Comparative analysis of dose verification between computed tomography scan phantom and virtual digital phantom of Delta4

Ting-Ting Liu1,∗ | Zhi-Tao Dai2,∗ | Kai-Lian Kang2 | Li-Ying Gao1 | Rui-Feng Liu1 | Shui-Gen Ou-Yang1

1 Department of Radiation Oncology, Gansu Provincial Cancer Hospital, Lanzhou, China
2 National Cancer Center/National Clinical Research Center for Cancer/Cancer Hospital & Shenzhen Hospital, Chinese Academy of Medical Sciences and Peking Union Medical College, Beijing, China

Correspondence
Zhi-Tao Dai, National Cancer Center/National Clinical Research Center for Cancer/Cancer Hospital & Shenzhen Hospital, Chinese Academy of Medical Sciences and Peking Union Medical College, Beijing, P.R. China. Email: daizt_sinap@163.com

∗Ting-Ting Liu and Zhi-Tao Dai contribute equally to the manuscript.

Funding information
Chinese Medicine Administration Foundation of Gansu Province, Grant/Award Number: GZK-2017-40; China Postdoctoral Science Foundation, Grant/Award Number: 2018M640725; Medical Scientific Research Foundation of Guangdong Province, Grant/Award Number: A2018020; Innovation Foundation of Lanzhou City, Grant/Award Number: 2017-RC-23

Abstract
Objective: This study compared the dose verification results between plans created based on computed tomography (CT) scan and digital virtual phantom.
Methods: We retrospectively analyzed the treatment plan of 10 patients with head and neck cancer. CT scanned phantom and digital virtual phantom measured using Delta4 3-D matrix were used to generate verification plans for each patient. The doses based on the effective measurement volume of the two phantoms were compared, and the verification results were analyzed using gamma index analysis.
Results: For the body, the minimum dose, the maximum dose, the average dose, and the total dose were $0.72 \pm 0.46$ cGy, $251.86 \pm 49.83$ cGy, $58.10 \pm 10.93$ cGy, and $154.67 \pm 20.28$ cGy, respectively, in the CT-scan group, and $0.62 \pm 0.36$ cGy, $248.34 \pm 48.59$ cGy, $57.20 \pm 10.77$ cGy, and $151.57 \pm 19.73$ cGy, respectively in the Uniform group. The difference between the groups was significant ($P < 0.05$). In the Delta4 analysis software, the dose deviation, distance to agreement, and gamma passing rates were $73.39 \pm 10.75\%$, $95.25 \pm 1.00\%$, and $96.67 \pm 1.415\%$, respectively in the CT-scan group, and $83.36 \pm 10.15\%$, $98.61 \pm 0.810\%$, and $99.38 \pm 0.452\%$, respectively, in the Uniform group. The two plans were significantly different ($P < 0.05$), and there was a 3% difference in the gamma passing rate. Therefore, the conclusions relating to the examined dose applied, the groups were significantly higher than those of CT-scan groups. (both $P$-values were $< 0.05$). As the parameter value increases, the difference decreases. In the 3 mm/3% standard, both groups met the clinical requirement of gamma passing rate of $> 95\%$, but the Uniform group had a higher passing rate than the CT-scan group.
Conclusions: Because the passing rate was higher in the Uniform group than in the CT-scan group, it is recommended to use digital virtual phantom modules to generate verification plans in clinical practice.

This is an open access article under the terms of the Creative Commons Attribution License, which permits use, distribution and reproduction in any medium, provided the original work is properly cited.
© 2020 The Authors. Precision Radiation Oncology published by John Wiley & Sons Australia, Ltd on behalf of Shandong Cancer Hospital & Institute.
1 | INTRODUCTION

Intensity-modulated radiation therapy (IMRT) planning is important in cancer therapy owing to the precision and complexity of treatment delivery. IMRT has more advantages than the traditional 3-D conformal radiotherapy, especially for patients with complex target tumors. Therefore, the treatment plan needs an accurate dose verification system. A proper quality assurance (QA) procedure is essential to verify the accuracy of dose delivery before IMRT (3-D conformal IMRT) can be carried out. There are many types of dosimeters on the market for ensuring QA, such as ion chambers, film, 2-D diodes, ion chamber matrix detectors, electronic portal imaging devices, gel dosimetry, and 3-D diode arrays. Delta4 is one of the most widely used tools for 3-D dose verification. Many published studies showed that the Delta4 with the 3-D diode arrays is stable and reliable, making it an ideal tool for dose verification. However, there are some limitations that should be considered when silicon diode detectors, such as Delta4, are used as radiation detectors. It might cause X-ray attenuation on the phantom, resulting in unwanted artifacts, inaccuracy in the low-energy photon fields, and slight distortion in images. For clinical QA plans, the establishment of a verification plan is based on the digital phantom provided by the manufacturer, which is an ideal model and reduces the error introduced by the detectors. Alternatively, the verification plan is based on the reconstruction images acquired by computed tomography (CT) scanning. Although it is similar to the real state of Delta4, it might show some differences with the clinical measurement results. Few studies have reported the effects of detector scattering on the Delta4 devices using low-dose CT scanning. The present study aimed to compare differences between CT-scan and digital virtual phantom (Uniform) in the Delta4 equipment that can influence the accuracy and reliability of dose verification, and provide an accurate QA plan.

2 | METHODS

2.1 | Patient population and imaging collection

A retrospective view of IMRT QA results was carried out by randomly selecting 10 patients with head and neck cancer who were treated with fixed-field IMRT between 2017 and 2018 in our hospital (Gansu Cancer Hospital). To provide a broad selection of clinical data, clinical patient treatment plans were selected from four patients with nasopharyngeal carcinoma, two with oropharyngeal carcinoma, three with laryngeal carcinoma, and one with nasal sinus carcinoma. The treatment plans were all based on a nine-field average distribution starting at 0° field.

The scanned images of Delta4 phantom were collected with CT simulation positioning (Toshiba Medical Systems, Japan). The CTs were acquired at 0.3-cm thickness, 0.3-cm intervals under the conditions of voltage 120 kV and current 250 mA. The QA phantom was generated in the Eclipse treatment planning system (Varian Medical Systems, Palo Alto, CA) including the effective volume.

This study was approved by the institutional review board of the Tongji Medical College of Huazhong University of Science and Technology. All methods were carried out in accordance with the relevant guidelines and regulations.

2.2 | QA planning and testing

Two QA plans were developed for each patient as follows: CT-scan group as the reference verification plan, which scanned and imported the Delta4 phantom into the planning system to establish the model; Uniform group as the test verification plan, which was generated by the artificial dataset of the uniform polymethyl methacrylate cylinder provided by the manufacturer (its relative density is 1.147). During the planning process, the outer contour of the two phantoms (named as Body) was manually drawn for statistical analysis of the dosimetric indices. Rigid registration was carried out to ensure that the outer contours of the two bodies were the same. The two sets of QA plans were transmitted to the accelerator control room and Delta4 analysis software for preparation. The investigated dose values were the minimum ($D_{min}$), maximum ($D_{max}$), mean ($D_{mean}$), and isocenter dose ($D_{iso}$) to the body obtained from dose-volume histograms generated by the treatment planning system.

2.3 | Verification equipment

All QA plans were carried out on the Varian 600CD linear accelerator with 6-MV X-rays. Delta4, a 3-D dose verification system from ScandiDos, Uppsala, Sweden, was used as the verification system. It includes a Delta4 phantom and computer dosimetric software. The phantom matrix consists of 1069 silicone diodes distributed around two orthogonal boards, which is in a 22-cm diameter cylindrical polymethyl methacrylate phantom. The dose distribution in two dimensions is analyzed in the two orthogonal measurement planes, and the dose distribution in the third dimension is derived from the measured dose.

2.4 | Collection of verification data

The 3-D dose distribution was measured for each patient. The dose differences between the CT-scan group and the Uniform group were...
compared by the Delta4 analysis software. Gamma index analysis with global dose error normalization, such as distance to agreement (DTA), dose deviation (DD), and gamma passing rate, was carried out to compare the calculated and delivered dose distributions at 1%/1 mm, 2%/2 mm, and 3%/3 mm thresholds for each set of DD/DTA. The default dose threshold used in the analysis is 20%, and voxels below the threshold will not be considered in the gamma-pass rate analysis.

2.5 | Statistical analysis

The Statistical Package of Social Sciences program version 19.0 (Armonk, NY: IBM Corp, USA) was used to carry out statistical analysis. A paired t-test was used to evaluate the association between the passing rates and the different modeling patterns. All statistical data are expressed as the mean ± standard deviation, and P < 0.05 is considered statistically significant.

3 | RESULTS

Table 1 lists the $D_{\text{min}}$, $D_{\text{max}}$, $D_{\text{mean}}$, and reference dosimeter of the isocenter point ($D_{\text{iso}}$) to illustrate the dose differences in the body. The $D_{\text{min}}$, $D_{\text{max}}$, $D_{\text{mean}}$, and $D_{\text{iso}}$ were 0.72 ± 0.46 cGy, 251.86 ± 49.83 cGy, 58.10 ± 10.93 cGy, and 154.67 ± 20.28 cGy, respectively, in the CT-scan group, and 0.62 ± 0.36 cGy, 248.34 ± 48.59 cGy, 57.20 ± 10.77 cGy, and 151.57 ± 19.73 cGy, respectively, in the Uniform group. In this study, all the dose parameters evaluated were distinctly higher in the CT-scan group than in the Uniform group.

Figure 1 shows the 3-D profile of the dose distribution of a nasopharyngeal carcinoma patient in which the first and second rows were the Uniform and CT-scan groups, respectively. The dose distributions of the transverse plane, sagittal plane, and coronal plane are shown from left to right. Although, in the dose visualization, the curves of the CT-scan group were close to those of the Uniform group, the CT-scan group had slightly elevated doses. The comparison between the two groups based on the dose-volume histogram of the body dose is shown in Figure 2a. As there were slight differences between the two groups, we subtracted the two curves to acquire detailed information on the distribution differences, as shown in Figure 2b. The Uniform group had a slightly larger irradiation volume in the low-dose area, but lower irradiation volume in the medium-dose area and the high-dose area than the CT-scan group, and this is consistent with the results in Table 1.

Meanwhile, we compared the dose differences between the dose-volume histogram and the measured dose distributions by the Delta4 matrix. The QA results were evaluated by analyzing the passing rate of DTA, DD, and gamma in the two groups. The results are shown in Figure 3 and Table 2. Gamma index analysis at thresholds 1%/1 mm, 2%/2 mm, and 3%/3 mm was carried out to compare the delivered dose distributions. The Uniform group had a higher gamma passing rate than the CT-scan group. There were significant differences between the two groups (P < 0.01). With an increase in the parameter value,
LIU ET AL.

Comparison of the verification plan of body dose-volume histogram between uniform phantom and computed tomography (CT)-scan phantom in one patient. (a) the red dashed line represents the uniform phantom, and the black solid line represents the CT scan phantom; (b) the figure shows the difference between the two dose-volume histograms.

Comparison of the gamma passing rates of verification plans generated by uniform phantom and computed tomography scan phantom in 10 patients: the passing rate of (a) DD, (b) DTA, and (c) gamma in turn. The abscissa represents the distance and dose tolerance standard from left to right: 1 mm/1%, 2 mm/2%, and 3 mm/3%, respectively. The circles in the figure represent the data of each case: the black represents computed tomography scan phantom, the red represents uniform phantom.

The difference decreased. When the gamma tool used the 3%, 3 mm as usual, the DD, DTA, and gamma passing rates were 73.39 ± 10.75%, 95.25 ± 1.00%, and 96.67 ± 1.415%, respectively, in the CT-scan group. Therefore, all the investigated dose distributions passed the gamma evaluation (a passing rate > 95%), but the Uniform group had a higher passing rate than the CT-scan group.

4 | DISCUSSION

The characteristics of fast processing speed and high sensitivity of diodes make the measurement of external irradiation dose increasingly popular. Silicon semiconductor diodes, which are easy to measure, small in size, and have good mechanical durability, are commonly used as radiation detectors. A study showed that the p-type silicon diode is more conducive to radiation therapy than other types of diodes, and there are 1069 p-type silicon semiconductor diode array detectors distributed on the Delta4 plates. Studies have shown that low-energy X-ray is more susceptible to harden in material attenuation than high-energy X-ray. Errors caused by scattering might lead to CT artifacts and inaccurate CT numbers. Artifacts can degrade CT simulation imaging and impair accurate delineation of tumors for radiation treatment planning purposes. Even though many artifacts from the early days of CT are now substantially reduced, some artifacts remain, and new technologies might introduce incompletely characterized...
artifacts. Modern techniques for artifact reduction were studied and described.\textsuperscript{23} In IMRT verification planning, it is necessary to establish a verification phantom on the planning system that simulates the CT scanning of the patient. Huang \textit{et al.} used a human-like phantom reconstructed from a 3-D diode array to assess the patient’s CT dose.\textsuperscript{13} Density scaling artifacts were reported in the treatment planning system.\textsuperscript{14} A small change in the density could imply a systematic error of 1–2\% in the calculated dose. This systematic error could be significant for QA calculations carried out for non-unity density phantom materials. Tani \textit{et al.} proposed an optimum density scaling factor for phantom materials for a commercially available 3-D dose verification system (Delta4) to improve the accuracy of the calculated dose distributions in the phantom material.\textsuperscript{15} Due to the characteristics of a semiconductor probe, the dose verification needs to be carefully designed.\textsuperscript{16} Therefore, the artifacts of the Delta4 phantom need to be further optimized to ensure the accuracy of modeling verification in an effective way.

QA of IMRT dose measurement has become an important topic,\textsuperscript{17} and the parameters DTA, DD, and index are important for the acceptance or rejection of the treatment plan.\textsuperscript{18,19} Since the introduction of the gamma analysis method, the developed gamma filter method was proved successful for the efficient comparison of calculated versus measured IMRT dose distribution. A filter cascade of multiple levels was designed to obtain a fast and accurate comparison of the two dose distributions under evaluation. The actual comparison consists of classification into accepted or rejected data points with respect to user-defined acceptance criteria (DD and DTA).\textsuperscript{20} Bakai \textit{et al.} introduced a limited acceptance threshold that depends on dose gradients.\textsuperscript{21} Low and Dempsey examined the gamma distribution behavior in two dimensions and evaluated the gamma distribution in the presence of data noise.\textsuperscript{22} Both the DTA and gamma functions are sensitive to noise, and if they exceed by a fraction of points in clinical evaluations, they change the interpolated resolution. Furthermore, the continuous improvement of parameters DTA, DD, and gamma is an important guarantee for the passing rate of dose verification.

The passing rate of DD, DTA, and gamma index were collected with the protocol of 95\% gamma value (3\% DD, 3 mm DTA) from the Delta4 analysis software.\textsuperscript{23,24} The present study shows that the verification plans generated from the CT-scan and Uniform phantom had significant differences in dosimetric indicators and verification comparison results. The reasons can be explained as follows: on the one hand, as the Uniform group ignored the high-density areas of semiconductor detectors and electronic devices in Delta4, it would result in a flat dose distribution and a small 3-D dose distribution gradient that would result in a high gamma passing rate. It was found that the absolute dose deviation close to the maximum dose depth would be higher than other depth in the non-uniform medium.\textsuperscript{25,26} Therefore, the dose of the high-density area calculated by the Uniform phantom is lower than the actual situation. At the same time, the calculated dose in the high-density area is lower than the actual situation, because the high-density area in the phantom is neglected. On the other hand, the flatness of the dose distribution generated by the verification plan will worsen due to the influence of the artifacts generated by CT-scan. The calculated dose distribution in the artifact area is higher than the actual measurement.

There were certain limitations to the present study. First, we used the Anisotropic Analytical Algorithm in the Treatment Planning System, which has some shortcomings dealing with particle transport in heterogeneous materials. Acuros XB algorithms could be a promising algorithm in the latest version of Eclipse for providing an accurate assurance. Second, the QA results did not consider factors, such as accelerator output and mechanical errors in the gamma analysis; therefore, the quantitative analysis was not accurate. Third, there might be some differences between the two phantoms compared with the actual measurement conditions. Therefore, it is suggested that a precise digital virtual phantom should be designed based on the actual physical parameters of the Delta4 phantom to further improve the reliability and accuracy of the verification results.

In the present study, we compared the verification results and quantitatively evaluated the differences between the CT-scan group and digital virtual phantom (Uniform) group in the QA of IMRT patients, and found that the volume of the CT-scan group was higher than that of the Uniform group in both the intermediate measurement area and the high-dose area, but a slightly lower volume in the low-dose area.

\textbf{FIGURE 4} Schematic diagram of percentage depth dose curve (PDD) of 6-MV X-ray incident into digital phantom (red dashed line) and computed tomography scan module (black solid line). The blue shaded areas in the figure represent the high-density areas in the phantom.

Therefore, the low-dose area was slightly higher, whereas the high-dose area was somewhat lower in the Uniform group than in the CT-Scan group. The details are explained in Figure 4. To simplify the problem, we assumed a pencil beam on the phantom. Figure 4 shows a typical build-up curve for a 6-MV X-ray beam at a 0\° angle of incidence. CT-Scan phantom has the same percentage depth dose as the uniform phantom before the beam is incident on the high-density area. The dose deposition of CT-Scan phantom will increase to a certain extent in high-density regions, resulting in a decrease in photon fluence with the exception of high-density area; therefore, the percentage depth dose curve after the high-density region will be lower than the Uniform phantom. Thus, the body of the percentage depth dose curve in the CT-scan group will be low in the low-dose area, but elevated in the high-dose area.
Data analysis under different parameter settings showed that the Uniform group had a significantly higher passing rate than the CT-scan group. Therefore, the use of digital virtual modules to generate validation plans is recommended in clinical practice, and the design of this type of phantom requires further improvement. However, there are still some limitations for plan verification based on uniform phantom, in which the fine structure in the Delta4 phantom was not taken into account. Therefore, in clinical practice, the design of the phantom should be further refined to ensure more accurate dose verification.

ACKNOWLEDGMENTS
This study was supported in part by the Chinese Medicine Administration Foundation of Gansu Province (GZK-2017-40), China Postdoctoral Science Foundation (Grant No. 2018M640725), Medical Scientific Research Foundation of Guangdong Province (Grant No. A2018020), and the Innovation Foundation of Lanzhou City (2017-RC-23).

CONFLICT OF INTEREST
The authors declare that they have read the article and there are no competing interests.

ORCID
Ting-Ting Liu https://orcid.org/0000-0001-8348-2591

REFERENCES
1. Ren F, Li S, Zhang Y, et al. Efficacy and safety of intensity-modulated radiation therapy versus three-dimensional conformal radiation treatment for patients with gastric cancer: a systematic review and meta-analysis. Radiat Oncol. 2019;14(1):84.
2. Li G, Wu K, Peng G, et al. A retrospective analysis for patient-specific quality assurance of volumetric-modulated arc therapy plans. Med Dosim. 2014;39(4):309-313.
3. Sadagopan R, Bencomo J, Martin R, et al. Characterisation, commissioning and evaluation of DELTA4 IMRT QA system. Med Phys. 2007;34(6):2560.
4. Calvo O, Gutiérrez A, Stathakis S, et al. SU-FF-T-3-86: validation of the Delta4 dosimetry phantom against ionometric measurements. Med Phys. 2009;36(6):2610-2610.
5. Simard D, Thakur V, Sci-Fri PM: dosimetry -03: Delta4 diode absolute dose response for large and small target volume IMRT QA. Med Phys. 2014;41(8Part3):27-27.
6. Lu SH, Tsai YC, Lan HT, et al. SU-F-T-238: analyzing the performance of MapCHECK2 and Delta4 quality assurance phantoms in IMRT and VMAT plans. Med Phys. 2016;43(6):3517-3517.
7. Rikner G, Grussell E. General specifications for silicon semiconductors for use in radiation dosimetry. Phys Med Biol. 1987;32(9):1109-1117.
8. Haba T, Aoyama S, Koyama T, et al. Pin-photodiode array for the measurement of fan-beam energy and air kerma distributions of X-ray CT scanners. Physica Med. 2016;32(7):905-913.
9. Brooks RA, Chiro GD. Beam hardening in X-ray reconstructive tomography. Phys Med Biol. 1976;21(3):390-398.
10. Joseph PM, Spital RD. The effects of scatter in x-ray computed tomography. Med Phys. 1982;9(4):464-472.
11. Abelson JA, Murphy JD, Wiegner EA, et al. Evaluation of a metal artifact reduction technique in tonsillar cancer delineation. Pract Radiat Oncol. 2012;2(1):27-34.
12. Boas FE, Fleischmann D. CT artifacts: causes and reduction techniques. Imaging Med. 2012;4(2):229-240.
13. Huang M, Faught A, Benhabib S, et al. SU-F-BRE-06: evaluation of patient CT dose reconstruction from 3D diode array measurements using anthropomorphic phantoms. Med Phys. 2014;41(6):392-392.
14. Dickof P. Density scaling artifacts in dosimetry calculations. J Appl Clin Med Phys. 2005;6(3):118-121.
15. Kensuke T, Yukio F, Akihisa W, et al. Density scaling of phantom materials for a 3D dose verification system. J Appl Clin Med Phys. 2018;19(4):1-11.
16. Woon M, Ravindran P B, Ekayake P, et al. A study on the effect of detector resolution on gamma index passing rate for VMAT and IMRT QA. J Appl Clin Med Phys. 2018;19(2):230-248.
17. Pan YX, Yang RJ, Zhang SM, et al. National survey of patient specific IMRT quality assurance in China. Radiat Oncol. 2019;14:69.
18. Natali M, Capomolla C, Russo D, et al. Dosimetric verification of VMAT dose distribution with Delta4 Phantom. 3rd Workshop - Plasmi, Sorgenti, Biofisica ed Applicazioni. 2013:15(2):22-26.
19. Low D A, Morele D, Chow P, et al. Does the y dose distribution comparison technique default to the distance to agreement test in clinical dose distributions? Med Phys. 2013;40(7):071722.
20. Depuydt T, Esch AV, Huyskens DP. A quantitative evaluation of IMRT dose distributions: refinement and clinical assessment of the gamma evaluation. Radiother Oncol. 2002;62(3):309-319.
21. Annemarie B, Markus A, Fridtjof N, et al. A revision of the y-evaluation concept for the comparison of dose distributions. Phys Med Biol. 2003;48:3543-3553.
22. Low DA, Dempsey JF. Evaluation of the gamma dose distribution comparison method. Med Phys. 2003;30(9):2455-2464.
23. Bedford JL, Lee YK, Wai P, et al. Evaluation of the Delta 4 phantom for IMRT and VMAT verification. Phys Med Biol. 2009;54(9):167-176.
24. Low DA, Harms WB, Mutic S, et al. A technique for the quantitative evaluation of dose distributions. Med Phys. 1998;25(5):656-661.
25. Alagar AGB, Mani GK, Karunakaran K. Percentage depth dose calculation accuracy of model based algorithms in high energy photon small fields through heterogeneous media and comparison with plastic scintillator dosimetry. J Appl Clin Med Phys. 2016;17(1):132-142.
26. Maerz K, Mittermair P, Krauss A, et al. Iterative metal artifact reduction improves dose calculation accuracy. Strahlenther Onkol. 2016;192(6):403-413.

How to cite this article: Liu T-T, Dai Z-T, Kang K-L, Gao L-Y, Liu R-F, Ou-Yang S-G. Comparative analysis of dose verification between computed tomography scan phantom and virtual digital phantom of Delta4. Prec Radiat Oncol. 2020;4:38-43. https://doi.org/10.1002/pro6.1092