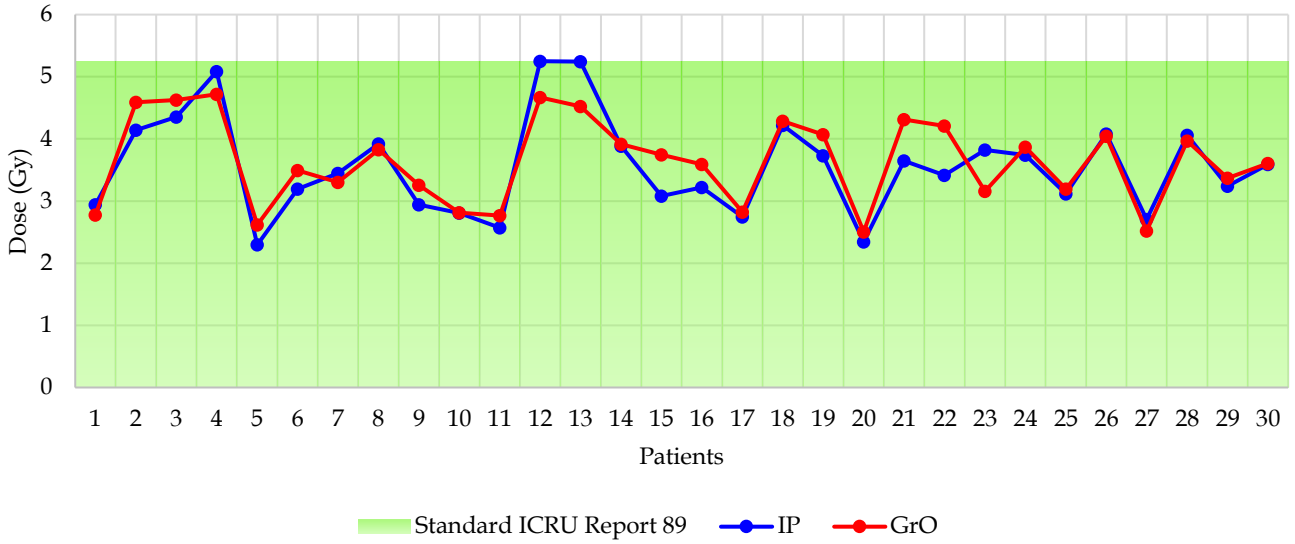

Figure 5. Comparison chart of D_{2cc} rectum values with ICRU Report 89 standards

Discussion

Brachytherapy has long been a cornerstone of cervical cancer treatment, with its primary benefit lying in the ability to administer precise radiation doses to the tumor site while reducing exposure to surrounding healthy tissues and organs at risk through advanced dose optimization techniques. Dose optimization determines the appropriate dose distribution to target cancerous tissues without harming surrounding healthy organs. Several dose optimization techniques exist, including Graphical Optimization (GrO) and Inverse Planning (IP). GrO involves manually adjusting isodose lines to achieve optimal dose distribution(Roy et al., 2021). In contrast, IP requires medical physicists to input representative dose constraints, which are then used by a computer to calculate optimal dwell positions and dwell times, resulting in an optimal dose distribution(Gül et al., 2024).

In 2024, Gül et al. compared dose distribution values between GrO and IP techniques for 15 cervical cancer brachytherapy patients. Their findings revealed no significant difference (sig = 0.476) in D_{90} HRCTV values between GrO and IP. However, the IP technique produced significantly lower D_{2cc} rectum values (sig = 0.002) than GrO. In this study, the mean D_{90} HRCTV value for GrO (7.260 Gy) was statistically significantly higher than that for IP (7.161 Gy), with a significance level of 0.006. These results align with the findings by Palled et al. (2020), who also reported higher mean D_{90} HRCTV values with GrO compared to IP. Additionally, the mean Dose Homogeneity Index (DHI) for GrO (0.352) was significantly higher than that for IP (0.330), with a significance level of 0.030, indicating that GrO provides better dose homogeneity. Meanwhile, the two techniques demonstrated comparable average Conformal Index (COIN) values, with no statistically meaningful differences observed between them (sig = 0.686), suggesting equivalent dose conformity. The study also found no significant differences in D_{2cc} bladder and D_{2cc} rectum values between GrO and IP (sig = 0.627 and 0.685, respectively), demonstrating that both techniques optimally protect surrounding healthy organs.

However, overall dose distribution values for GrO showed a significant difference (sig = 0.011) compared to IP. This is attributed to GrO allowing medical physicists greater manual control over dwell positions and dwell times, facilitating dose optimization in complex anatomical geometries, albeit with longer planning times compared to IP(Palled et al., 2020). Based on these results, GrO remains a viable technique for brachytherapy planning, as it offers superior optimization for target dose coverage (D_{90} HRCTV) and dose homogeneity. The results of this study indicate that the D_{90} HRCTV distribution values for both GrO and IP techniques remain within the recommended range of ICRU Report 89, as illustrated in Figure 2. The D_{2cc} bladder values, shown in Figure 3, demonstrate that values for both GrO and IP techniques comply with the limits recommended by ICRU Report 89, with mean and standard deviation values of (4.689 ± 0.591) Gy for GrO and (4.771 ± 0.704) Gy for IP. Similarly, the D_{2cc} rectum values, depicted in Figure 4, confirm that values for both techniques also adhere to ICRU Report 89 standards, with mean and standard deviation values of (3.639 ± 0.693) Gy for GrO and (3.561 ± 0.786) Gy for IP. These results demonstrate that both GrO and IP techniques provide dose distributions that meet the requirements of ICRU Report 89.

Conclusion

The GrO technique provides higher D_{90} values and better dose homogeneity compared to the IP technique. However, there is no significant difference in the doses received by OARs or in dose conformity between the GrO and IP results. Both techniques also deliver dose distributions that comply with the ICRU Report 89 standards.

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Author Contributions
Conceptualization N.N.R. & I.P.W.A.J; Methodology and conductor of experiment G.N.S, I.P.W.A.J & I.W.B.S; data analyzer and data visualization N.P.Y.N & I.P.T.I & I.P.W.A.J.

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Conflicts of Interest
The authors declare no conflict of interest.

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