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Review paper

Challenges in calculation of the gamma index in radiotherapy – Towards good practice

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ABSTRACT

The gamma index (γ) is one of the most commonly used metrics for the verification of complex modulated radiotherapy. The mathematical definition of the γ is computationally expensive and various techniques have been reported to speed up the calculation either by mathematically refining the γ or employing various computational techniques. These techniques can cause variation in output with different software implementations. The γ has traditionally been used to compare a 2D measured plane against a 2D or 3D dose distribution. Recently, software algorithm and hardware improvements have led to the possibility of using measured 2D data from commercial detector arrays to reconstruct a 3D-dose distribution and perform a volumetric comparison against the treatment planning system (TPS). A limitation in this approach is that commercial detector arrays have so far been limited by their spatial resolution which may affect the accuracy of the reconstructed 3D volume and subsequently the γ calculation. Additionally, 3D versus 3D γ comparison adds a layer of complication in the calculation of the γ given the increase in the number of calculation points and the result cannot be as easily interpreted in the same way as 2D comparison. This review summarises and highlights the computational challenges of the γ calculation and sheds light on some of these issues by means of a bespoke MATLAB software to demonstrate the impact of interpolation, γ search distance, resolution and 2D and 3D calculations. Finally, a recommendation is made on the minimum information that should be reported when publishing γ results.

Contents

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1. Introduction

The gamma index (γ) is one of the most commonly used metrics for the verification of complex radiotherapy deliveries such as intensity modulated radiotherapy (IMRT) and volumetric modulated arc radiotherapy (VMAT) [1]. The metric has been widely accepted and is implemented into most commercial verification analysis software. By combining dose difference and distance-to-agreement, the γ provides the means for an efficient analysis which is particularly important within a busy clinical environment [2,3]. Its popularity can be seen in the number of times that it has been used in the scientific peer reviewed literature. In the Elsevier Scopus citation database it was found that the original γ paper [1] has been cited 1088 times in the literature since it was published, as of January 2017. Of these, there were 978 original research articles; the remainder were composed of 81 conference proceedings, 20 review papers and the remainder as book chapters, letters, or Editorials.

The mathematical definition of the γ is computationally expensive and a full calculation can take a significant amount of time depending on the number of data points and the processing speed of the computer being used [4,5]. This has led to computational challenges where there have been various reports in the literature focused on either mathematically refining the γ or employing various computational techniques to speed up the process [4–8]. These various techniques can potentially cause variation in output with different software implementations. Often the exact technique employed to calculate the γ in commercial software is not well defined, with manufacturers typically referencing the original paper by Low et al. [1], but the implementation having subtle variations.

The γ has traditionally been used to compare a 2D measured plane against a 2D or 3D dose distribution. There have been quasi-3D commercial systems available [2,9–11]; however these have not constructed a true 3-dimensional dose distribution. Recently, software algorithm and hardware improvements have led to the possibility of using measured 2D data from commercial detector arrays to reconstruct a 3D-dose distribution and perform a volumetric comparison against the treatment planning system (TPS). A limitation in this approach is that commercial detector arrays have so far been limited by their spatial resolution which may affect the accuracy of the reconstructed 3D volume and subsequently the γ calculation due to under-sampling [12]. Additionally 3D versus 3D γ comparison adds an extra layer of complication in the calculation of the γ given the increase in the number of calculation points and therefore the limited speed of calculation and the result cannot be as easily interpreted in the same way as a 2D comparison.

This review article seeks to summarise and highlight the computational challenges of the gamma index calculation and shed light on some of these issues by means of bespoke in-house written MATLAB software to demonstrate the impact of interpolation, gamma index search distance, resolution and 2D and 3D calculations.

2. Definition of the gamma index

The gamma index combines dose difference and distance difference to calculate a dimensionless metric for each point in the evaluated distribution. The ***reference dose distribution*** is generally taken as the 'gold standard', e.g. it could be the dose distribution that has been measured. In theory the distribution could be a single point (e.g. ionisation chamber measurement), 1D (e.g. a line profile), 2D (e.g. film measurement) or 3D (e.g. gel dosimetry, Monte Carlo simulation). The ***evaluated dose distribution*** is what is being compared. In most cases this will be the predicted TPS dose distribution that is being checked for accuracy in modelling the delivered dose.

2.1. Formalism of the gamma index

The γ is calculated based on finding the minimum Euclidean distance for each reference point, see Fig. 1 in conjunction with the following description. For each reference point in the dose distribution, calculate against each point in the evaluated distribution:

1. the distance between reference to evaluated point: $\Delta r(\mathbf{r}_R, \mathbf{r}_E)$
2. the dose difference between the reference and evaluated point: $\Delta r(\mathbf{r}_R, \mathbf{r}_E)$

Where $\mathbf{r}_R$ is the reference point, $\mathbf{r}_E$ is the evaluated point. The dose difference is calculated using Eq. (1):

$$\Delta D(r_R, r_E) = D_E(r_E) - D_R(r_R) \tag{1}$$

where $D_E(r_E)$ is the dose at a point in the evaluated dose distribution, r_E, and $D_R(r_R)$ is reference point dose.

Then for each point in the evaluated distribution, calculate the γ using Eq. (2):

$$\Gamma(\mathbf{r_R}, \mathbf{r_E}) = \sqrt{\frac{\Delta r^2(\mathbf{r}_R, \mathbf{r}_E)}{\delta r^2} + \frac{\Delta D^2(\mathbf{r}_R, \mathbf{r}_E)}{\delta D^2}} \tag{2}$$

where δr is the distance difference criterion and δD is the dose difference criterion.

The γ is then taken as the minimum value calculated over all evaluated points as shown in Eq. (3):

$$\gamma(\mathbf{r}_R) = min\{\Gamma(\mathbf{r_R}, \mathbf{r}_E)\} \forall \{\mathbf{r_E}\} \tag{3}$$

The δr and δD criteria form an ellipsoid around the reference point as shown in Fig. 1. If an evaluated point is located within this then the reference point will pass since γ will be <1.

For nomenclature it is standard to report the passing criteria in the format $\delta D(\%)/\delta r(\text{mm})$. The most common passing criteria used is 3%/3 mm which was originally recommended in the work by Low et al. [1]. The γ was originally developed to compare measured water tank beam data against a treatment planning system algorithm. The criteria of 3%/3 mm were used due to the limitations of TPS algorithms at the time, where particularly penumbra modelling was a source of uncertainty [1]. Because the γ takes into account dose difference and distance difference it was well-suited to the modulated fields in IMRT, however the criteria of 3%/3 mm has persisted. This standard nomenclature is used throughout this review. In order to eliminate dose in the out-of-field region where a large relative dose difference can be calculated and hence skew the γ result, it is typical to set a lower dose threshold below which the γ result is ignored. Therefore, it is common to