

Modification of the gamma function for the recognition of over- and under-dose regions in three dimensions

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ABSTRACT

In order to evaluate two-dimensional radiation dose distributions, an algorithm called the Gamma function has recently been modified. The current study concentrates on modification of the gamma function as a three-dimensional dose distribution evaluation tool, and includes the recognition of over-dose/under-dose areas. Using a sign term, the conventional gamma function separates the disagreed areas into two parts: over-dose and under-dose areas. The new gamma function was modified using an extension of the dose difference criterion, ΔD , from two dimensions into three dimensions. In order to provide two-dimensional dose maps for analysis, several images were acquired for a range of regular and irregular radiation fields using a Scanning Liquid Ionization Chamber Electronic Portal Imaging Device. The raw images were then converted into two-dimensional transmitted dose maps using an empirical method. They were utilized as reference dose maps. Translational and rotational manipulations were performed on the reference dose distribution maps to provide evaluated dose maps. The reference and evaluated dose maps were then compared using conventional and modified gamma tools. The results indicated that the modified algorithm is able to enhance the over- and under-dose regions. In addition, a slight increase of the agreement percentage for reference and evaluated dose maps were observed by the extension of ΔD to three dimensions. It is concluded that the modified method is more realistic and applicable for the evaluation of both two-dimensional and three-dimensional dose distributions.

Key words: Dose distribution, gamma function, two-dimensional dose distribution, two-dimensional dosimetry

Introduction

Evaluation of radiation dose distribution is essential in radiation therapy. Due to the existence of a high-dose gradient region with variations of dose up to 30% per centimeter in the two-dimensional dose distribution, the evaluation of dose delivery is more complicated. In order to cope with this problem, the gamma function is

the most popular algorithm reported so far to evaluate two-dimensional dose distributions. The algorithm was originally developed as a binary “composite” map^[1] and was then improved as positive continuous values.^[2,3] Two criteria were defined as the dose difference (ΔD) and the distance to agreement (DTA), Δd , to evaluate low- and high-dose gradient regions, respectively. The gamma response, which is called the gamma index, is a positive value which is ≤ 1 for agreed areas and > 1 for disagreed areas. The typical gamma criteria utilized for gamma analysis for clinical purposes are $\Delta D = 3\%$ and $\Delta d = 3 \text{ mm}$.^[2,4-6]

The concept of the gamma function algorithm has been discussed in detail by Low *et al.*^[3] It has been mentioned that “the evaluated distribution will have at least as high a dimensionality as the reference distribution. For example, the reference distribution may be a two-dimensional film dose distribution measurement, while the evaluated distribution may be a full three-dimensional dose distribution calculation.” But there is no report of the development of the gamma function for a three-dimensional practical comparison. In addition, as current treatment planning systems are able to provide a three-dimensional dose distribution, their output can be used

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as a reference dose distribution while the evaluated dose distribution remains a two-dimensional dose map.

Several attempts were reported to extend the gamma function as a three-dimensional dose distribution evaluation tool. Based on the gamma function definition, a new function, χ , was proposed by Bakai *et al.* and the results were then compared with those achieved using the gamma function. The χ function produces similar results, however, it does not involve a search algorithm.^[7] In addition, Wendling *et al.* reported a three-dimensional gamma function applied to evaluate a three-dimensional dose distribution grid calculated using a back projection technique. The results were, however, segmented two-dimensional gamma maps arranged for each distance.^[8,9]

The gamma function was used to evaluate two-dimensional dose distributions in numerous reports to quantify the agreement between a reference and an evaluated dose distribution map.^[4,5,7,10-15] However, there are several issues, which need to be taken into consideration. Firstly, the dose distribution is a three-dimensional concept. Therefore, the relevant uncertainties should be addressed in a three-dimensional volume. In addition, although the gamma function is a powerful tool to recognize the agreed and disagreed areas, it is not able to separate the over and underdose regions.^[16] Moreover, if there is a search for a consistent dose value in neighboring points in a two-dimensional area, this cannot be extended into a volume. The hypothesis of this study is that “with extension into the third dimension, consideration of the “less or more” fluctuations in the z direction, caused by patient positioning, organ motion, couch positioning, and isocenter calibration, for the point dose displacement in the z dimension can be achieved”.

The current work concentrates on the evaluation of a typical measured dose distribution as an evaluated dose map and its deviation from a simulated reference dose distribution and vice versa. The gamma function, as one of the popular dose distribution evaluation tools, is used in the current study and modified to enhance the over- and under-dose areas for regions of disagreement. In addition, the gamma function is modified for a three-dimensional assessment.

Materials and Methods

Several digital images were acquired using a Scanning Liquid Ionization Chamber Electronic Portal Imaging Device (SLIC-EPID) for $10 \times 10 \text{ cm}^2$, $20 \times 20 \text{ cm}^2$ open, $16 \times 21 \text{ cm}^2$ wedged and multileaf collimated fields. In order to create high dose gradient regions on image central area, several images were also acquired in the presence of a 10 cm attenuator layer, covering half of the radiation field. The raw EPID images were then converted into

two dimensional dose maps using an appropriate method reported elsewhere.^[17-19] The acquired fluence maps were translated 1 to 5 pixels and rotated 1 to 5° then compared with the original fluence maps. All of the work procedures were performed using in-house codes written in MATLAB 7 (MathWorks Inc, Natick, MA).

In order to recognize and enhance the over and underdose areas in a gamma map, a sign matrix was added to the gamma map as follows:

$$\text{Sign Matrix}_{i,j} = \frac{\text{RDM}_{i,j} - \text{EDM}_{i,j}}{\left| \text{RDM}_{i,j} - \text{EDM}_{i,j} \right|}$$

Where $\text{RDM}_{i,j}$ and $\text{EDM}_{i,j}$ are corresponding pixel values in reference and evaluated dose maps, respectively. The sign matrix is able to create a binary map of 1 and -1. The modified gamma function is shown in Equation 1.

$$\text{Developed Gamma}_{i,j} = \frac{\text{RDM}_{i,j} - \text{EDM}_{i,j}}{\left| \text{RDM}_{i,j} - \text{EDM}_{i,j} \right|} \times \gamma_{(\text{ref})i,j} \dots (1)$$

where $\gamma_{(\text{ref})}$ is the conventional gamma function, developed by Low *et al.*^[2] and based on a quantitative evaluation method to compare the measured and calculated dose distribution values:^[20]

$$\gamma(\bar{r}_e) = \min\{\Gamma(\bar{r}_e, \bar{r}_r)\} \forall (\bar{r}_e) \dots (2)$$

where

$$\Gamma(\bar{r}_e, \bar{r}_r) = \sqrt{\frac{r^2(\bar{r}_e, \bar{r}_r)}{\Delta d^2} + \frac{\delta^2(\bar{r}_e, \bar{r}_r)}{\Delta D^2}}$$

Where \bar{r}_e and \bar{r}_r are points of interest in evaluated and reference dose maps respectively. Δd and ΔD are DTA and dose difference criteria at the position. \bar{r}_r

The dose difference criterion can be expressed as:

$$\delta(\bar{r}_e, \bar{r}_r) = D_e(\bar{r}_e) - D_r(\bar{r}_r) \dots (3)$$

where $D_e(\bar{r}_e)$ and $D_r(\bar{r}_r)$ are evaluated dose and reference dose D_r at positions \bar{r}_e and \bar{r}_r , respectively.^[3] Output of the gamma function can be categorized as the pass-fail criteria:

$$\gamma(\bar{r}_m) \leq 1, \text{ calculation passes,} \dots (4)$$

$$\gamma(\bar{r}_m) \geq 1, \text{ calculation fails.}$$

In order to extend the DTA to a three dimensional criterion, the conventional DTA was extended as follows:

$$\Delta d = \left| r_{eva} - r_{ref} \right| = \sqrt{(x_{eva} - x_{ref})^2 + (y_{eva} - y_{ref})^2 + (z_{eva} - z_{ref})^2} \dots (5)$$

where $(z_{eva} - z_{ref})^2$ was added into the conventional formula. In order to create a three-dimensional map for analysis, two

two-dimensional fluence maps located above and below the reference two-dimensional fluence map were extracted from a dose grid calculated using the Pinnacle^[3] treatment-planning system. The three-dimensional map was then compared with that obtained from an EPID image (the reference dose map) using the modified three-dimensional gamma algorithm.

Since different approaches were used to obtain reference and evaluated dose maps, the pixel/voxel size of primary images may alter the accuracy of the current study. In order to prevent any interpolation in image resizing and due to the SLIC-EPID pixel size of 1.27 mm × 1.27 mm, the dose difference and DTA criteria was selected as 3% and 2.54 mm, respectively.

In order to verify the results of the modified gamma for clinical cases, the dose distribution evaluation tools were also applied for two lung and breast cases. To do this, several portal images from two anonymous patients were collected, and after conversion, the raw portal images were converted to dose maps using a developed empirical method and the results were compared with the corresponding predicted portal dose maps calculated using the Pinnacle^[3] treatment planning system (ADAC Inc., PHILIPS Medical System, Milpitas, CA, USA). The details of portal dose calculation and measurement were explained extensively in previous reports.^[19,21,22]

Results and Discussion

Modification of the gamma function to enhance over- and under-dose regions

The outcome of gamma evaluation was investigated for a range of rotated and translated open, wedged and irregular fields. Irregular fields were created using MLCs and also open fields with a 10-cm attenuator layer covering half of the field. Typical results of conventional gamma, relative dose difference maps and the gamma modified with the sign term are shown in Figure 1 for regular fields and for an

irregular field with 5 pixel translation and 5 degree rotation around the image centre. The values for conventional and modified gamma distributions in agreed areas are shown in grey and in contrast, the disagreed regions for conventional gamma are shown in color. For modified gamma maps, over- and under-dose regions are shown in red and blue respectively.

Quantitatively, percentages of agreement and disagreement for the conventional and modified gamma in the above mentioned cases are shown in Table 1 for a 5 pixel translation and 5° image rotation. As Table 1 shows no significant difference was observed in the percentage of agreed areas using the modified gamma algorithm for a 5 pixel translation. The modified gamma method is able to enhance the over-dose/under-dose areas.

The sign term added to the conventional gamma function is able to produce positive and negative values corresponding to the over- and under-dose areas. This could be a helpful tool to find an appropriate approach including possible translational and rotational misalignments to find the position of the evaluated dose map compared to the reference one. In addition, the dose distribution evaluation, indicating the under- and over-dose region can be a helpful tool in optimizing image alignment using gamma function results.

Modification of the gamma function as a three dimensional dose distribution assessment tool

The results of the gamma function modified for three-dimensional DTA and three dimensional dose difference is shown in Figure 2 for a 5 pixels translational and for a 5° rotational manipulation. The comparison of two and three dimensional sign-gamma functions is also shown in Figure 2 as differences between two- and three-dimensional gamma assessment (C series). Results show that in all cases studied in the current work, applying the three dimensional gamma function slightly increases the percentage of agreement compared to the two dimensional gamma function.

Table 1: Percentage of agreement and disagreement achieved and the contribution of over- and under-dose regions in the disagreed regions for a range of radiation fields for a 5 pixels translation and 5 rotation of reference dose maps

<i>Radiation field</i>	<i>Modification</i>	<i>Agreement (%)</i>	<i>Total disagreement (%)</i>	<i>Disagreement for over-dose region (%)</i>	<i>Disagreement for under-dose region (%)</i>
Open 10 × 10 cm ²	5 pixel	96.8	3.2	1.6	1.6
	5 °	97.9	2.1	0.8	1.3
Open 20 × 20 cm ²	5 pixel	93.9	6.1	3.0	3.0
	5 °	92.7	7.3	3.2	4.1
Open wedged (W60)	5 pixel	70.3	29.7	22.4	7.3
	5 °	55.5	44.5	24.4	20.1
Open 10× 10 cm ² with attenuator at half field	5 pixel	54.0	46.0	24.4	21.6
	5 °	90.0	10.0	5.0	5.0
MLC field	5 pixel	94.4	5.6	2.7	2.9
	5 °	94.2	5.8	3.1	2.7

Tabulated results in Table 2 indicate that the extension of gamma function to three dimensions, which basically produces a three dimensional DTA, increases the percentage of agreement. Although the differences in the percentage of agreement for open fields is low, but comparisons of high dose gradient regions in the dose distribution maps, the difference increases significantly. This can be observed for wedged field and an open field where an attenuator is positioned in half of the radiation field.

For a two-dimensional dose distribution evaluation, in order to control unavoidable misalignments between reference and evaluated dose distributions, a two-dimensional DTA criterion is defined. However, several misalignments, and consequently misreading of dose values, due to more or less attenuations and different contribution of scattered radiation reaching to the point of interest can possibly occur in the off-plane area. This kind of mismatching can come from vertical displacement of treatment couch, geometrical patient positioning during set-up procedure, undesired organ motion, which

cause more or less attenuation of the beam on-axis and perpendicular to the two-dimensional dose map. As a result, variations of dose values in an evaluated dose distribution map can occur. The important thing is that the inconsistency can be detected by a both two- and three-dimensional gamma functions. However, if the dose variation is within the tolerance with other points in a three dimensional comparison, the three-dimensional gamma function classifies the point as agreed dose area while the two-dimensional classifies it as a disagreed area.

As results in Tables 1 and 2 shows the wedged condition, which can be categorized as a medium gradient region, has significant differences between conventional and modified methods. This has led us to conclude that the two-dimensional gamma in the medium gradient region is not able to show the real agreement between two reference and evaluated dose distributions. It should be noted that the two-dimensional gamma function mostly concentrates on low gradient and high gradient regions. In this case, a three-dimensional gamma may improve the results of

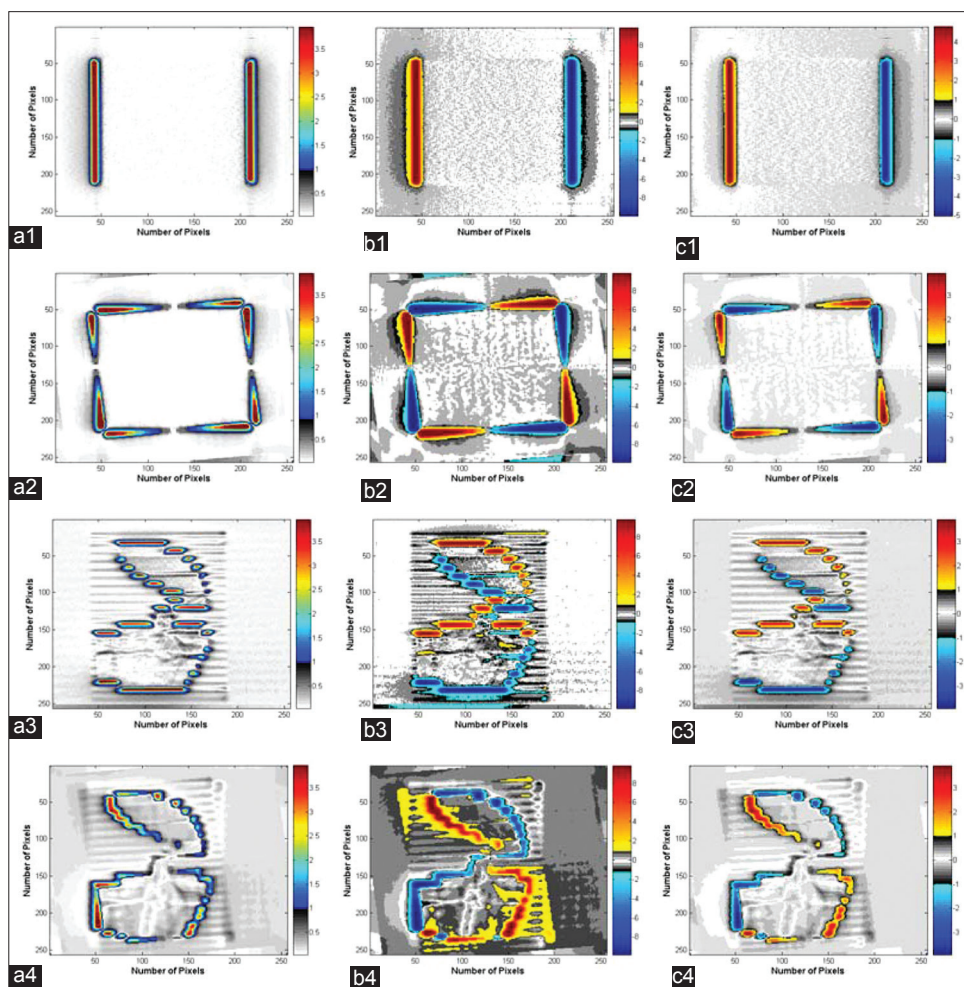


Figure 1: Conventional gamma maps (a series), relative dose difference maps (b series) and modified gamma maps for over- and under-dose area enhancement (c series) for a 20×20 cm² (first and second rows), and a MLC field (third and fourth rows) for 5 pixels transition and for 5° rotation (first and third rows, respectively) with 3%/2.5 mm criteria

comparison at medium gradient regions. Regarding the abovementioned issues, the real dose values can be found in upper or lower dose maps in the third dimension.

In order to evaluate the results with clinical situations, the modified sign and three-dimensional dose distribution evaluation gamma functions were applied for two lung and

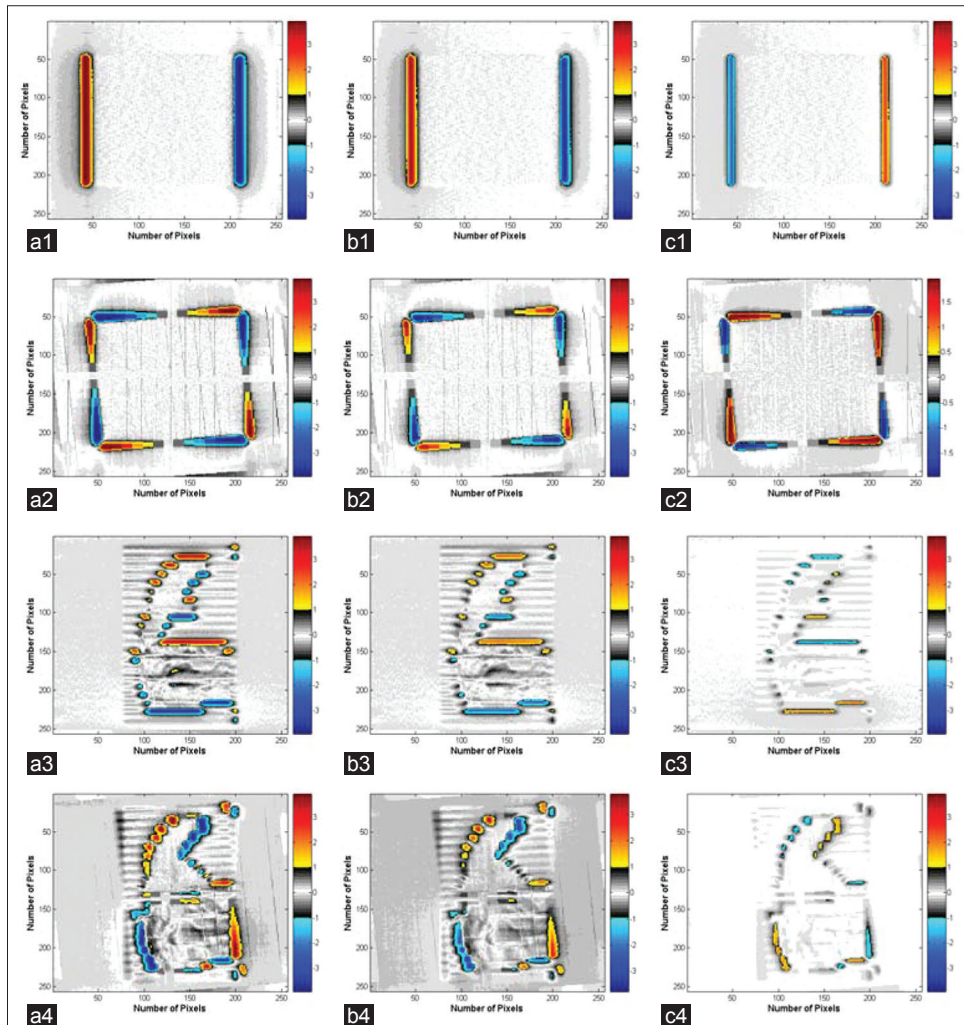


Figure 2: Two-dimensional (a series), three-dimensional modified gamma maps (b series) and the difference between two- and three-dimensional gamma maps (c series) for a 20×20 cm² (first and second rows), and a MLC field (third and fourth rows) for a 5 pixel transition and for a 5° rotation (first and third rows, respectively) with 3%/2.5 mm criteria

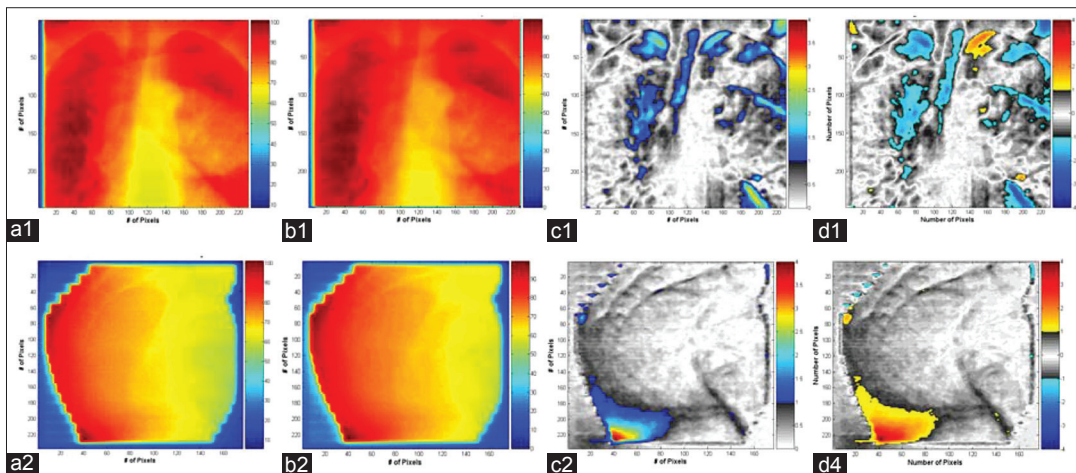


Figure 3: Two-dimensional relative dose map (a series) measured using a SLIC-EPID (b series), calculated using a treatment planning system (c series), three dimensional gamma map (d series) and three dimensional signed gamma map for a lung (first row) and breast (second row) cases with 3%/2.54 mm criteria

Table 2: Percentage of agreement and disagreement achieved using modified two- and three-dimensional gamma functions and the contribution of over- and under-dose regions in disagreed regions for a range of radiation fields with a 5 pixel translation and 5 rotation of reference dose maps

Radiation Field	Modification	2D Modified gamma			3D Modified gamma			Agreement difference (3D-2D) (%)
		Agreement (%)	Disagreement (%)		Agreement (%)	Disagreement (%)		
			Over-dose	Under-dose		Over-dose	Under-dose	
Open 10×10 cm ²	5 pixel	96.4	1.8	1.8	97.1	1.5	1.5	0.7
	5°	98.0	0.7	1.3	99.2	0.2	0.6	1.2
Open 20×20 cm ²	5 pixel	93.2	3.4	3.4	94.2	2.9	2.8	1.0
	5°	94.6	3.2	2.3	94.7	2.2	3.1	0.2
Open Wedged (W60)	5 pixel	62.6	25.4	12.0	75.7	16.6	7.7	13.1
	5°	42.6	30.6	26.7	49.8	27.6	22.5	7.2
Open field with attenuator at half field	5 pixel	48.5	25.4	26.1	62.0	18.3	19.7	13.5
	5°	61.6	26.2	12.2	75.9	16.1	8.0	14.4
MLC field	5 pixel	95.9	2.1	2.0	97.1	1.5	1.4	1.2
	5°	94.5	2.8	2.7	96.5	1.7	1.8	2.0

Table 3: Percentage of agreements and disagreements achieved using conventional, modified two- and three-dimensional gamma functions and the contribution of over- and under-dose areas in disagreed regions for typical breast and lung cases

Radiation Field	2D Modified gamma			3D Modified gamma		
	Agreement (%)	Disagreement (%)		Agreement (%)	Disagreement (%)	
		Over-dose	Under-dose		Over-dose	Under-dose
Breast case	91.3	7.9	0.8	92.6	6.7	0.7
Lung case	83.3	1.9	14.8	86.2	1.8	12.0

breast cases. The results of three-dimensional and signed three-dimensional gamma functions are shown in Figure 3. The numerical values of the investigation are also provided in Table 3. The results show that like the non-clinical cases shown previously, the three-dimensional gamma function improves the agreement between reference and evaluated dose maps. In addition, a signed gamma map for both approaches (two- and three-dimensional) is able to provide more information about the location of under- and over-dose regions. In the clinical cases, the pixel size in the predicted dose image matrix is not identical with the corresponding transmitted dose maps measured using the SLIC-EPID and an image resizing tool is used to make them the same size compared to measured dose maps. This perhaps decreases the slope of dose gradient in high gradient regions.

Although the reference dose map is a two-dimensional dose distribution, each point of a two-dimensional dose maps can be compared with other peripheral points. This leads to a three-dimensional dose comparison. The significance of the difference is that the two-dimensional case underestimates the agreement between two two-dimensional dose maps. In contrast, a three-dimensional gamma map is more practical and results are closer to the real situation.

Conclusion

Although the conventional gamma function is able to

recognize the agreed and disagreed regions, it is not able to illustrate the contribution of over-and under-dose regions. In the current work, it has been shown that by combining the dose difference map with a sign term it is possible to highlight the over- and under-dose regions in the disagreed areas. The enhancement can also be extended for agreed areas if required.

The desired dose map for a three-dimensional dose distribution evaluated in the current study is an array of 3 two-dimensional dose maps and it can be extended into 5 or 7 dose maps pending DTA criterion and the size of dose grid voxels. This extension could be a helpful effort to approach more realistic dose distribution comparisons for two-and three-dimensional dosimetry.

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