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Gamma analysis of patient specific quality assurance by hybrid acceptance criterion method

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► ***Original article***

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ABSTRACT

***Background*:** Gamma analysis is an effective tool used to verify treatment plan accuracy with regard to patient specific quality assurance. In this method, accuracy is validated through the major parameters presented in the acceptance criterion (AC). The Hybrid AC (HAC) method has been proposed and validated via the Traditional AC (TAC) method of comparison. ***Materials and Methods*:** The performance of the HAC method was investigated through one-dimensional (1D) relative dose profile and clinical planar dose distribution. By employing the HAC method, Gamma values were observed at different regions of the profile as well as at the different treatment sites of clinical planar dose distribution. Both results were compared by employing the TAC method, but only planar dose distribution was analyzed by 95% confidence interval of statistics. ***Results*:** The results of the HAC method indicate higher Gamma values at the penumbra of the dose profile when compared with the results of the TAC method. In low dose and high dose areas, both methods produced comparable results. In terms of planar dose distribution, the proposed method demonstrated a higher degree of sensitivity than the TAC method by indicating low values for the Gamma passing rate at all treatment sites. ***Conclusion*:** The HAC method could effectively increase the sensitivity of the tool at a high dose gradient of planar dose distribution, whereas it had no impact on the area of the low dose gradient. Therefore, this method could be an alternative option for evaluation of treatment planning accuracy in clinical practice.

INTRODUCTION

Radiation therapy is one of the primary procedures utilized for the treatment of cancer. Various treatment planning and delivery techniques are employed in this procedure [1-4]. All these treatment techniques aim to deliver a high radiation dose to the target, whereas the surrounding tissue would receive as low a radiation dose as possible. Certain sophisticated treatment techniques, such as Intensity Modulated Radiotherapy (IMRT) and Intensity Modulated Arc Therapy (IMAT), are considered appropriate techniques in complex cases that involve irregular target shapes or target tissue adjacent to the organs at risk (OARs) [1, 3]. The relevant treatment conditions can lead to a treatment plan that generates a complex degree of intensity for the radiation beam. The intensity map contributes to a high dose of radiation being delivered to the target, whereas the OARs would be subjected to a low dose. Accordingly, dose gradient is dependent upon the target shape and the relationship between the target and any OARs. Moreover, the dose gradient between the target and the organs is not only relevant in terms of the location of the target but also in terms of the dose level. A high degree of dose gradient can result in a large difference in the dose levels and a short distance between the objects.

By utilizing the intensity modulation of the radiation beam, specific patient quality assurance (SPQA) is an essential procedure that guarantees a degree of accuracy between the treatment plan (the calculated dose) and what is delivered (the measured dose). In this procedure, the dose distribution of the 2 -dimensional array detectors was compared with the patient specific dose distribution obtained from treatment planning. Gamma analysis [5] is the primary tool used to evaluate the accuracy of the radiation dose when comparisons were made between the measurement and the calculation, and what was calculated by employing the equation (1):

$$\gamma(\mathbf{r}_m) = \min\{\Gamma(\mathbf{r}_m, \mathbf{r}_c)\} \forall \{\mathbf{r}_c\} \quad (1)$$

where r_m, r_c are representative of the position of interest for the measured dose and the calculated dose, respectively. According to equation (1), the gamma value was calculated by employing the equation (2):

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$$\gamma = \sqrt{\frac{|\mathbf{r}_c - \mathbf{r}_m|^2}{\Delta d_M^2} + \frac{(D_c(\mathbf{r}_c) - D_m(\mathbf{r}_m))^2}{\Delta D_M^2}} \quad (2)$$

where $D_c(r_c)$ and $D_m(r_m)$ are representative of the calculated dose and the measured dose at r_c and r_m, respectively. Accordingly, the d_M and D_M values are representative of the criterion of DTA and PDD, respectively. In order to interpret the results, the acceptance tolerance of the gamma value was set as one. Accordingly, the gamma value was less than or equal to the value that passed the criterion. On the other hand, the gamma value was above the value that failed the criterion. This index is commonly used as an evaluation tool in the treatment plan. The denominators of both terms of the equation (2) are presented in the criterion to allow for the passing of the gamma value. These values are referred to as '*Acceptance Criterion, AC*' and expressed in terms of PDD/DTA such as 3%/3mm. The AC can be simulated as the model of the ellipsoid that is revealed in figure 1. The size of this model is dependent upon the value of the AC. In terms of the modulated intensity of the treatment plan, the composite AC criterion were set at 3%/3mm of the global normalization method that was commonly employed in the analysis of the treatment plans at various treatment sites [6-10].

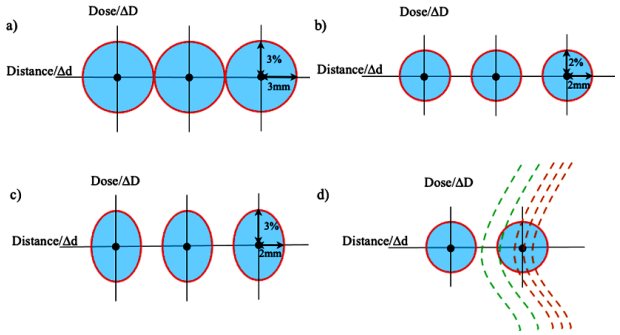

Figure 1. Diagram of the acceptance criterion. The ellipsoid represents the acceptance criterion that is specified by the percent dose difference and the distance to agreement. **a)** The 3%/3mm ellipsoid. **b)** The 2%/2mm ellipsoid. **c)** the 3%/2mm ellipsoid. **d)** The 2%/2mm ellipsoid in the high (orange dash line) and low dose gradient (green dash line).

To evaluate the treatment plan, Gamma passing rate (GPR) is utilized for the judgement of the treatment plan [11-13]. Accordingly, the value of AC is one of the most impactful factors for this evaluation method [14]. The values presented in this criterion are then adapted in relation to the treatment site or the treatment protocol installation of each center [15]. With particular regard to the high dose gradient, many publications have indicated that the local normalization method could be more sensitive than the global normalization method.[14-16] However, utilization of the local normalization method would not only result in an overestimation on the clinical practices[14] but also be indicative of a failure within the region of the high dose gradient [16]. To increase the sensitivity of the global normalization method, a decrease in the AC value could serve as an attractive alternative. Heilemann *et al.* [17] demonstrated that a low value of AC, 2%/2mm, could be indicative of a clinically unacceptable treatment plan. Moreover, Miften *et al.*[12] reported that a low value of the AC, such as 3%/2mm and 2%/2mm, could be supportive of the application of moderately/complex modulated plans. By utilizing this composite AC, either a high value or a low value in the criterion would be indicative of the constant shape of the model, as is shown in the figures 1(a, c). Consequently, the aim of this decreased value could be used to precisely evaluate the high dose gradient of the treatment plan. However, the low value of the AC could have an impact on the evaluation of the low dose area. The model presented in figure 1(d) indicates that the impact of a low AC value was utilized in the analysis.

Therefore, a separate analysis of the areas of high dose gradient and low dose gradient may reveal any limitations in the type of gamma analysis and the level of the AC. Van Dyk *et al.*[18] recommended that the dose distribution should be separately analyzed between the high dose and the low dose gradient area. The criterion of their work clearly revealed that PDD was utilized within the dose in the low gradient area, whereas DTA was analyzed on the high gradient area. This study then proposed an alternative method that could be used to separately analyze the planar dose distributions between the treatment plan and the dose measurement as determined by different values of the AC. Instead of utilizing the traditional acceptance criterion (TAC) method, the method of hybrid acceptance criterion (HAC) was used to determine the local dose gradient before the gamma analysis. The proposed method applied a criterion of 3%/3mm on the low dose gradient area, whereas a criterion of 3%/2mm was observed on the high dose gradient area. Both methods were performed not only on the one-dimensional relative dose profile but also on the clinical planar dose distributions.

MATERIALS AND METHODS

Ethical clearance

The dose distribution of the patient was collected and evaluated through comparisons made between the measurement and the calculation. This retrospective study recruited the treatment plan of patients from January to December of 2020. However, the performance of this study has been questioned as a consequence of this limited time period. Ethical clearance was granted by the Chiang Mai University Ethical Committee on January 30, 2020 (Study code: RAD-2562-06971).

Hybrid acceptance criterion (HAC) method

Accordingly, the gamma analysis was applied to

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every area or point of interest of the planar dose distribution. To separately analyze the area of the planar dose between the high gradient and low gradient, each area was then evaluated for the appropriate dose gradient before the selected AC was applied. To calculate the dose variation, the area of the calculated planar dose distribution was divided into a small area (namely*'patch'*) within a size of 10×10 mm^2. Moreover, each patch was also used to correlate the position with the detector point of the planar dose measurement. The variation of each patch was then determined by employing the equation (3):

$$PDG_i = \left| \frac{(D_{max_i} - D_{mim_i}) \times 100}{D_{max_i}} \right| \quad (3)$$

where PDG represents the percent dose gradient (for i = 1,...,n). Accordingly, the D_{max} and D_{min} values are representative of the maximum and minimum doses of the i patch, respectively. The value of PDG in the equation (3) indicates the status of the high dose gradient or the low dose gradient in each patch.

According to the recommendations of the International Commission on Radiation Units and Measurements (ICRU) [19], the cut-off value of the PDG values between the high and low dose gradients was observed at 20% of the dose variation. The patch revealed a dose variation value lower than 20% as the status of the low dose gradient, whereas a dose variation value above 20% was representative of the status of the high dose gradient. To increase the sensitivity of the analyzed tool, the DTA involved two levels of analysis. The high value of the AC (3%/3mm) was employed on the area of the low dose gradient, while the area of the high dose gradient was analyzed by employing the low value of the AC (3%/2mm).

In this study, the AC of the HAC was expressed as 3%/3-2mm. This would mean that 3% was the appropriate criterion for the dose difference, whereas a range of 3-2mm was used in the criterion for determination of the area of the low dose gradient and the high dose gradient, respectively. The simulated various shapes of the ellipsoid are presented in the figure 2(a). Accordingly, the width of the ellipsoid was adopted to correspond to the area of the dose gradient. By utilizing the proposed method, the low value of the DTA was utilized on the area of the high dose gradient, whereas the area of the low dose gradient was evaluated by the high value of the DTA, as is shown in the figure 2(b).

Performance validation of HAC method

To validate the performance of the proposed method, two experiments were employed. The first experiment aimed to test the proposed method in the one-dimensional relative dose profile. This test focused not only on the performance of the high dose gradient detection but also on the gamma value that was determined after applying the different AC. The second experiment focused on the clinical practice in terms of a performance analysis. Moreover, the gamma value of the proposed method was compared with that of the method of the TAC.

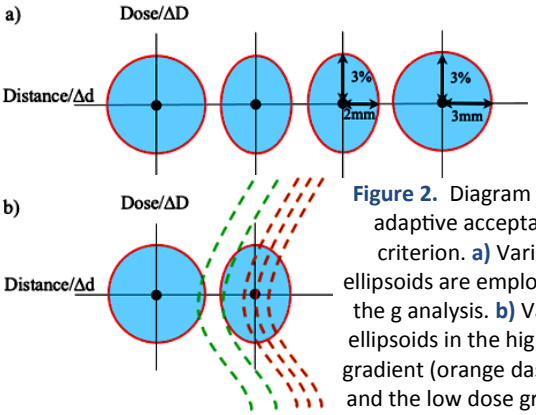

Figure 2. Diagram of the adaptive acceptance criterion. **a)** Various ellipsoids are employed on the g analysis. **b)** Various ellipsoids in the high dose gradient (orange dash line) and the low dose gradient (green dash line).

One-dimensional relative dose profile

The performance of this proposed method was evaluated by utilizing the one-dimensional relative dose profile. The relative 6 MV dose profile for a field size of 10×10 cm^2 at a depth of the maximum dose (d_{max}) in the homogeneity phantom was created from the Pinnacle^3 treatment planning system v.16.0 (ADAC, Philips Radiation Oncology Systems, USA), as is presented in figure 3(a). The spatial resolution of the relative dose profile was observed at 1 mm intervals. For the purposes of an impartial evaluation, the relative dose profile was duplicated and named as a *'Synthetic measured dose'*. One line was indicative of the measured dose profile, and the other line was representative of the calculated dose profile. An error analysis was done by comparing these two dose profiles by employing the translation method at 2 and 3 mms. The half dose profile was then analyzed for the purposes of conducting a conclusive investigation and establishing a clear explanation. The gamma values were observed along with the distance (x) from the central ray within a range of 0 mm ≤ × ≤ 100 mm, as is presented in figure 3(b).

Clinical planar dose distribution

The planar dose distribution was also used to conduct a performance analysis between the TAC and the HAC methods. The treatment plans of the patient were recruited during the period of January to December, 2020. These planar dose distributions included the treatment plans of breast cancer, pelvic cancer, and head-and-neck cancer patients, and were performed via the treatment planning system employed by Hi-Art ver.5.1.4 (Accuray Inc., Sunnyvale, CA, USA) and delivered by the ring based linear accelerator (Hi-Art, Tomotherapy, Accuray Inc., WI, USA) was established in the treatment plan of the Hi-Art. By random measurements of the PSQA routine, there were 106 plans that had employed the

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measured planar dose distribution at 39 plans, 25 plans, and 42 plans for breast cancer, pelvic cancer, and head-and-neck cancer, respectively.

The calculated planar dose distributions techniques were created by utilizing the SNC patient® software (Sun Nuclear Inc., Fl, USA) and extracted from the snc file of the Dicom Dose. Each point of the calculated dose was administered at 1 mm intervals. On the other hand, the measured planar dose was acquired by the ArcCHECK® (Sun Nuclear Inc., Fl, USA). Subsequently. the measured planar dose distribution was extracted from the txt file which had been created by employing the same software. The total detector number of the ArcCHECK® was recorded at 1,386 detectors; thus, the interval of each detector was recorded at 1 cm. The interval of each measured dose point was observed at a distance of ten millimeters. The low dose threshold (LDT) at 10% was applied to the cut-off of the low dose. Table 1 reveals the patient characteristics of the observative treatment plans. For each of the observative plans, the dose was prescribed for various dose schematics.

Statistical analysis

SPSS ver.25 (IBM Corp., NY, USA) software was employed to analyze the data. The statistics were then used to analyze any significant differences, not only among the treatment site but also between each pair of treatment sites and for each pair of the g analysis method. The Kolmogorov-Smirnov test was used to establish the normal distribution of the data. The group of non-normal distribution values were analyzed by; 1) Kruskal-Wallis test for the treatment sites, 2) Mann-Whitney U test for each pair of treatment sites, and 3) Wilcoxon Signed Rank test for each pair of the gamma analysis methods. A confidence interval of 95% was used in this statistical analysis.

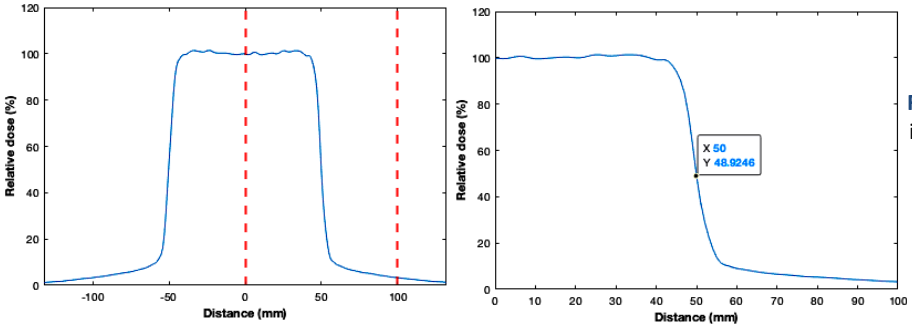

Figure 3. Region of dose profile for the investigation. **a)** The selected region of the dose profile is presented between the red dash lines. **b)** The selected gradient of the dose profile.

Table 1. Patient characteristic of the observative cancers.

Category	Breast cancer		Pelvic cancer		Head and neck cancer	
Sample size (plans)	39		25		42	
	Conservative breast	38.5%	Rectum	36.0%	Nasopharynx	30.9%
					Soft palate	2.3%
			Prostate	32.0%	Maxillary sinus	2.3%
	Mastectomy breast	61.5%			Hypopharynx	2.3%
			Cervix	4.0%	Glottic	2.3%
					etc.	7.1%
Age	56.9 ± 11.3		64.1 ± 12.9		52.6 ± 12.1	
Fraction dose (Gy)	2.8 ± 0.2		2.3 ± 0.4		2.1 ± 0.1	
Number of fractions	16.3 ± 1.6		24.1 ± 5.3		32.5 ± 1.7	

RESULTS

Performance validation of the HAC method on one-dimensional relative dose profile

This experiment observed the high dose gradient detection of the proposed method. The relative dose profile was employed to observe the performance of the HAC method. The results indicate that two regions of the dose profile were detected. The ranges were -79 mm – -47 mm and 53 mm – 82 mm and recorded from the central axis that was the penumbra of the dose profile. The doses at these regions were 7.8% - 96.5% and 8.4% - 97.5% at distances of 32 mm and 29 mm, respectively. Figure 4 presents the detected region on the one-dimensional relative dose profile by utilizing the proposed method. This hybrid method detected the penumbra that was situated in the region of the high dose gradient, as is indicated by a red cross (×), whereas the inner/outer radiation fields (the low dose gradient) were not detected.

The superimposed lines between the calculated dose (blue line) and the synthetic measured dose (blue dotted line) are presented in figure 5, where the left and right axis are representative of the relative dose (%) and the gamma value, respectively. The tolerance of the gamma value is 1, which is represented by the black dotted line in the figure. The distances between these two dose profiles were 2 mm and 3 mm as has been presented in the left column and the right column of figure 5, respectively. The top row of figure 5 presents the results of the gamma value as represented by the red line. This was established by employing the TAC method, whereas

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the bottom row displays the results of the gamma value by utilizing the HAC method. Table 2 summarizes the results in terms of the g value that corresponds to the region of the dose profile in this experiment. The region of the penumbra indicates that the gamma value was higher than other regions of the dose profile.

Performance validation of the HAC method on clinical planar dose distribution

The clinical treatment plans were used to observe the performance of the TAC and HAC methods. The results are presented in table 3. The data reveal that a comparable number of detectors (active detectors) was used to measure the different treatment sites by employing a mean value, but the statistics indicate a significate difference among the treatment sites. The number of active detectors involved in the treatment planning for the breast area was significantly less than for the other treatment sites ($p < 0.041$). The number of detector points was separated according to the areas of the high dose and low dose gradients. These values could be used to indicate any significant differences in the areas of the high dose gradients among the different treatment sites ($p < 0.001$). The treatment plans for the head-and-neck cases revealed an area of the high dose gradient that was lower than the others ($p \leq 0.027$).

The results of the low dose gradient exhibited the same trend of the high dose gradient results. The value of GPR was not only compared among the treatment sites, but also for the gamma analysis methods of each treatment site. The results indicate a significant difference among the treatment sites when both the TAC ($p = 0.002$) and HAC ($p < 0.001$) methods were employed. All treatment sites indicated significant differences between the TAC and HAC methods. The two levels of the GPR have been reported in terms of the number of treatment plans and their percentages. The results indicate that the passing rate was higher when the TAC method was utilized at all treatment sites at levels of 90% and 95%, except for a level of 90% that was used for head-and-neck treatment planning.

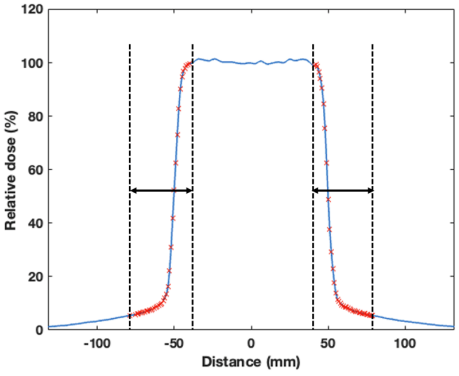

Figure 4. Performance detection of the HAC method on the one-dimensional relative dose profile. The red crosses within the dash line are the detected point by utilizing the HAC method.

Table 2. gamma value and range in the shifted relative dose profiles between the calculated and synthetic measured dose by applied the TAC and HAC methods.

Method		Region of relative dose profile from central axis		
		High dose area	Penumbra	Low dose area
2 mm, distance shift				
TAC	gamma value Range	≤ 0.36 0 mm ≤ × ≤ 41 mm	0.67 42 mm ≤ × ≤ 54 mm	≤ 0.45 × ≥ 55 mm
HAC	gamma value Range	≤ 0.90 0 mm ≤ × ≤ 43 mm	0.98 44 mm ≤ × ≤ 53 mm	≤ 0.90 × ≥ 54 mm
3 mm, distance shift				
TAC	gamma value Range	≤ 0.48 0 mm ≤ × ≤ 41 mm	1.00 42 mm ≤ x ≤ 52 mm	≤ 0.99 × ≥ 53 mm
HAC	gamma value Range	£ 1.00 0 mm ≤ × ≤ 40 mm	1.04 ≤ g ≤ 1.50 41 mm ≤ × ≤ 54 mm	≤ 0.66 × ≥ 55 mm

Abbreviation: TAC = Traditional Acceptance Criterion, HAC = Hybrid Acceptance Criterion, g = Gamma and x = distance.

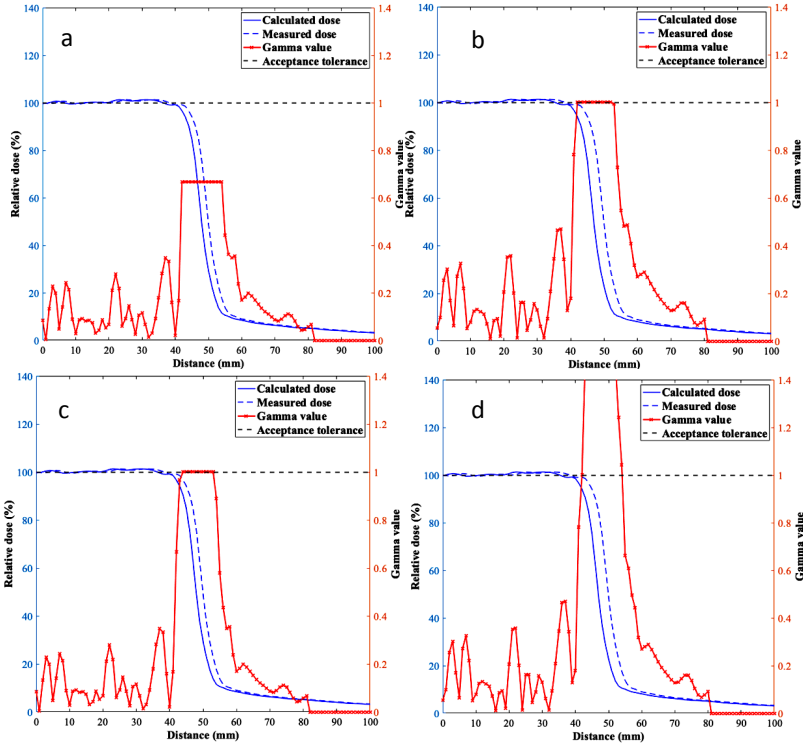

Figure 5. Superimposed lines among the calculated dose line (blue line), the synthetic measured dose line (blue dash line), and the gamma value line (red cross line). The black dash line represents acceptance tolerance. The displacement of the measured dose line was applied by 2 mm (left column) and 3 mm (right column) of the translation method. The 3%/3mm and 3%/3-2mm of the AC on the TAC and HAC methods, respectively, were employed in this investigation. The g value on the top row is the result of the TAC method whereas the bottom row is the HAC method.

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Table 3. Performance validation result in the clinical practice.

Treatment plan	Breast	Pelvis	Head and Neck	*p*-value
Active detector (point)	1,124.4 ± 259.3	1,287.9 ± 93.8	1,281.8 ± 155.7	$p = 0.006$ $^{a}p = 0.041$ $^{c}p = 0.003$
Dose gradient				
High dose gradient				$p < 0.001$ $^{b}p = 0.027$ $^{c}p < 0.001$
Point	403.0 ± 122.1	496.0 ± 278.8	280.0 ± 69.5	
Percentage	37.6 ± 13.8	39.3 ± 23.0	22.2 ± 6.1	
Low dose gradient				
Point	1,058.3 ± 254.8	1,221.5 ± 107.4	1,240.1 ± 166.5	
Percentage	62.4 ± 13.8	60.7 ± 23.0	77.8 ± 6.1	
GPR (%)				
TAC	94.1 ± 5.3	94.9 ± 5.0	96.7 ± 4.3	$^{d}p = 0.002$ $^{e}p < 0.001$ $^{f}p < 0.001$ $^{g}p < 0.001$ $^{h}p < 0.001$
HAC	91.5 ± 6.2	92.8 ± 6.1	95.7 ± 5.2	
Number of treatment plan				
GPR ≥ 90% (%)				
TAC	84.6	96.0	88.0	-
HAC	66.7	88.0	88.0	
GPR ≥ 95% (%)				
TAC	59.0	52.0	84.0	-
HAC	35.9	28.0	80.0	

Remark: a = Breast vs Pelvis, b = Pelvis vs Head and Neck, c = Breast vs Head and Neck, d = among different treatment site of TAC, e = among different site of HAC, f = TAC vs HAC of Breast, g = TAC vs HAC of Pelvis and h = TAC vs HAC of Head and Neck.
Abbreviation: GPR = Gamma passing rate, TAC = Traditional acceptance criterion and HAC = Hybrid acceptance criterion.

DISCUSSIONS

An evaluation of the treatment plans was conducted by utilizing the gamma analysis across all decades. This tool can produce a very effective degree of performance by employing a combination of the specified quantities in terms of dose and distance. However, the values of the AC are the key paremeters that indicate the treatment plan accuracy. By observing the impacts of the local normalization method in the gamma analysis, a global normalization method with a low value of the AC was widely utilized. The results indicate an increasing degree of sensitivity in the analysis. However, this determination of sensitivity impacted all evaluation points in the planar dose. This impact has been reported in a number of published reports [15-16, 20]. According to the work of Song *et al.* [16], the impact of the GPR value was observed by employing a different percent level of the LDT. In comparison with the different AC values, the value of the GPR decreased when a low value of the AC had been applied at the same percent level of the LDT. The value of the GPR observation in the brain decreased from 99.86% to 98.51% when values of 3%/3mm and 2%/2mm were employed, respectively at a 0% level of the LDT. This would indicate that the sensitivity of the evaluation tool had increased. By employing a 2%/2mm value of the AC at 10% LDT, the GPR decreased to 97.04%.

To determine the value of GPR at each level of LDT, a value of 2.82% was representative of the residual value in all comparisons made between the 3%/3mm of the AC value at 0% LDT and the 2%/2mm of AC value at 10% LDT. On the other hand, 1.35% was the residual value between the 3%/3mm and 2%/2mm of AC at the same level of LDT. This would indicate that the passing criterion points of the GPR were eliminated from the results at 1.47%. This impact was clearly demonstrated by the gamma value (red line) in the one-dimensional dose profile and is presented in figure 6. In figures 6(a) and 6(b), the ggamma values were observed at 3%/3mm and 2%/2mm. By employing the low value of the AC in the TAC method, the gamma value increased in both areas of the low and high gradients, as has been presented in figure 6(b). This could be used to confirm the above-mentioned hypothesis. In contrast, the HAC method increased the degree of sensitivity without an area of low dose gradient interruption. In figure 6(c), the sensitivity of the tool only increased for the area of the high dose gradient, whereas the area of the low dose gradient was consistent.

To determine the appropriate dose variation, the HAC method was employed to separate the area of the planar dose distribution in comparisons made between the high gradient and the low gradient. This study employed the cut-off value of the ICRU recommendation [19], whereas this value was lower than the recommendation proposed by Van Dyk *et al.*

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[18]. However, this proposed cut-off value could have a significant impact on the value of the GPR in terms on the planar dose distribution area in the g analysis. Accordingly, a low value of GPR was observed.

In the clinical practice, clinical treatment plans were recruited to investigate the performance of both gamma analysis methods. The results indicate that there was a significant difference in the active detectors in the breast cancer treatment plans, while the area of this treatment plan was smaller than for the pelvis and the head-and-neck treatment plans. However, the complexity of the treatment plan is of significant interest. The data reveal that the head-and -neck treatment plans resulted in a significantly lower number of detector points than the other treatment plans. Meanwhile, this treatment plan might be less complex when compared with those of other publications such as those reported by Kathirvel *et al.* [21] and Stieler *et al.* [22]. The complexity of the treatment planning then might be determined not only by the number of OARs in the treatment sites but also by the dose and distance between the target and each OAR. Therefore, the PSQA should be performed for all treatment plans; however, our center would have a limitation in this regard. The treatment site was randomly selected for each separate procedure to ensure the mechanical accuracy of the treatment machine [11, 13]. During the pandemic of COVID-19 in 2020, our center reduced the number of patients receiving radiation treatments, which was a consequence of the low numbers present in the clinical sample size.

In comparisons of the GPR, our study revealed a decreased value of the GPR when the HAC method was applied. As has been reported in other publications [8, 10, 14-17], the decreasing value of the AC led to an increase in the sensitivity of this analysis tool. However, the degree of sensitivity of the proposed method was concentrated only at the area of the high dose gradient, as has been explained above. Although an AC value of 2%/2mm was not employed in this study, this method could result in a GPR value that was between AC values of 3%/3mm and 2%/2mm according to the TAC method. Another point of consideration in the GPR would be the number of head-and-neck treatment plans. The outcomes of this site indicate that a high number of the plan passed both 90% and 95% of the GPR when compared with the other sites. This could help to confirm the complexity of each treatment site. However, the optimal value of the AC employed in this method was not investigated. Accordingly, the optimal AC value should be further studied to clarify what would be best for each treatment site and for each treatment technique.

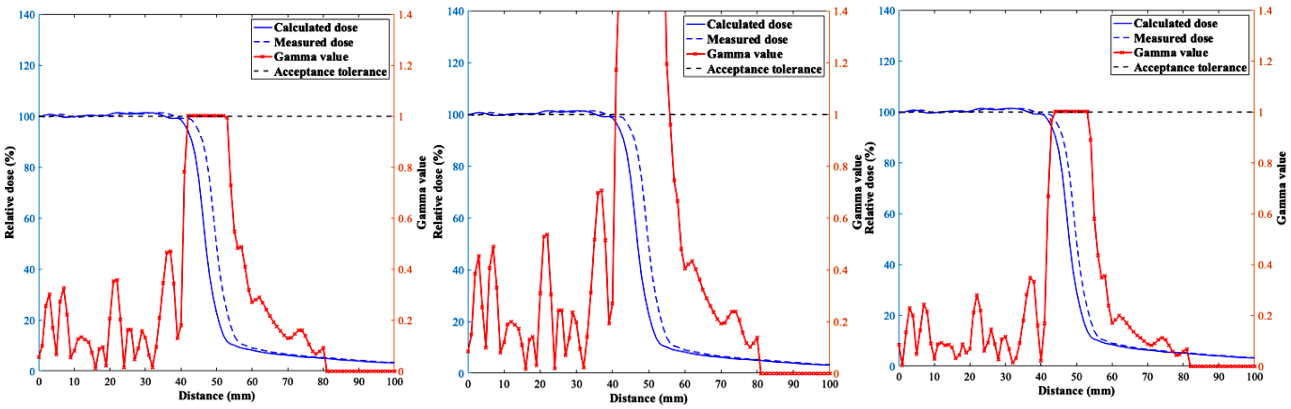

Figure 6. gamma value of different acceptance criteria. **a)** 3%/3mm by TAC method. **b)** 2%/2mm by TAC method. **c)** 3%/3-2mm by HAC method.

CONCLUSION

Gamma analysis is an effective tool that can be used to evaluate the accuracy of the treatment plan. To increase the sensitivity of the analysis, the high dose gradient of the planar dose distribution can be increased in the HAC method, whereas this would not have an impact on the area of the low dose gradient. Consequently, this method can be used to effectively evaluate the accuracy of the treatment plan in the clinical practice.

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***Author contribution*:** A.W.: Conceptualization, investigation, data curation, formal analysis, writing - original draft, writing - review and editing. I.C.: Conceptualization, formal analysis, writing - review and editing, supervision.

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