Development of automated delivery quality assurance analysis software for helical tomotherapy

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Method Article

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Abstract

Background: To develop a fully-automated in-house gamma analysis software for the “Cheese” phantom-based delivery quality assurance (QA) of helical tomotherapy plans.

Methods: The developed in-house software was designed to automate several procedures, which need to be manually performed using commercial software packages. The region of interest (ROI) for the analysis was automatically selected by cropping out film edges and thresholding dose values (>10% of the maximum dose). The film-measured dose was automatically aligned to the computed dose. An optimal film scaling factor was determined to maximize the percentage of pixels passing gamma (gamma pass rate) between the measured and computed doses (3%/3 mm criteria). This gamma analysis was repeated by introducing setup uncertainties in the anterior-posterior direction. For 73 tomotherapy plans, the gamma analysis results using the developed software were compared to those analyzed by medical physicists using a commercial software package.

Results: The developed software successfully automated the gamma analysis for the tomotherapy delivery QA. The gamma pass rate calculated by the developed software was higher than that by the clinically used software by 3.0%, on average. While, for 1 of the 73 plans, the gamma pass rates by the manual gamma analysis were higher than 90% (pass/fail criteria), the gamma analysis using the developed software resulted in fail.

Conclusions: The use of the automated and standardized gamma analysis software can improve both the clinical efficiency and veracity of the analysis results. Furthermore, the gamma analyses with various film scaling factors and setup uncertainties will provide clinically useful information for further investigations.

Background

Patient-specific quality assurance (QA) is an essential routine process for the safe delivery of radiation treatment. This process typically includes pretreatment delivery verification which identifies discrepancies between calculated and delivered radiation doses. So far, the delivery quality assurance (DQA) processes which use water equivalent phantoms with inserted ionization chambers/films or detector arrays [1-6] are well-established methods. The gamma analysis [7] has been commonly used to compare the measured doses to the calculated doses.

Recently, there has been a strong interest in developing and clinically implementing log-based (or phantom-less) patient-specific QA methods [8-10]. Many studies have evaluated the feasibility of a log-based patient-specific QA for tomotherapy [8, 9, 11-13]. Han et al. developed an in-house software which incorporated leaf open times (as measured by the exit detector) into the independent dose calculation using the Mobius3D® QA platform (Varian Medical Systems, Palo Alto, CA, USA). However, no commercial software is currently available for the log-based patient-specific QA. Therefore, for the patient-specific QA for tomotherapy, the cylindrical Virtual Water™ phantom (Gammex RMI, Middleton, WI;
called the “Cheese” phantom) is widely used because it is available upon the purchase of a tomotherapy machine.

While detailed guidelines for patient-specific QA procedures for helical tomotherapy have been published in the American Association of Physicists in Medicine (AAPM) Task Group (TG) reports [14, 15], the gamma analysis software provided by the vendor and commercial software has several shortcomings. First, performing a gamma analysis using the vendor-provided and commercial software packages involves several procedures that need to be manually performed by medical physicists, such as the determination of region-of-interest (ROI), alignment of the film to the dose calculation grids, determination of film scaling factor, and creation of the report. In consequence, the gamma analysis results often may vary depending on the knowledge and experience levels of the medical physicist. Second, it is labor-intensive to identify the reason for the failure when the gamma analysis result does not meet the criteria. When the DQA fails, the AAPM TG-148 report recommends that the medical physicist should investigate the causes. Further investigations typically necessitate multiple analyses by adjusting and/or verifying several parameters, which include, but are not limited to, the ROI, film alignment, and film scaling factor.

To overcome these problems, an automated in-house gamma analysis software package was developed for the Cheese phantom-based pretreatment beam verification for helical radiotherapy plans, which complies with the guidelines provided in the AAPM TG-148 and TG-218 reports. The developed in-house software was designed to automate the aforementioned procedures (typically performed manually) with the use of standardized parameters, thereby minimizing user-dependency of the gamma analysis results. Furthermore, the developed software is capable of not only finding the maximum gamma passing rate, but also providing clinically relevant information, such as gamma passing rates calculated under various film scaling factors and setup uncertainties.

**Methods**

**A : A Development of in-house automated DQA software**

**A.1: Automation in developed software**

The workflow of the gamma analysis for the tomotherapy pretreatment beam verification is shown in Fig 1. The gamma analysis that uses commercial software packages, such as TomoDQA Station (Accuray, Inc., Sunnyvale, CA, USA) or RIT (Radiological Imaging Technology, Inc., Colorado Springs, CO, USA), requires users to manually perform several steps. However, the newly-developed software has automated the following: 1) selection of region-of-interest (ROI) for gamma analysis, 2) determination from the various film scaling factors, 3) alignment of the film-measured dose to the computed dose, and 4) repeated gamma analysis with setup errors in the anteroposterior (A-P) direction. Details of the automation implemented in the developed software are described below.

First, the pre-defined ROI selection for the gamma analysis was automated by only including regions inside 10% of each height and width from the film edge and doses larger than 10% of the maximum dose.
Using the TomoDQA Station, only a rectangular region can be selected manually, which leaves room for user-dependent and non-standardized gamma analysis. However, gamma analysis results could be inaccurate with the pre-defined ROI only due to the inclusion of the phantom edge in the pre-defined ROI. This is because inhomogeneous characteristics of film optical densities (unexpectedly far different from the calculated dose) can be observed near the phantom edge, resulting in high gamma index values along the phantom edge. This procedure to exclude the region in close proximity to the phantom edge should be manually performed for the gamma analysis using a more advanced commercial software package such as RIT.

In the developed software, the location of the phantom edge was automatically calculated by detecting a horizontal line, along which the percentage of pixels passing gamma (gamma pass rate) was lower than 20%; for this calculation of the gamma pass rate, only a central part of each horizontal line (approximately 10 cm; 300 pixels in this investigation) was chosen to focus the analysis on high dose region as illustrated in Fig 2. When multiple lines with gamma pass rate < 20% were found, the innermost line was determined to be the phantom edge. This phantom edge detection based on the gamma analysis results was performed only in 20% top and bottom regions of the film, in which the phantom edge can be located. After specifying the phantom edge, pre-defined ROI modified into phantom edge with additional 10 mm cropped from the for the analysis, following the recommendation by the AAPM TG-148 report [14]. It is noted that the region near the phantom edge was excluded at the end of the workflow as described in Fig 1 because the phantom edge detection was based on the gamma analysis results, in which the pre-defined region (10% border exclusion and 10% threshold) of the film was subjected to the gamma analysis.

Second, gamma analysis was performed with a range of film scaling factors (0.9 to 1.1 with an interval of 0.1). The purpose of this analysis was not only to automatically find an optimal film scaling factor that maximized the gamma pass rate, but also to provide additional information that would be useful for further investigation, i.e., variation of the gamma pass rate as a function of the film scaling factor.

Third, the film-measured dose was automatically aligned to the computed dose. This was performed in two steps. The first step was to find the A-P location of the film inserted in the Cheese phantom. The film A-P location was calculated using the geometric relationship (A-P distance) between the film plane and the metal balls in the phantom as illustrated in Fig 3. Specifically, the A-P coordinates of the film plane was calculated by adding the film-to-metal ball distance in the A-P direction (94.7 mm, Fig 3) to the red laser A-P location, available in the DICOM RT plan file. This was followed by two-dimensional image registration using a built-in MATLAB multi-modal registration algorithm. In the automatic image registration, a mutual information-based image metric was minimized to find optimal translation and rotation vectors using a global optimization algorithm (One Plus One Evolutionary Optimizer).

Fourth, gamma pass rates were calculated at various film-aligning A-P locations, simulating setup uncertainty in the A-P direction. This perturbation analysis helped assess the setup uncertainty in the film-based measurement. Specifically, gamma analysis was conducted with setup uncertainties of -3.0 to 3.0
mm at intervals of 0.5 mm, in addition to the gamma analysis performed with the exact A-P film location, calculated in the film alignment process. A negative setup uncertainty simulates a measurement setup in which the phantom is placed 1 mm posterior of the reference position.

As a result of the development of this software, all the institution- and machine-specific gamma analysis parameters can be saved as a pre-defined configuration file. In addition to this, all of the automated steps can also be manually implemented, if so desired.

A.2 Further details of gamma analysis

Film optical density scanned by VIDAR TWAIN version 5.2 software (Vidar Systems Corporation, Hendon, VA, USA) and was converted to a dose [16-19] using a text file containing a measured data set of the delivered doses and the corresponding optical densities. Film-measured doses were converted from the optical density values using a bi-cubic interpolation of the discrete sets of the optical density and dose values. The file path can be saved to the configuration file and reset whenever a film calibration is performed. The noise level in the film-measured dose was reduced by applying a medial filter according to the recommendation by the AAPM TG-218 report; a 5 × 5 median filter was set as the default, which can be adjusted by the user. For the gamma analysis, the film-measured dose and computed dose were resampled with a pixel dimension of 1.0 × 1.0 mm².

The gamma index was calculated using the formula described in the previous study by Low et al. [7]. The gamma analysis was performed using a criterion of 90% gamma pass rate with a 3% dose difference, and 3 mm distance-to-agreement (DTA), as recommended in the AAPM TG-148 report. The percentage dose difference was calculated with respect to the maximum calculated dose (global normalization).

B : Performance evaluation

The performance of the developed in-house software was evaluated for 73 tomotherapy intensity-modulated radiation therapy (IMRT) plans, which were delivered by three tomotherapy machines (Machine 1 : TomoTherapy® HD, Machine 2 and 3 : TomoTherapy® HDA; Accuray, Inc., Sunnyvale, CA, USA). The treatment sites of the IMRT plans included in this study are summarized in Fig 4. All of the DQAs for these IMRT plans were performed using the Cheese phantom with a radiochromic EBT3 film (Ashland Specialty Ingredients, Bridgewater, NJ, USA). At the time of commissioning, each of the machine-specific Cheese phantoms was scanned and registered with the treatment planning system. The voxel dimensions of the phantom CT images were 1.9 × 1.9 × 3.0 mm³ (machines 1 and 3) or 2.0 × 2.0 × 3.0 mm³ (machine 2).

To evaluate the performance of the developed in-house software, the gamma analysis results were compared to those obtained using RIT version 6.8, which was currently in clinical use. At the authors’ institute, two software packages were available for the tomotherapy DQA gamma analysis: TomoDQA Station and RIT. Both of the software packages had been used for the gamma analysis until this investigation was initiated: TomoDQA Station for TomoTherapy machines and RIT for Radixact
machines. For simplicity of clinical procedure and due to reduced computing time with RIT, RIT was only used for the gamma analysis. It is noted that the analysis procedures, which were automated by the in-house software, should be manually performed in both TomoDQA Station and RIT.

Film calibration was performed on a monthly basis using flattening filter-free 6 MV X-ray beams of an Elekta Versa HD linear accelerator (Elekta, Stockholm, Sweden). For the film calibration, several doses ranging from 0 to 18 Gy were delivered to the radiochromic film. The film optical density values were measured 9 hours after the beam delivery for full film development. For the IMRT plans under consideration, two film calibration curves were used as films with two different lot numbers were used for the DQAs.

C : Software installation and requirement

The in-house gamma analysis software was developed using MATLAB v2021 (Mathworks, Inc., Natick, MA, USA) and compiled using the MATLAB compiler to create a standalone executable. Therefore, the software can be run without MATLAB installation and freely downloaded from https://drive.google.com/file/d/1lhICIV9kBIAfqwUfx8-A2uaoceVMM7g/view?usp=sharing. This software has been tested on Windows 10 professional (build 19041.1415 and 19042.1415) with 64-bit operating system.

Results

A : A Development of in-house automated DQA software

Fig 5 shows the graphical user interface of the developed DQA software, in which a gamma analysis for one patient is displayed. Specifically, the graphical user interface displays various comparisons between the measured and computed doses: (1) the comparison of the two-dimensional dose distributions, (2) the comparison of the doses along two user-specifiable lines (horizontal and vertical), (3) the two-dimensional distribution of the computed gamma index values, and (4) the gamma pass rates calculated with various film scaling factors and film A-P alignment uncertainties. Furthermore, in the “Configuration” tab, the gamma analysis parameters (set to default values) used for the analysis were displayed. These parameters can be set either by importing settings from a pre-defined configuration file, or by manually adjusting each value. After clicking “Run DQA,” the analysis will proceed, and all of the steps can be completed in approximately 1 minute – this will lead to the generation of a gamma analysis summary report. The in-house DQA analysis software is designed, so that users can opt out of the perturbation analysis with various A-P film alignment conditions. Without this optional feature (denoted as “A-P uncertainty”), the analysis takes approximately 10 seconds per plan, further improving clinical efficiency.

B : Performance evaluation

B.1 : Selection of region-of-interest
Fig 6 demonstrates the impact of the selected ROI for the gamma analysis on the resulting gamma pass rate. In Fig 6, the two rectangular regions represent a simulated region (smaller region; represented as red dashed line), which can be defined by field medical physicists, and the automatically-selected region (larger region; white solid), processed by the developed software. The gamma pass rates with the manually- and automatically-defined regions were 91.7% and 85.7%, which corresponded to “pass” and “fail” by the gamma analysis pass/fail criterion in this study (90%), respectively.

Fig 7 shows that the developed software successfully detected the phantom edge (upper describes the impact of the phantom edge cropping on the gamma analysis results. While the gamma pass rate was 89.6% without an appropriate exclusion of the phantom edge region, the gamma analysis resulted in a gamma pass rate of 92.7%. Among the 73 patient cases, the phantom edge location was incorrectly calculated by the developed algorithm for only one case.

B.2 : Automatic determination of film scaling factor

Fig 8 compares the film scaling factors determined by the medical physicists (RIT-based gamma analysis) and by the developed software for all the patients; for both analyses, a film scaling factor with a maximum gamma pass rate was found. The overall trends of the film scaling factors obtained by the two analysis methods showed a reasonable agreement across the patient cases. The median (± standard deviation) of the difference in the film scaling factor between both methods was 0.018 ± 0.021. The film scaling factors by the gamma analyses using RIT and the developed software for machines 1, 2, and 3 were 0.955 ± 0.030, 0.979 ± 0.030, 0.976 ± 0.027 vs. 0.944 ± 0.025, 0.962 ± 0.029, 0.959 ± 0.030, respectively.

B.3 : Automatic film alignment to calculated dose

Fig 9 shows an automatic image registration result between the film-measured and computed doses. As demonstrated in small difference values in Fig 9 (c), the automatic image registration algorithm reasonably aligned the film-measured dose to the computed dose.

B.4 : Gamma analysis with setup uncertainty

Fig 10 illustrates how the gamma analysis results can be affected by the simulated setup uncertainties. With setup uncertainties in the A-P directions of -3.0, -1.5, and 0.0 mm, the resulting gamma pass rates were 88.7%, 92.5%, and 88.0%, respectively.

Fig 11 presents box plots of the gamma pass rates (maximum values with optimal film scaling factors) calculated across all patient plans with the setup uncertainties ranging from -3.0 to 3.0 mm at regular intervals of 0.5 mm. In addition, for each of the setup uncertainties, the number of occurrences of the maximum gamma pass rate (best gamma analysis results across all setup uncertainties) are presented in Fig 12. With setup uncertainties of -1.5 mm, the largest gamma pass rates were calculated for 13 of the 73 plans; this number of occurrences was highest across the setup uncertainties for all machines.
B.5 : Comparison of final gamma pass rate

Fig 13 presents a scattered plot of the difference between the final gamma pass rates obtained using RIT (manual analysis by the medical physicists) and the newly-developed software (automated analysis). On average, the gamma pass rate by the analysis using the developed software was 3.0% higher than those of the RIT-based analysis. For 54 of the 73 plans (74.0%), the gamma pass rate calculated using the developed software program was higher than that using RIT.

Discussion

We developed a novel automated in-house software for DQA gamma analysis of tomotherapy radiation treatment plans. Although pretreatment beam verification is essential for the safe delivery of radiation treatment plans, performing gamma analysis using commercial software packages, such as Tomotherapy DQA Station and RIT, requires repeated and labor-intensive manual procedures. Therefore, this investigation is an attempt towards automating several procedures in the tomotherapy DQA gamma analysis, which are both labor-intensive and can be user-dependent. Furthermore, the software adheres to the guidelines provided by the AAPM Task Group reports. The use of this newly-developed in-house software will improve the clinical efficiency of the tomotherapy DQA process while also enhancing the veracity of the DQA gamma analysis. Furthermore, a decrease in the processing time for the gamma analysis will allow medical physicists to focus their time on further investigation upon DQA failure.

The ROI selection was automated and standardized in the newly-developed software. As demonstrated in Fig. 6, the gamma analysis results can vary depending on the ROI selected by medical physicists. A gamma analysis with an inappropriately selected ROI can lead to false positive or false negative results. The automated ROI selection, implemented in the newly-developed software, can prevent these errors by employing a standardized definition of the ROI for the analysis and further facilitate pair evaluations across all plan cases. Furthermore, the phantom edge investigation was automated as demonstrated in Figs. 2 and 7. The automatic phantom edge detection is particularly important to achieve the goal of this study to fully automate the gamma analysis. Without this automation of excluding a region near the phantom edge, clinical physicists need to manually select ROI for each gamma analysis using currently available commercial software packages including RIT and TomoDQA station.

The procedure of finding an appropriate film scaling factor is labor-intensive. As shown in Fig. 7, the developed software successfully calculates optimal film scaling factors which are similar to those found manually by medical physicists. These results indicate that the developed software can find appropriate film scaling factor values, mimicking the “trial and error” process, in which medical physicists test various film scaling factors during gamma analysis. The developed software also provides the gamma analysis results for various film scaling factors, which may be useful to medical physicists. Both the average film scaling factors found by medical physicists and by the developed software were smaller than 1.0. These deviations from 1.0 can be attributed to film calibration error, machine output error, and dose calculation error in treatment planning system. For the gamma analysis in the developed software, it was assumed
that the analysis evaluates the level of “relative” agreement between the measured and computed dose distributions, as the absolute dose evaluation is performed via an ionization chamber measurement.

In the developed software, both automatic alignment of the film-measured dose to the computed dose and perturbation analysis with simulated setup uncertainties were implemented. By these capabilities in the developed software, the labor-intensive alignment procedures were eliminated, and the setup uncertainty in the A-P direction was automatically assessed. Consequently, for the patient plans considered in this study, maximum gamma pass rates were typically found with negative setup uncertainties. These results indicated that on average, the phantom was positioned posteriorly with respect to the planned position, requiring further investigations by medical physicists. Calculating the film-inserting plan using the red laser coordinates from DICOM RT plan files may introduce uncertainties, as the red laser is manually located by dosimetrists (or medical physicists) when creating a phantom plan. However, this localization error may be relatively small compared to the setup uncertainties, although users should be aware of this possible alignment error due to manual localization.

The gamma pass rates obtained by the developed software were higher than those obtained by medical physicists, on average. These results indicate that the gamma analysis shows a comparable performance to that of the commercial software and can replace the software in typical clinical use. More importantly, one false negative error was detected by the developed software, despite its higher average gamma pass rate. These results demonstrated that the developed software facilitated a standardized gamma analysis with an improved clinical efficiency and an enhanced capability to detect clinically feasible errors.

Although the developed software proposed a clinically efficient gamma analysis for the tomotherapy patient-specific QA method via standardization and automation, this study has several limitations as follows. First, the AAPM TG-218 report [15] recommended a tighter pass/fail criterion (gamma pass rate with 3%/2 mm ≥ 95%) than that used in this investigation [14]. However, users can customize the gamma criteria when using the developed gamma analysis software. Second, relative dose agreement was evaluated for the film dosimetry in this study while absolute dosimetry was recommended by the AAPM TG-218 report. However, an absolute dose verification using an ionization chamber was performed, complementing the relative dosimetry using film. For clinical efficiency, it was determined at the authors’ institution that a relative dose agreement was investigated for the film dosimetry with film calibration on a monthly basis. Although absolute dose verification is desirable for the film dosimetry, absolute dosimetry using film requires time-intensive procedures for appropriate calibration and its maintenance [20, 21]. In addition, using the developed software in case of performing an absolute dose verification using film can be still beneficial as the results by the automated analysis provide gamma analysis results without film scaling.

Conclusions
The developed in-house software successfully automated and standardized several manual procedures in the gamma analysis for the tomotherapy DQA. This will improve the clinical efficiency of the tomotherapy patient-specific QA process while enhancing the veracity of the gamma analysis results. The gamma analysis results with various film scaling factors and setup uncertainties can provide useful information for further investigations that need to be performed by medical physicists upon DQA failure.

Declarations

Ethics approval and consent to participate

This retrospective study was approved by the institutional review board of Severance Hospital, Seoul, South Korea (4-2022-0310). The need for written consent was waived owing to the retrospective nature of the study.

Consent for publication

Not applicable

Availability of data and materials

The data that support the findings of this study are available from corresponding author Jihun Kim and Jin Sung Kim but restrictions apply to the availability of these data, which were used under data protection laws for the current study, and so are not publicly available. Data are however available from the authors upon reasonable request and with permission of the patients.

Competing interests

The authors have no conflict of interest to disclose.

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Authors’ contributions

YH Yoon wrote and revised the manuscript, and developed a program. H-B Shin supported to test the developed program. MC Han, H Kim, DW Kim and C-S Hong contributed to the discussion on the conceptual design of this investigation. J Kim designed and supervised the study. JS Kim provide funds and commented on the study. All authors read and approved the final manuscript.

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References


Figures

**Figure 1**

**Workflow comparison between the gamma analyses methods.**

(a) Commercial software (RIT) and (b) the developed software. Upon patient-specific QA failure, manual investigation via iterations of trial and error may be required for the gamma analysis using commercial software. On the other hand, all of the manual procedures are automated and standardized in the developed software.
Figure 2

Phantom edge detection for the region-of-interest selection for the gamma analysis.

Phantom edges were investigated by detecting horizontal lines with a gamma pass rate < 20%. Only a central part (solid line) of each horizontal line was chosen for this investigation (i.e., dotted-line represents excluded part). This phantom edge detection based on the gamma analysis results was performed only in 20% top and bottom regions of the film, in which the phantom edge can be located.
Figure 3

Geometric relationship between the metal balls and film-inserting plan

In a tomotherapy Cheese phantom, distance between metal ball and film inserted plane was 94.7 mm. Image in white dashed-line magnified at right side.
Figure 4

Treatment sites for 73 treatment plans with the specific treatment machines

Treatment machine colored differently (i.e., 1, 2, and 3 are colored as blue, orange, yellow, respectively). The total number of plans is indicated at the top of each bar. PALN = Para aortic lymph node; PNS = Paranasal Sinus
Figure 5

Graphical user interface of the newly-developed delivery quality assurance software.

MRN: medical record number, GPR: gamma pass rate. DTA: distance to agreement.

Figure 6

An example of the impact of ROI on DQA gamma analysis

(a) Dose distribution and (b) gamma index distribution. The gamma pass rates with a region selected by a medical physicist (red dashed) and a standardized region defined by the developed software (white...
solid) were 91.7% and 85.7%, respectively.

Figure 7

An example of the phantom edge cropping result in gamma analysis.

At the top of the film image, a gamma-failed region (colored as red) due to unexpectedly high radiation doses near the phantom edge was observed. The gamma pass rate (a) with the region near the phantom edge cropped was 92.7% while that (b) with the default ROI (10% border exclusion and 10% dose threshold) was 89.6%.
**Figure 8**

**Comparison of the film scaling factors**

Film scaling factors compared between determined by medical physicists (clinical software; RIT) and the developed in-house software, whose average values are represented as black dashed-dot and blue dashed lines, respectively.
Figure 9

**Automatic alignment of film-measured dose to calculated dose**

(a) Film-measured dose distribution, (b) registered calculated dose distribution, and (c) the difference between the film dose and calculated dose.

![Images of dose distributions and gamma pass rates for different setup uncertainties](image)

Figure 10

**Comparison among the A-P uncertainties.**

Comparison of the calculated doses (top row), the difference between the measured and computed doses (middle), and the gamma index (bottom) with various setup uncertainties (0.0, -1.5, and -3.0 mm). A region with high dose gradients region is indicated by a white arrow.
Figure 11

Box plots of the maximum gamma pass rates

Highest gamma pass rate with an optimal film scaling factor calculated across the all patient plans for each of the setup uncertainties ranging from -3.0 to 3.0 mm at regular intervals of 0.5 mm: (a) for all machines, and separately, (b) for machine 1, (c) for machine 2, and (d) machine 3, respectively.
Figure 12

The number of occurrences of the best gamma analysis results

Maximum gamma pass rate across the simulated setup uncertainties for each of the setup uncertainties.
Figure 13

Gamma pass rate comparison between commercial software and in-house software.

Comparison of the maximum gamma pass rates (GPR) calculated for all the patient plans using the commercial software (RIT) and in-house software. Red dashed lines represent the gamma pass/fail criterion, i.e., 90% in this investigation.