Effect of dose grid resolution on the results of patient-specific quality assurance for intensity-modulated radiation therapy and volumetric modulated arc therapy

M. Chun[1,2,3], J.I. Kim[1,2,3], D.H. Oh[4], H.G. Wu[1,2,3,5], J.M.Park[1,2,3,6*]

[1]*Department of Radiation Oncology, Seoul National University Hospital, Seoul, Republic of Korea*
[2]*Biomedical Research Institute, Seoul National University College of Medicine, Seoul, Republic of Korea*
[3]*Institute of Radiation Medicine, Seoul National University Medical Research Center, Seoul, Republic of Korea*
[4]*Department of Radiation Oncology, Chung-Ang University Hospital, Seoul, Republic of Korea;*
[5]*Department of Radiation Oncology, Seoul National University College of Medicine, Seoul, Republic of Korea*
[6]*Robotics Research Laboratory for Extreme Environments, Advanced Institute of Convergence Technology, Suwon, Republic of Korea*

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***Corresponding authors:**
Jong Min Park Ph.D.,
E-mail:
leodavinci@naver.com

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ABSTRACT

Background: This study aims to investigate the effect of reference dose calculation grid size (RDCGS) on gamma passing rate (GPR) for patient-specific quality assurance of intensity-modulated radiation therapy (IMRT) and volumetric modulated arc therapy (VMAT). ***Materials and Methods:*** A total of 20 patients were retrospectively selected. Both IMRT and VMAT plans were generated for each patient. Reference dose distributions for gamma analysis were calculated with RDCGS of 1–5 mm at intervals of 1 mm. Dose distributions were measured using MapCHECK2 and ArcCHECK dosimeters. Both global and local gamma analyses with gamma criteria of 3%/3 mm, 2%/3 mm, 2%/2 mm, and 2%/1 mm were performed with various RDCGS. ***Results:*** As the RDCGS increased from 1 mm to 5 mm, the average global GPRs with 2%/2 mm for VMAT with MapCHECK2 and ArcCHECK decreased by 9.3% and 5.9%, respectively. The average local GPRs decreased by 14% and 11.7%, respectively. For IMRT, the global GPRs decreased by 4.8% and 6%, respectively, whereas the local GPRs decreased by 10.5% and 8.6%, respectively. The effect of the RDCGS on the GPRs became larger when performing local gamma analysis as well as when applying small distance-to-agreement (DTA). As the RDCGS increased, the average changes in the GPR per mm of DTA change increased regardless of the type of radiotherapy, detector, or gamma analysis. ***Conclusion:*** For an accurate verification of the IMRT and VMAT plans, it is recommended that the reference dose distribution must be calculated with the smallest possible RDCGS.

Keywords: *Dose calculation grid, gamma analysis, intensity-modulated radiation therapy, patient-specific QA, volumetric modulated arc therapy.*

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INTRODUCTION

To acquire optimal dose distributions, modulation of photon beam fluence is performed by modulating multi-leaf collimator (MLC) positions alone for intensity modulated radiation therapy (IMRT), while volumetric modulated arc therapy (VMAT) modulates photon beam fluences by simultaneous modulations of MLC positions, gantry rotation speeds, and dose-rates during rotations of a gantry around a patient (1-4). To determine the values of these modulation parameters, inverse optimization algorithms are generally used in the clinic for both IMRT and VMAT, of which process is not intuitive [5,6]. Moreover, highly irregular and small beam apertures are frequently used to generate IMRT and VMAT plans, of which dose calculation accuracy is not relatively high [7,8]. In terms of beam delivery, small errors in the dynamic motions of various mechanical components of a linac during delivery of IMRT or VMAT could cause discrepancy in the dose distributions between the calculation and the actual delivery to a patient [7,8]. Therefore, both the IMRT and VMAT plans involve uncertainties and the errors in the IMRT and VMAT plans are difficult to be detected owing to the non-intuitive planning procedure. In this respect, the errors in the IMRT and VMAT plans should be detected before a patient's treatment, and planar gamma analysis has been widely adopted as patient-specific quality assurance (QA) in the clinic [9-15].

Because the results of the gamma analysis, i.e., gamma passing rates (GPRs), are strongly influenced by its setting (gamma criteria, threshold value, resolution of the detector, dose calculation resolution, etc.), numerous studies on gamma analysis have been performed to investigate the changes in GPR as its setting is varied [13-21]. However, few studies have investigated the effect of reference dose calculation grid size (RDCGS) on the GPR [20,21]. Tanooka *et al.* demonstrated that the GPRs with an RDCGS of 1 mm were higher than those with an RDCGS of 2 mm in performing 3D radiochromic film dosimetry for VMAT using the spiral water phantom developed by the authors [20]. Shang *et al*. revealed that the verification plans calculated with a 2 mm grid exhibited a higher GPR than those with a 3 mm grid utilizing nine IMRT plans [21]. They concluded that a higher resolution of the calculated dose distributions could offer a greater opportunity to find a point satisfying the gamma criteria. Although some studies have reported that an increase in the GPR as increases the RDCGS, no thorough study has investigated the effect of the RDCGS on the GPR with various gamma criteria, analysis types, radiotherapy techniques, and detector types.

In this study, we investigated the changes in both the global and local GPRs according to the changes in the RDCGS. We analyzed the changes in the GPR with various gamma criteria, which were 3%/3 mm, 2%/3 mm, 2%/2 mm, and 2%/1 mm. The GPRs were analyzed for both IMRT and VMAT with two types of detectors: MapCHECK2™ (Sun Nuclear Co., Melbourne, FL, USA), and ArcCHECK™ (Sun Nuclear Co., Melbourne, FL, USA).

MATERIALS AND METHODS

Patient selection

Ten patients with brain tumor and ten patients with head and neck (HN) cancer (a total of 20 patients) were retrospectively selected for this study after an institutional review board Ethical committee approval from Seoul National University Hospital (IRB No. 1706-155-863). The IRB committee of Seoul National University Hospital waived the requirement for informed consent. Every patient underwent CT scans using the Brilliance CT Big Bore™ (Phillips, Amsterdam, Netherlands) with a slice thickness of 2 mm.

Treatment planning

For each patient, an IMRT plan and a VMAT plan were generated using 6-MV photon beams from the TrueBeam STx™ with the high definition (HD) 120™ MLC (Varian Medical Systems, Palo Alto, CA, USA). All the IMRT and VMAT plans were generated using the Eclipse™ system (Varian Medical Systems, Palo Alto, CA, USA). For IMRT optimization, dose volume optimizer (DVO, ver.10, Varian Medical Systems, Palo Alto, CA, USA) was used, while progressive resolution optimizer (PRO3, ver.10, Varian Medical Systems, Palo Alto, CA, USA) was used for VMAT optimization. For both IMRT and VMAT plans, anisotropic analytic algorithm (AAA, ver.10, Varian Medical Systems, Palo Alto, CA, USA) was used to calculate dose distributions.

The prescription dose for brain tumor was 30 Gy with a daily dose of 3 Gy (10 fractions). For IMRT, from five to eight non-coplanar fields were used to generate an optimal plan. According to locations of the tumor and organs at risk (OARs), various gantry angles combined with the couch rotation angles were used. For VMAT, two full coplanar arcs or two partial non-coplanar arcs were used according to the locations of the tumor and OARs. Both the IMRT and VMAT plans for brain tumor were normalized to cover 90% of the planning target volume (PTV) with 100% of the prescription dose.

For HN cancer, simultaneously integrated boost (SIB) plans were generated with a total of three target volumes: $PTV_{67.5Gy}$, PTV_{54Gy}, and PTV_{48Gy}. Prescription doses of 67.5 Gy (daily dose of 2.25 Gy), 54 Gy (daily dose of 1.8 Gy), and 48 Gy (daily dose of 1.6 Gy) were delivered to $PTV_{67.5Gy}$, PTV_{54Gy}, and PTV_{48Gy}, respectively (30 fractions). For IMRT, eight non-opposed coplanar fields were used, while two full coplanar arcs were used for VMAT. The gantry angles used for IMRT planning were 40˚, 60˚, 100˚, 160˚, 200˚, 260˚, 300˚, and 320˚. As with the brain plans, both the IMRT and VMAT plans for HN cancer were normalized to cover 90% of the $PTV_{67.5Gy}$ with 100% of the prescription dose of 67.5 Gy.

Measurement of 2D dose distributions

For each plan, patient-specific QA was performed with MapCHECK2 inserted in the MapPHAN™ (Sun Nuclear Co., Melbourne, FL, USA) as well as with the ArcCHECK. The maximum field size that can be measured with MapCHECK2 is 32 cm × 26 cm. The array diameter and length of ArcCHECK are both 21 cm. The detector spacing and active detector volume of MapCHECK2 are 7.07 mm and 0.019 mm^3, respectively, while those of ArcCHECK are 10 mm and 0.019 mm^3, respectively. Both MapCHECK2 and ArcCHECK use the same type of diodes, SunPoint® diode detector (Sun Nuclear Co., Melbourne, FL, USA). For patient-specific QA using MapCHECK2 with MapPHAN and ArcCHECK, verification plans identical to the treatment plans were generated with CT images of MapPHAN and ArcCHECK, respectively. When generating the verification plans, couch rotation angles were set to be 0º. The reference dose distributions were generated with dose calculation grid sizes of 1–5 mm at an interval of 1 mm for MapCHECK2, and of 1–4 mm at an interval of 1 mm for ArcCHECK. Because the gamma analysis software of the ArcCHECK does not allow imports of calculated dose distributions with RDCGS equal to or larger than 5 mm, the RDCGS of 5 mm could not be calculated for ArcCHECK. Before performing the measurements with MapCHECK2 or ArcCHECK, the output of TrueBeam STx was calibrated following the American Association Physicists in Medicine (AAPM) task group (TG) 51 protocol to keep the output deviation lower than 0.1% [22]. Before measurements of the dose distributions with MapCHECK2 and ArcCHECK for patient-specific QA were conducted, both dosimeters were calibrated according to each calibration procedure provided by the manufacturer (Sun Nuclear Co., Melbourne, FL, USA). When the dosimeter was set-up, cone-beam computed tomography (CBCT) was used to set up the devices accurately.

Gamma analysis

For 2D gamma analysis with MapCHECK2 and ArcCHECK, SNC patient™ software (ver. 6.1.2, Sun Nuclear Co., Melbourne, FL, USA) was used. The 2D gamma analysis was performed with absolute doses rather than relative doses. For each plan, the dose distribution of a single measurement was compared to those calculated with various RDCGS as mentioned above (from 1 mm to 5 mm for MapCHECK2 and from 1 mm to 4 mm for ArcCHECK). The threshold value was 10%. The gamma criteria used for this study were 3%/3 mm, 2%/3 mm, 2%/2 mm, and 2%/1 mm for both IMRT and VMAT. There are two modes of gamma analysis: global and local. For global gamma analysis, the percentage dose differences of each point are calculated relative to the maximum dose, while for local analysis they are calculated relative to doses at each point. Both the global and local gamma analyses were performed for both IMRT and VMAT.

RESULTS

Gamma analysis with VMAT plans

The global GPR with various gamma criteria

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and various RDCGS, which were acquired with MapCHECK2 and ArcCHECK, are shown for VMAT in table 1. Corresponding results for the local GPR are shown in table 2.

As the RDCGS increased, the global GPR decreased for both MapCHECK2 and ArcCHECK. For a gamma criterion of 2%/2 mm, the average values of the global GPR of VMAT acquired with MapCHECK2 decreased from 97.5% to 88.2% (9.3% decrease) on increasing the RDCGS from 1 mm to 5 mm, while those acquired with ArcCHECK decreased from 99.4% to 93.5% (5.9% decrease) on increasing the RDCGS from 1 mm to 4 mm. Up to a RDCGS of 2 mm, no VMAT plans acquired with MapCHECK2 showed global GPR of less than 90% with 2%/2 mm; however, global GPR of less than 90% were observed from the RDCGS larger than 3 mm. For ArcCHECK, up to an RDCGS of 3 mm, no VMAT plans showed GPR of less than 90% with 2%/2 mm, while some VMAT plans showed GPR of less than 90% with the RDCGS of 4 mm. A similar tendency was observed for the local GPR. The average values of the local GPR with 2%/2 mm decreased from 88.6% to 74.6% (14% decrease) on increasing the RDCGS from 1 mm to 5 mm acquired with MapCHECK2, while they decreased from 94.5% to 82.8% (11.7% decrease) on increasing the RDCGS from 1 mm to 4 mm with ArcCHECK. A similar tendency with respect to changing the RDCGS was observed in the local GPR as in the global GPR; however, the decrease was more rapid in the local GPR. With 2%/2 mm criteria, the GPR from 1 mm to the maximum grid size (5 mm for MapCHECK2 and 4 mm for ArcCHECK) decreased by 14.1% for local and by 9.2% for global gamma analysis when using the MapCHECK2 dosimeter. For ArcCHECK, those decreases were 11.7% for local and 6.0% for global gamma analysis. The decreases in the global and local GPR with 2%/2 mm acquired with MapCHECK2 and ArcCHECK are shown in figure 1.

The sensitivity of the GPR according to the RDCGS increased on increasing the tightness of the gamma criterion, i.e., on decreasing the percentage dose difference and the distance-to-agreement (DTA) of the gamma criterion. The decreases in the local GPR with an increase in the RDCGS were larger than those in the global GPR.

Gamma analysis with IMRT plans

The global GPR with various gamma criteria and various RDCGS, which were acquired with MapCHECK2 and ArcCHECK are shown for IMRT in table 3, and the local GPR for the same are shown in table 4.

As the RDCGS increased, the global GPR decreased for both MapCHECK2 and ArcCHECK, as with the results of VMAT. For a gamma criterion of 2%/2 mm, the average values of the global GPR of IMRT acquired with MapCHECK2 decreased from 93.1% to 88.3% (4.8% decrease) as the RDCGS increased from 1 mm to 5 mm, while those acquired with ArcCHECK decreased from 97.6% to 91.6% (6.0% decrease) as the RDCGS increased from 1 mm to 4 mm. Up to a RDCGS of 2 mm, no IMRT plans showed global GPR of less than 80% with MapCHECK2 for 2%/2 mm; however, global GPR of less than 80% were observed from RDCGS equal to or larger than 3 mm. For ArcCHECK, up to a RDCGS of 2 mm, no IMRT plans showed GPRs less than 90% for 2%/2 mm, while some IMRT plans showed GPRs less than 90% for RDCGS equal to or larger than 3 mm. A similar tendency was observed for the local GPR. The average values of the local GPR with 2%/2 mm decreased from 80.1% to 69.6% (10.5% decrease) on increasing the RDCGS from 1 mm to 5 mm with MapCHECK2, while they decreased from 76.3% to 67.7% (8.6% decrease) on increasing the RDCGS from 1 mm to 4 mm with ArcCHECK. A similar tendency with respect to changing the RDCGS was observed in the local GPR as in the global GPR; however, the decrease was more rapid in the local GPR. With 2%/2 mm criteria, the GPR from 1 mm to the maximum grid size decreased by 10.5% for local and by 8.2% for global gamma analysis when using the MapCHECK2 dosimeter. For ArcCHECK, those decreases were 8.6% for local and 6.0% for global gamma analysis. The decreases in the global and local GPR of IMRT with 2%/2 mm acquired with MapCHECK2 and ArcCHECK are shown in figure 2.

The sensitivity of the GPR with respect to the RDCGS increased as the tightness of the gamma

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criterion increased. The decreases in the local GPRs as the RDCGS increased were larger than those in the global GPRs, as with the results of VMAT.

DTA vs. RDCGS

The variations in the average global and local GPRs of VMAT with a percentage dose difference of 2% and a DTA from 1 mm to 3 mm are shown in figure 3. Those of IMRT are shown in figure 4. As the DTA increased, both the global and local GPRs increased for both VMAT and IMRT, which is expected because increasing DTA makes the gamma criteria less strict. As the RDCGSs of VMAT and IMRT increased, both the global and local GPRs also increased. Examining the slopes of the fitting curves on the plots, i.e., the amount of increase in the GPR per DTA of 1 mm (ΔGP/ΔDTA), that of the global gamma analysis was always lower than that of the local gamma analysis. The values of ΔGP/ΔDTA for the global and local gamma analyses using MapCHECK2 and ArcCHECK are shown in table 5 for both VMAT and IMRT. It is observed that the values of ΔGP/ΔDTA of IMRT were always higher than those of the VMAT.

Table 1. Global gamma passing rates of volumetric modulated arc therapy (VMAT) plans with various gamma criteria and various dose calculation grid sizes acquired with MapCHECK2 and ArcCHECK.

Gamma criterion	MapCHECK2	ArcCHECK	*p*
Reference dose calculation grid size (RDCGS) of 1 mm			
3%/3 mm	99.4 ± 0.8 (96.7 – 100.0)	100.0 ± 0.1 (99.7 – 100.0)	0.005
2%/3 mm	98.2 ± 1.7 (93.2 – 100.0)	99.8 ± 0.3 (98.8 – 100.0)	< 0.001
2%/2 mm	97.5 ± 1.9 (92.7 – 99.5)	99.4 ± 0.7 (97.3 – 100.0)	< 0.001
2%/1 mm	94.0 ± 3.0 (84.2 – 97.8)	94.6 ± 5.2 (82.7 – 100.0)	0.351
RDCGS of 2 mm			
3%/3 mm	99.3 ± 0.9 (96.4 – 100.0)	99.7 ± 0.4 (99.0 – 100.0)	0.035
2%/3 mm	97.9 ± 1.5 (93.3 – 99.5)	99.2 ± 0.7 (98.0 – 100.0)	0.004
2%/2 mm	96.9 ± 1.9 (92.0 – 99.5)	98.5 ± 1.3 (95.9 – 100.0)	0.008
2%/1 mm	92.9 ± 2.9 (83.9 – 97.9)	92.5 ± 5.7 (79.8 – 100.0)	0.403
RDCGS of 3 mm			
3%/3 mm	98.8 ± 1.0 (96.2 – 100.0)	99.3 ± 0.9 (97.1 – 100.0)	0.083
2%/3 mm	96.5 ± 1.8 (91.9 – 98.8)	98.1 ± 1.6 (95.3 – 100.0)	0.007
2%/2 mm	94.7 ± 2.2 (88.2 – 97.7)	97.1 ± 2.0 (94.2 – 100.0)	0.002
2%/1 mm	88.2 ± 3.2 (78.9 – 92.6)	89.5 ± 7.1 (74.6 – 99.9)	0.236
RDCGS of 4 mm			
3%/3 mm	98.1 ± 1.3 (95.8 – 99.6)	97.5 ± 2.4 (93.7 – 100.0)	0.188
2%/3 mm	95.2 ± 1.9 (89.3 – 97.8)	96.1 ± 2.9 (91.4 – 100.0)	0.154
2%/2 mm	92.8 ± 2.5 (84.4 – 96.8)	93.5 ± 4.4 (87.1 – 100.0)	0.292
2%/1 mm	85.0 ± 3.4 (75.4 – 90.6)	83.9 ± 10.0 (66.2 – 99.6)	0.324
RDCGS of 5 mm			
3%/3 mm	95.9 ± 1.6 (92.1 – 98.5)	-	-
2%/3 mm	92.3 ± 2.1 (84.7 – 94.5)	-	-
2%/2 mm	88.2 ± 2.6 (80.2 – 92.7)	-	-
2%/1 mm	78.1 ± 3.8 (69.3 – 86.4)	-	-

Table 2. Local gamma passing rates of VMAT plans with various gamma criteria and various dose calculation grid sizes acquired with MapCHECK2 and ArcCHECK.

Gamma criterion	MapCHECK2	ArcCHECK	*p*
Reference dose calculation grid size (RDCGS) of 1 mm			
3%/3 mm	94.5 ± 2.0 (90.5 – 99.3)	98.7 ± 1.1 (95.0 – 99.7)	< 0.001
2%/3 mm	93.0 ± 2.4 (88.1 – 98.5)	97.6 ± 1.6 (93.8 – 99.4)	< 0.001
2%/2 mm	88.6 ± 2.7 (80.0 – 92.0)	94.5 ± 2.9 (88.1 – 98.4)	< 0.001
2%/1 mm	74.1 ± 6.3 (61.8 – 84.6)	77.7 ± 10.0 (57.5 – 91.9)	0.041
RDCGS of 2 mm			
3%/3 mm	93.9 ± 2.0 (89.9 – 97.8)	97.2 ± 1.9 (93.1 – 99.7)	< 0.001
2%/3 mm	92.1 ± 2.3 (87.1 – 97.1)	95.5 ± 2.4 (91.4 – 99.0)	< 0.001
2%/2 mm	87.2 ± 3.1 (77.9 – 91.1)	91.8 ± 3.8 (83.6 – 97.9)	< 0.001
2%/1 mm	72.2 ± 6.3 (60.5 – 82.9)	74.0 ± 10.3 (54.6 – 91.8)	0.168
RDCGS of 3 mm			
3%/3 mm	92.4 ± 2.3 (86.5 – 96.4)	96.0 ± 2.6 (91.0 – 99.6)	< 0.001
2%/3 mm	89.8 ± 2.7 (82.3 – 93.5)	93.8 ± 3.2 (88.6 – 98.8)	< 0.001
2%/2 mm	84.1 ± 3.9 (73.3 – 89.5)	88.9 ± 5.4 (79.6 – 97.8)	< 0.001
2%/1 mm	66.4 ± 7.8 (55.4 – 81.2)	70.0 ± 11.7 (51.3 – 93.6)	0.038
RDCGS of 4 mm			
3%/3 mm	90.7 ± 3.0 (84.2 – 94.9)	92.1 ± 5.0 (82.5 – 99.2)	0.091
2%/3 mm	87.7 ± 3.1 (80.0 – 92.1)	88.0 ± 10.0 (49.9 – 98.5)	0.452
2%/2 mm	80.8 ± 4.6 (70.6 – 89.4)	82.8 ± 8.1 (48.2 – 96.9)	0.118
2%/1 mm	62.6 ± 8.2 (51.8 – 80.2)	62.1 ± 14.0 (45.3 – 91.7)	0.423
RDCGS of 5 mm			
3%/3 mm	86.6 ± 4.0 (78.7 – 93.9)	-	-
2%/3 mm	83.4 ± 4.0 (74.1 – 90.7)	-	-
2%/2 mm	74.6 ± 5.8 (65.0 – 87.1)	-	-
2%/1 mm	54.6 ± 9.4 (43.6 – 76.9)	-	-

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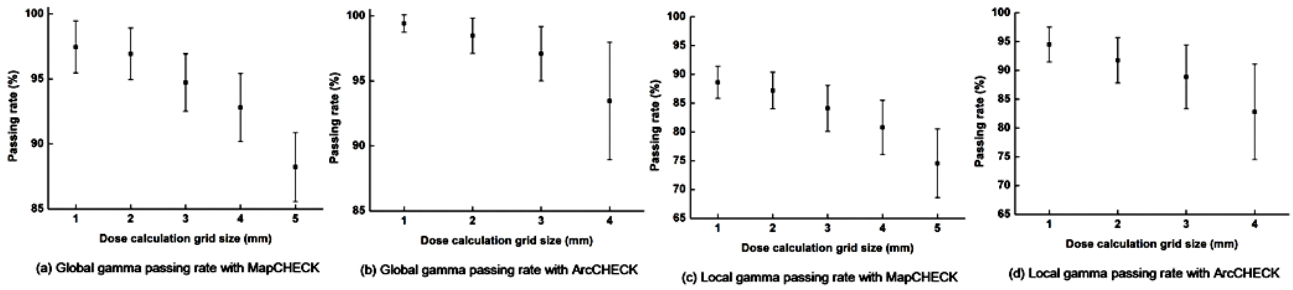

Figure 1. Changes in GPR for a gamma criterion of 2%/2 mm VMAT plans according to the RDCGS. GPR with RDCGS of 1 mm showed statistical significances with respect to those of all other grid sizes (p < 0.001).

Table 3. Global gamma passing rates of intensity modulated radiation therapy (IMRT) plans with various gamma criteria and various dose calculation grid sizes acquired with MapCHECK2 and ArcCHECK.

Gamma criterion	MapCHECK2	ArcCHECK	*p*
Reference dose calculation grid size (RDCGS) of 1 mm			
3%/3 mm	98.5 ± 1.5 (95.3 – 100.0)	99.7 ± 0.4 (98.2 – 100.0)	0.003
2%/3 mm	95.3 ± 3.4 (89.0 – 100.0)	98.7 ± 1.4 (94.9 – 100.0)	< 0.001
2%/2 mm	93.1 ± 5.0 (82.3 – 100.0)	97.6 ± 2.3 (91.8 – 100.0)	< 0.001
2%/1 mm	86.5 ± 7.2 (72.6 – 97.5)	92.6 ± 3.8 (85.3 – 98.1)	0.001
RDCGS of 2 mm			
3%/3 mm	98.2 ± 1.7 (93.9 – 100.0)	99.4 ± 0.7 (96.9 – 100.0)	0.008
2%/3 mm	94.6 ± 3.8 (86.6 – 100.0)	98.1 ± 1.8 (94.0 – 100.0)	< 0.001
2%/2 mm	92.2 ± 5.2 (81.1 – 99.4)	96.7 ± 2.7 (90.0 – 99.8)	< 0.001
2%/1 mm	84.9 ± 7.3 (70.2 – 96.2)	90.1 ± 4.3 (82.7 – 97.0)	0.003
RDCGS of 3 mm			
3%/3 mm	97.8 ± 1.8 (93.2 – 100.0)	98.7 ± 1.3 (94.1 – 100.0)	0.047
2%/3 mm	93.7 ± 4.0 (84.6 – 99.6)	97.0 ± 2.3 (92.1 – 99.9)	0.001
2%/2 mm	90.8 ± 5.4 (78.4 – 98.8)	94.9 ± 3.1 (88.3 – 99.4)	0.001
2%/1 mm	82.4 ± 6.5 (69.8 – 91.9)	87.3 ± 4.6 (78.2 – 95.5)	0.004
RDCGS of 4 mm			
3%/3 mm	96.9 ± 2.3 (91.0 – 99.4)	97.7 ± 1.7 (93.0 – 100.0)	0.115
2%/3 mm	92.0 ± 4.7 (81.2 – 98.8)	95.0 ± 3.2 (88.9 – 100.0)	0.010
2%/2 mm	88.3 ± 5.6 (74.9 – 95.7)	91.6 ± 4.6 (83.5 – 100.0)	0.013
2%/1 mm	78.8 ± 6.4 (65.2 – 88.8)	82.9 ± 5.9 (72.6 – 94.4)	0.020
RDCGS of 5 mm			
3%/3 mm	95.4 ± 2.5 (90.2 – 98.7)	-	-
2%/3 mm	90.3 ± 4.3 (81.2 – 95.4)	-	-
2%/2 mm	84.9 ± 5.1 (74.9 – 92.0)	-	-
2%/1 mm	73.8 ± 5.0 (65.2 – 81.4)	-	-

Table 4. Local gamma passing rates of intensity modulated radiation therapy (IMRT) plans with various gamma criteria and various dose calculation grid sizes acquired with MapCHECK2 and ArcCHECK.

Gamma criterion	MapCHECK2	ArcCHECK	*p*
Reference dose calculation grid size (RDCGS) of 1 mm			
3%/3 mm	90.0 ± 6.2 (76.7 – 99.2)	88.3 ± 9.5 (73.7 – 99.2)	0.107
2%/3 mm	86.7 ± 7.8 (73.4 – 99.2)	85.0 ± 11.0 (67.6 – 98.5)	0.116
2%/2 mm	80.1 ± 10.6 (60.9 – 94.4)	76.3 ± 15.5 (54.0 – 95.6)	0.014
2%/1 mm	64.4 ± 13.5 (44.2 – 87.0)	57.6 ± 18.6 (29.6 – 84.7)	< 0.001
RDCGS of 2 mm			
3%/3 mm	89.5 ± 6.5 (76.0 – 99.2)	87.3 ± 9.8 (72.4 – 99.1)	0.059
2%/3 mm	85.3 ± 7.9 (71.0 – 97.6)	83.7 ± 11.4 (66.7 – 97.8)	0.123
2%/2 mm	78.2 ± 10.3 (59.1 – 92.9)	74.8 ± 15.6 (52.9 – 95.6)	0.029
2%/1 mm	62.1 ± 12.9 (41.7 – 84.9)	56.2 ± 19.4 (28.4 – 89.6)	0.008
RDCGS of 3 mm			
3%/3 mm	88.0 ± 6.1 (74.9 – 96.0)	85.6 ± 10.1 (70.2 – 97.9)	0.066
2%/3 mm	83.8 ± 7.3 (69.3 – 93.8)	81.6 ± 11.9 (63.7 – 96.1)	0.098
2%/2 mm	76.3 ± 9.9 (57.1 – 89.9)	71.8 ± 15.0 (50.4 – 92.8)	0.007
2%/1 mm	58.5 ± 11.4 (41.4 – 81.3)	51.2 ± 16.5 (27.9 – 78.3)	< 0.001
RDCGS of 4 mm			
3%/3 mm	85.9 ± 5.9 (73.6 – 93.9)	83.2 ± 10.4 (68.5 – 97.5)	0.069
2%/3 mm	81.5 ± 7.3 (67.2 – 92.7)	79.1 ± 11.5 (62.4 – 94.9)	0.081
2%/2 mm	73.2 ± 9.3 (56.3 – 88.6)	67.7 ± 13.9 (48.4 – 90.4)	0.003
2%/1 mm	55.6 ± 10.6 (40.9 – 76.6)	47.0 ± 14.4 (26.0 – 74.2)	< 0.001
RDCGS of 5 mm			
3%/3 mm	83.7 ± 6.1 (72.3 – 93.1)	-	-
2%/3 mm	79.4 ± 7.2 (66.0 – 91.1)	-	-
2%/2 mm	69.6 ± 8.3 (54.2 – 85.2)	-	-
2%/1 mm	50.3 ± 8.2 (39.2 – 65.3)	-	-

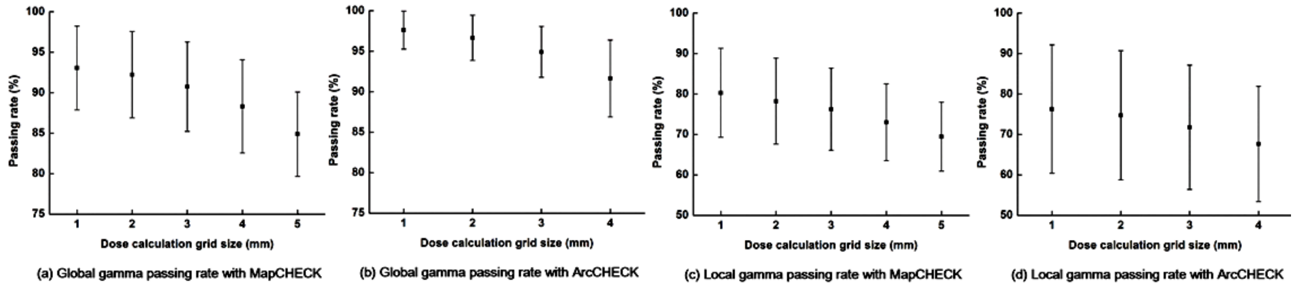

Figure 2. Changes in GPR for a gamma criterion of 2%/2 mm IMRT plans according to the RDCGS. GPR with RDCGS of 1 mm showed statistical significances with respect to those of all other grid sizes ($p < 0.001$).

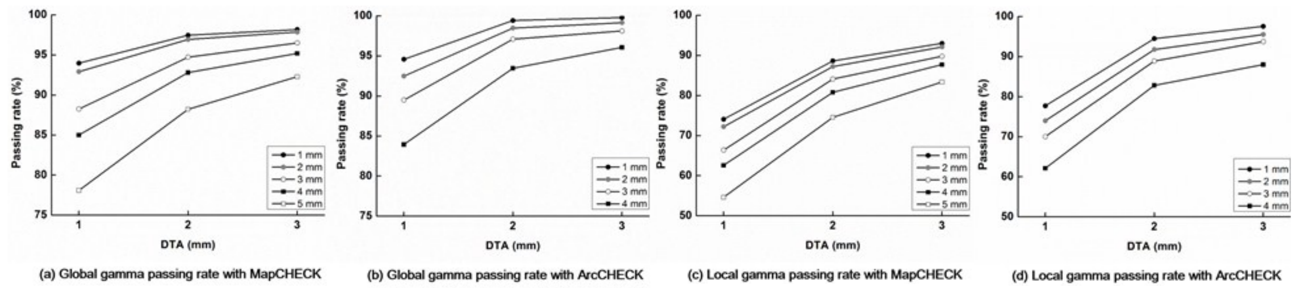

Figure 3. Changes in GPR of VMAT plans for a percentage dose difference of 2% and DTA from 1 mm to 3 mm, which were calculated with various RDCGS from 1 mm to 5 mm. p-values for changes in GPR with RDCGS of 1 mm with respect to those of other grid sizes were less than 0.001, except for those of 2 mm for MapCHECK2 which were 0.017 and 0.013 for global and local analysis, respectively.

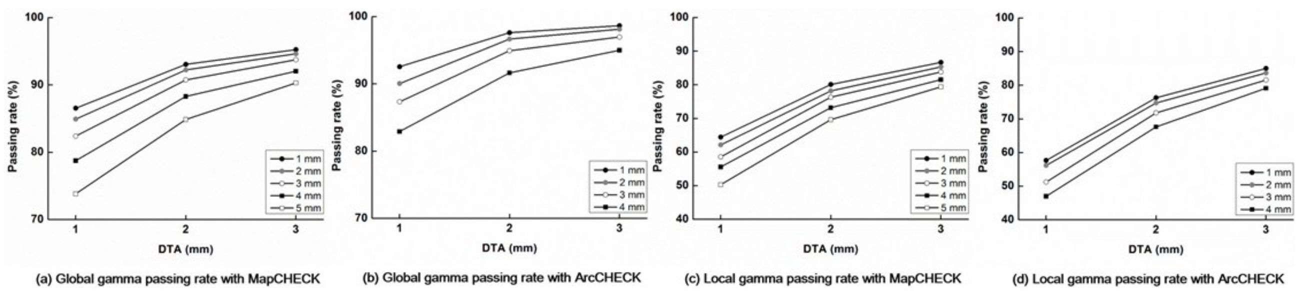

Figure 4. Changes in GPR of IMRT plans for a percent dose difference of 2% and DTA from 1 mm to 3 mm, which were calculated with various RDCGS from 1 mm to 5 mm. p-values for changes in GPR with RDCGS of 1 mm with respect to those of other grid sizes were less than 0.001, except for those of 2 mm for local analysis which were 0.019 and 0.935 for MapCHECK2 and ArcCHECK, respectively.

Table 5. Average changes in gamma passing rates per distance to agreement of 1 mm (ΔGP/ΔDTA).

Reference dose calculation grid size	1 mm	2 mm	3 mm	4 mm	5 mm
VMAT[1]					
Global gamma analysis (MC[3])	2.10	2.48	4.13	5.09	7.11
Local gamma analysis (MC)	9.47	9.95	11.71	12.58	14.39
Global gamma analysis (AC[4])	2.60	3.34	4.31	6.06	-
Local gamma analysis (AC)	9.92	10.76	11.87	12.94	-
IMRT[2]					
Global gamma analysis (MC)	4.36	4.85	5.67	6.65	8.25
Local gamma analysis (MC)	11.12	11.62	12.63	12.99	14.54
Global gamma analysis (AC)	3.05	4.04	4.82	6.04	-
Local gamma analysis (AC)	13.69	13.75	15.19	16.07	-

Abbreviations: [1]VMAT, volumetric modulated arc therapy; [2]IMRT, intensity modulated radiation therapy; [3]MC, MapCHECK2; [4]AC, ArcCHECK.

DISCUSSION

It has been previously recommended by Low and Dempsey that the optimal resolution of the evaluated dose distribution for gamma analysis, i.e., the measured dose distribution, is related to the DTA [23] . However, to the best of our knowledge, no recommendation has been made for the optimal resolution of the reference dose distribution for gamma analysis. Therefore, in this study, we analyzed GPR changes according to the RDCGS with various gamma criteria for both IMRT and VMAT plans.

Similarly to the results of the previous studies [19,20], we also observed decreases in the GPR with an increase in the RDCGS. As the previous studies demonstrated, this was because a higher resolution of dose distributions could offer a greater opportunity to find a point satisfying the gamma criteria [19]. The degree of decrease in the local GPR with increases in the RDCGS was higher than that of the global GPR, as the local gamma analysis is stricter than the global gamma analysis [15]. The stricter evaluation of each point of the local gamma analysis was more sensitive to the limited opportunity to find a point satisfying the gamma criteria. Similarly, the decrease in the GPR as the RDCGS increased became larger as we applied stricter gamma criteria from 3%/3 mm to 2%/1 mm.

Stricter gamma evaluation with stricter gamma criteria also made the sensitivity to the RDCGS higher. Since the local gamma analysis with tight gamma criteria, i.e., strict gamma analysis, showed higher sensitivity to RDCGS than the global gamma analysis for less strict gamma criteria, it is recommended to calculate reference dose distributions with a fine dose calculation resolution, especially for institutions adopting strict gamma methods for patient-specific IMRT (or VMAT) QA.

The gamma criterion of 3%/3 mm has been widely adopted in clinics for the patient-specific QA of IMRT [7,24]; however, Heilemann *et al.* and Fredh *et al.* recommended that the gamma criterion of 2%/2 mm should be used for VMAT by investigating the sensitivity of the global gamma analysis to detect errors in the VMAT plans [13,14]. In the same context, the GPR of VMAT plans in this study were always higher than those of IMRT plans even though the patient geometry and the prescription dose were identical for both IMRT and VMAT planning. Therefore, to increase the sensitivity of the gamma analysis for VMAT, a tighter gamma criterion, such as 2%/2 mm, should be used rather than the most popular gamma criterion of 3%/3 mm for IMRT.

As the RDCGS increased, sensitivity to the DTA increased regardless of the type of radiotherapy technique (IMRT or VMAT), type of the detector (MapCHECK2 or ArcCHECK), or type of gamma analysis (global or local). Therefore, when reducing the DTA of the gamma criterion, it is recommended to calculate the reference dose distribution with a fine RDCGS such as 1 mm. Otherwise, the GPR could appear lower than the tolerance level, indicating that the IMRT or VMAT plan has failed even though this is not the case. Since the results showed that the sensitivity to the DTA of the local gamma analysis and the gamma analysis for IMRT were more sensitive than that of the global gamma analysis and the gamma analysis for VMAT, respectively, cautions on the RDCGS are required to reduce the DTA, especially for the local gamma analysis of IMRT.

For the gamma criterion of 2%/2 mm, which has been recommended for the patient-specific QA of VMAT by previous studies, the global GPR appeared to be lower than 90% (tolerance level recommended by Heilemann *et al.*) with the RDCGS greater than 2 mm [14]. Therefore, to avoid misinterpretation of the results of gamma analysis with a 2%/2 mm gamma criterion for VMAT plans, the reference dose distribution should be calculated for a dose calculation resolution of at least 2 mm according to the results of this study. However, we cannot recommend 2 mm as an optimal RDCGS for gamma analysis as the number of cases in this study are not enough to make a recommendation. By utilizing more detector types and patient cases, we will recommend an optimal dose calculation resolution for reference dose distributions in the future. In the present study, it was found that the GPR can be considerably affected by the RDCGS, and it is at least recommended to use an RDCGS of 1 mm for an accurate verification of IMRT or VMAT plans.

CONCLUSIONS

In this study, the GPRs were considerably affected by the RDCGS. The effect of the RDCGS on GPR became larger when performing local gamma analysis and when applying a small DTA (tighter gamma criterion). For an accurate verification of IMRT or VMAT plans, the reference dose distribution is recommended to be calculated with a small dose calculation grid size, such as 1 mm.

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