


Patient-Specific Quality Assurance Using Monte Carlo Dose Calculation and Elekta Log Files for Prostate Volumetric-Modulated Arc Therapy

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Abstract

Log file-based methods are attracting increasing interest owing to their ability to validate volumetric-modulated arc therapy outputs with high resolution in the leaf and gantry positions and in delivered dose. Cross-validation of these methods for comparison with measurement-based methods using the ionization chamber/ArcCHECK-3DVH software (version 3.2.0) under the same conditions of treatment anatomy and plan enables an efficient evaluation of this method. In this study, with the purpose of cross-validation, we evaluate the accuracy of a log file-based method using Elekta log files and an X-ray voxel Monte Carlo dose calculation technique in the case of leaf misalignment during prostate volumetric-modulated arc therapy. In this study, 10 prostate volumetric-modulated arc therapy plans were used. Systematic multileaf collimator leaf positional errors (± 0.4 and ± 0.8 mm for each single bank) were deliberately introduced into the optimized plans. Then, the delivered 3-dimensional doses to a phantom with a certain patient anatomy were estimated by our system. These doses were compared with the ionization chamber dose and the ArcCHECK-3DVH dose. For the given phantom and patient anatomy, the estimated dose strongly coincided with the ionization chamber/ArcCHECK-3DVH dose ($P < .01$). In addition, good agreement between the estimated dose and the ionization chamber/ArcCHECK-3DVH dose was observed. The dose estimation accuracy of our system, which combines Elekta log files and X-ray voxel Monte Carlo dose calculation, was evaluated.

Keywords

patient-specific QA, log file, Monte Carlo, volumetric-modulated arc therapy, radiotherapy, oncology

Abbreviations

2D, two dimensional; 3D, three dimensional; DVH, dose-volume histogram; PTV, planning target volume; QA, quality assurance; TPS, treatment planning system; VMAT, volumetric-modulated arc therapy; XVMC, X-ray voxel Monte Carlo.

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Introduction

Volumetric-modulated arc therapy (VMAT) was developed to enable dynamic control of the multileaf collimator, jaw, and dose rate during gantry rotation. Thus, VMAT delivery technology allows for the generation of a highly modulated dose distribution over a shorter time frame than that observed in step-and-shoot or dynamic intensity-modulated radiotherapies. Using this delivery technique, VMAT output is evaluated to ensure that the patient effectively and safely receives radiotherapy through patient-specific quality assurance (QA) procedures.

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For developing patient-specific QA procedures, a log file-based method is used to estimate irradiated VMAT output with a 3-dimensional (3D) dose using a combination of linac component statuses (ie, leaf and jaw positions and delivered doses) and dose calculations performed in treatment planning systems (TPS)¹⁻⁴; examples of such systems include the Eclipse TPS (Varian Medical Systems, Palo Alto, California) with a Varian log file^{1,3} and the Pinnacle TPS (Philips Radiation Oncology Systems, Fitchburg, Wisconsin) with an Elekta log file. These methods can estimate the irradiated dose without a measurement device and allow additional machine availability.

However, one problem with log file-based methods is that the estimated dose is affected by the inaccuracy of the calculation implemented in the TPS for dose estimation. Thus, inaccurate dose calculations propagate discrepancies from the irradiated VMAT output to the estimated dose. Therefore, a log file-based method is desirable for estimating patient dose using a sufficiently accurate calculation. Previous data show that the X-ray voxel Monte Carlo (XVMC) dose calculation method implemented in a Monaco TPS (Elekta, Stockholm, Sweden) exhibits high accuracy⁵⁻⁹; moreover, the discrepancies between the calculated and measured doses in the XVMC method were found to be smaller than those in the kernel-based⁸ and Boltzmann equation solver-based dose calculations.⁹ Thus, XVMC dose calculation is suitable for log file-based methods.

The present report is among the first to implement a log file-based method employing an XVMC dose calculation in the Monaco TPS and to determine the accuracy of this method for leaf misalignment via cross-validation. The purpose of performing cross-validation is to compare our results with those obtained using a measurement-based method under the same conditions of treatment anatomy and plan, thereby allowing an efficient evaluation. In this study, the dose estimated using the log file-based method was cross-validated using ArcCHECK-3DVH (Sun Nuclear Corporation, Melbourne, Florida) doses, which are sufficiently accurate for clinical practice¹⁰⁻¹⁴ and ionization chamber doses.

Materials and Methods

Treatment Planning and Error Simulation

Optimized plans for 10 prostate VMAT treatments were generated by using Monaco TPS version 5.10 (Elekta, Stockholm, Sweden) with a dose of 74 Gy in 37 fractions and employing single-arc VMAT with a 10-MV photon beam of Synergy (Elekta). Error-induced plans were generated by modifying leaf positions systematically at every control point described in the optimized plans. Therefore, the different control points within the same plan have the same leaf error. There were 4 types of leaf errors with magnitudes of ± 0.4 and ± 0.8 mm in the isocentral plane for each single bank; they were added at each control point using in-house software. In this study, the same leaf errors were introduced into both the leaf banks. The leaf errors resulted in an expanded or restricted aperture depending

on their respective error magnitudes. The total number of error-induced plan was 40 (4 error-induced plans for each optimized plan \times 10 optimized plans).

Log File-Based Method Comprising an Elekta Log File and an XVMC Dose Calculation

Our log file-based method employs an Elekta log file and an XVMC dose calculation implemented in the Monaco TPS. X-ray voxel Monte Carlo calculations based on mass densities provide better accuracy than kernel-based and Boltzmann equation solver methods in homogeneous and heterogeneous regions.⁵⁻⁹ An Elekta log file contains the following machine dynamic parameters: leaf and gantry positions with precisions of 0.1 mm and 0.1° and a delivered dose with a precision of 0.1 monitor units. In this study, Elekta log files were recorded at 0.5-second intervals during VMAT irradiation at a continuously variable dose rate.

As shown in the upper part of Figure 1, to perform cross-validation of the log file-based dose using an ionization chamber/ArcCHECK-3DVH dose, an error-free log file was obtained during optimized plan irradiation. In addition, error-induced log files were obtained during error-induced plan irradiation. These log files were converted into the Monaco TPS original file format for each control point using an in-house program and subsequently imported to the Monaco TPS. For all log files, the mean doses to the CC13 ionization chamber (IBA Dosimetry, Schwarzenbruck, Germany) volume at its isocenter were estimated based on a computed tomography image set (18 cm \times 18 cm \times 18 cm) of a ImRT phantom (IBA dosimetry) that consists of water-equivalent material. The doses for each patient anatomy were also estimated. Dose estimation was performed using an XVMC dose calculation with a 2-mm dose grid and a 1.0% variance in the total beam.

Ionization Chamber/ArcCHECK-3DVH Dose

For cross-validation of the ionization chamber doses (as shown in the middle part of Figure 1), optimized/error-induced plan doses to the chamber volume at the isocenter of the ImRT phantom were measured in a CC13 ionization chamber. Before measurement, the CC13 ionization chamber was cross-calibrated using a Farmer-type TN 30013 ionization chamber (PTW, Freiburg, Germany) with a 10 \times 10 cm² field.

For the ArcCHECK-3DVH dose, as shown in the lower part of Figure 1, first, the continuity of our ArcCHECK measurement with previous data was ensured. Two-dimensional (2D) gamma passing rates for optimized/error-induced plans were calculated for comparing the ArcCHECK measurements and the TPS-calculated dose. Subsequently, to obtain the irradiated 3D dose according to patient anatomy for each plan, these ArcCHECK measurements were exported to the 3DVH software (Sun Nuclear Corporation).

Cross-validation was performed on the phantom geometry by comparing the mean dose to the ionization chamber volume estimated using the log file-based method with that measured

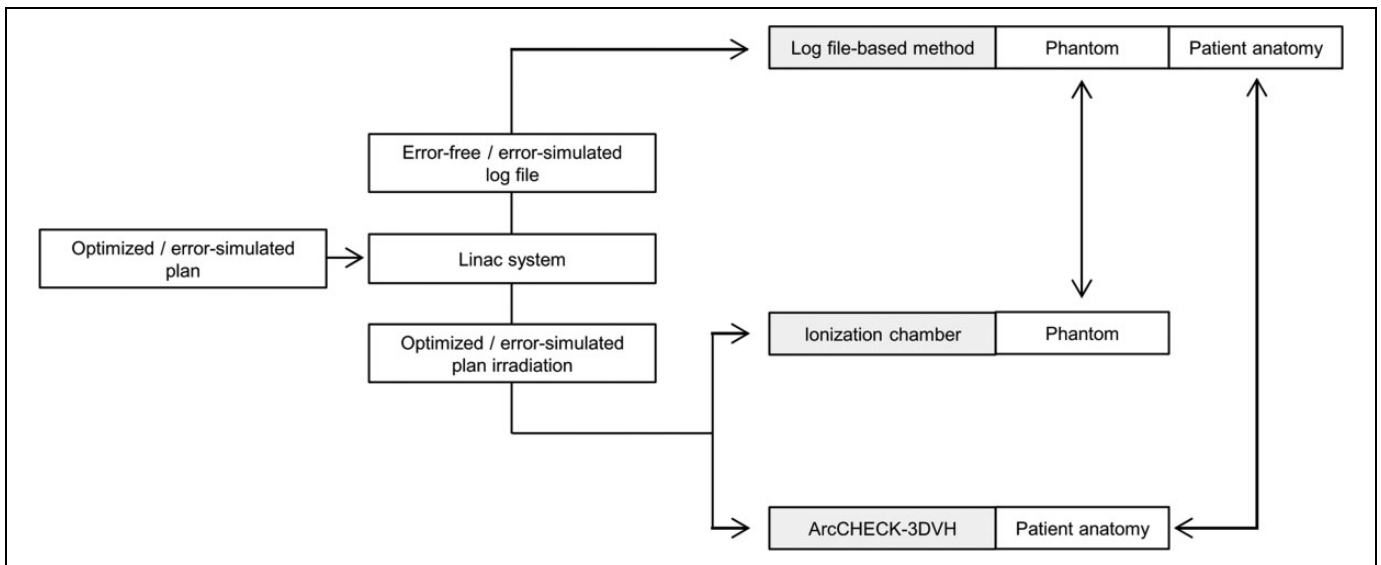


Figure 1. Flowchart of the cross-validation of the log file dose and ionization chamber/ArcCHECK-3DVH dose.

in the CC13 ionization chamber. In addition, for patient anatomy, the mean doses to the tumor and normal tissue volumes estimated using the log file-based method were compared with those obtained using ArcCHECK-3DVH and 3D gamma passing rate calculations.

Results

Basic ArcCHECK QA

For optimized/error-induced plans used in the 10 prostate cases, the mean 2D gamma passing rates for 3%/3 mm (3% absolute dose and 3 mm distance to agreement) and 2%/2 mm between the ArcCHECK measurement and the TPS dose are $99.1\% \pm 0.7\%$ and $93.5\% \pm 2.5\%$, respectively. Note that 2D gamma calculations used the global percentage dose error normalization, and the low threshold dose for gamma analysis was set to 10% of the maximum dose. The measurement uncertainty function of the SNC software (Sun Nuclear Corporation) was not utilized.

Log File Dose Versus Ionization Chamber/ArcCHECK-3DVH Dose

For the given phantom geometries, a cross-validation of the mean dose to the ionization chamber volume estimated using the log file-based method and that measured in the ionization chamber is shown in Figure 2. The correlation of the cross-validation result with Pearson correlation coefficient r was considered weak for $r < 0.4$, moderate for $r = 0.4$ to 0.7 , and strong for $r > 0.7$. The r in this case was 0.99 (statistical significance is confirmed for Pearson r value: $P < .001$), indicating that the estimated chamber dose is in good agreement with measured chamber dose. For 10 patients, the mean difference between the estimated and measured dose values across all cases was $0.00\% \pm 0.01\%$. In this study, each dose-volume

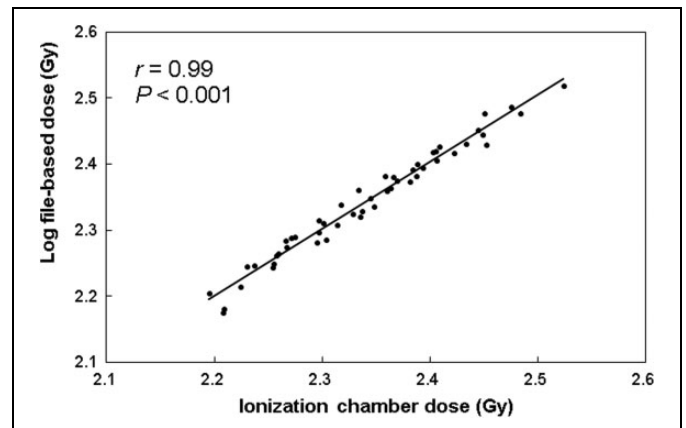


Figure 2. For the phantom geometry, the mean dose to the ionization chamber volume estimated using the log file-based method versus the ionization chamber measurement.

histogram (DVH) value was quantified using only the 3DVH application because Tyagi *et al* showed that quantified patient-organ dose values differ depending upon the application used.¹⁵

Similar to the results obtained for the phantom geometry, good agreement was found between the estimated and obtained patient doses under varying patient anatomy. Figure 3 shows a typical case of the 3D gamma distribution (1%/2 mm, global, and the low threshold was 20%). For the 10 prostate cases, the mean 3D gamma passing rate between the patient dose estimated using the log-file-based method and the obtained one was $96.0\% \pm 1.2\%$. The estimated dose also strongly coincided and showed a relatively good agreement with the ArcCHECK-3DVH dose. As shown in Figure 4, strong agreements between the mean doses to tumor and normal tissue volumes estimated using the log file-based method and ArcCHECK-3DVH were observed; r was 0.97 for the planning

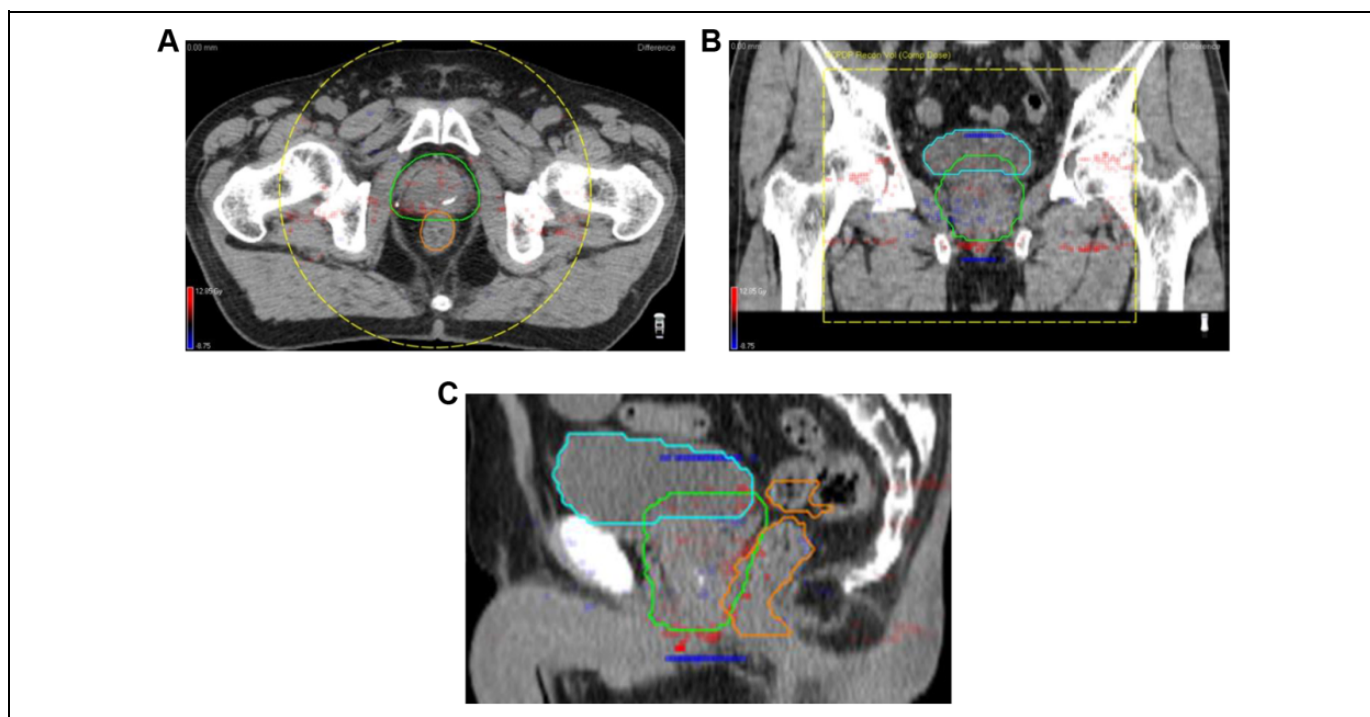


Figure 3. For the patient anatomy, the gamma index distributions (1%/2 mm, global, 20% dose threshold) between the log file and ArcCHECK-3DVH doses for typical cases; (A) axial plane, (B) coronal plane, and (C) sagittal plane. The planning target volume was contoured in green line, bladder was blue line, and rectum was orange line.

target volume (PTV), 1.00 for the bladder, and 0.98 for the rectum ($P < .001$). The mean difference ± 1 standard deviation (maximum difference) was 0.71 ± 0.7 Gy (2.62 Gy) for the PTV, 1.08 ± 1.0 Gy (3.51 Gy) for the bladder, and 0.21 ± 3.4 Gy (7.41 Gy) for the rectum.

Discussion

In this study, we established a log file–based patient–dose estimation system that uses an Elekta log file and an XVMC calculation implemented in the Monaco TPS. The major advantage of XVMC is that it enhances the accuracy of dose estimation. No significant differences between the doses estimated using our log file–based method and the ionization chamber/ArcCHECK-3DVH doses for both phantoms and patients were found, and these doses exhibited a strong correlation. The 3DVH software uses the 2D dose measured by the diodes implemented in ArcCHECK to obtain the 3D dose. The agreement between the 2D measured dose and the TPS dose for both optimized and error-induced plans in this study was consistent with the results of previous research.^{16,17} The agreement for prostate cases using the 2%/2 mm criterion was shown to be 99.7% by Nelms *et al.*¹⁶ Similarly, Kozelka *et al* demonstrated it to be 96.8%.¹⁷

In this study, systematic leaf error was applied as the error pattern because it was more suitable for determining the accuracy of our log file–based method instead of the random leaf bank error, in which each open leaf position at each control point is modified by a number generated from a truncated Gaussian distribution centered on zero using a user-defined

standard deviation. As a result, the dosimetric change arising from the optimized dose to error-induced plan dose due to systematic leaf bank errors was significantly larger than that due to random leaf bank error. For example, with respect to clinical target volume, Rangel and Dunscombe¹⁸ reported 2.72% discrepancies due to systematic leaf bank errors and -0.01% discrepancies due to random leaf bank shift. Therefore, for clinical use, the data validation by systematic leaf shift pattern in this study was sufficient as it does not underestimate the values.

It is important to note that dose estimation errors were introduced into the estimated dose in the log file–based method even if dose estimation was performed using the XVMC dose calculation. Linac statuses recorded in log file–based methods are insensitive to miscalibration.^{19,20} For example, leaf positions can be detected using leaf position measurement sensors installed in the linac and recorded in a log file with calibration accuracy. Therefore, a leaf calibrated with a general tolerance level of ± 0.5 mm²¹ has leaf positional errors ≤ 0.5 mm. Previous studies have shown that the dose estimation error for a leaf with a position accuracy of ± 0.5 mm for prostate VMAT is 1.22%, 0.95 Gy, and 0.45 Gy for the PTV, rectum, and bladder, respectively.¹⁹ However, in our data, the dose estimated using our log file–based method showed good agreement with the measured value. Because of this, in our clinic, the leaf was calibrated using an electronic portal imaging device–based fence test, which yields a miscalibration that is smaller than the general tolerance level.^{22,23} The more the leaf miscalibration is reduced, the more the reduction in the residual

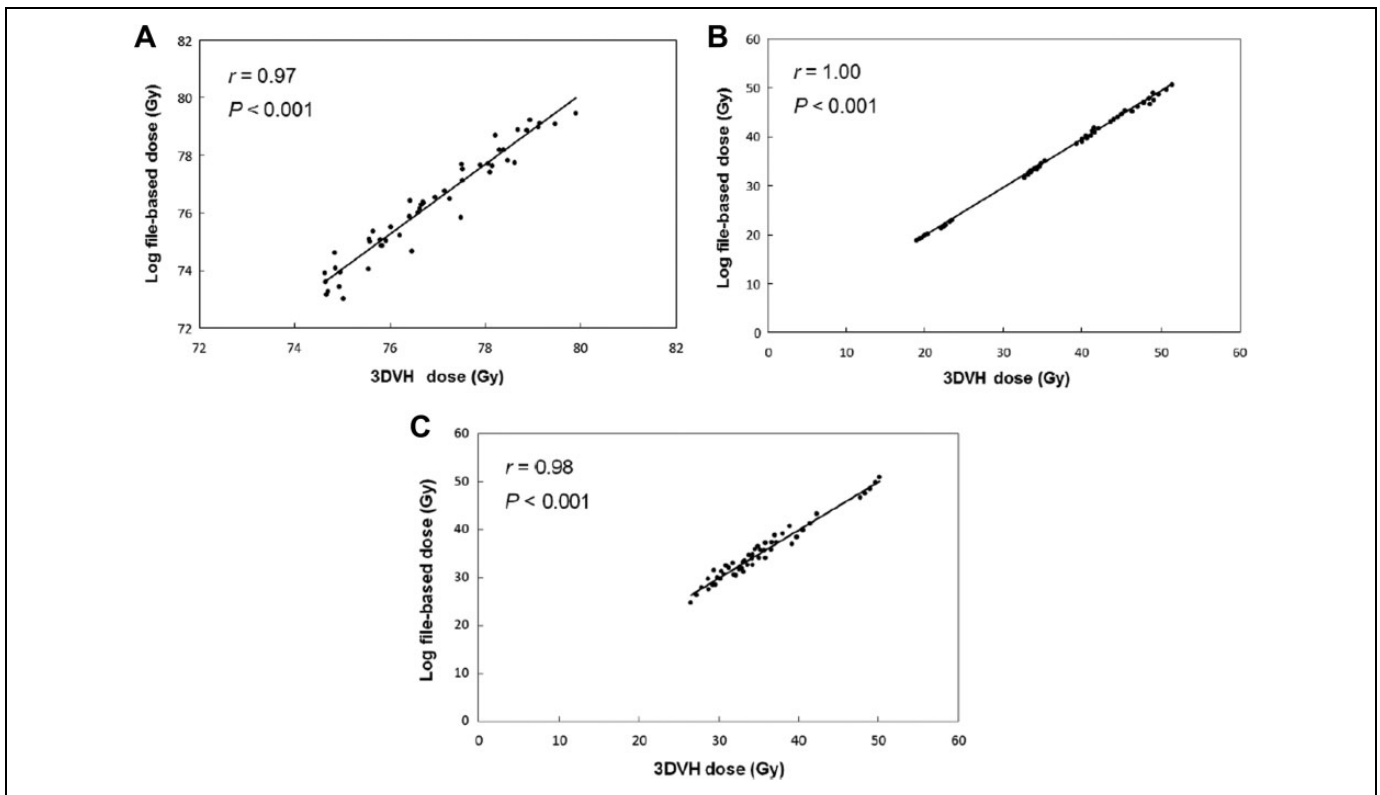


Figure 4. For the phantom geometry, the mean dose to tumor/normal tissue volumes estimated using the log file–based method versus that obtained using ArcCHECK-3DVH; (A) planning target volume, (B) bladder, and (C) rectum.

error.¹⁹ Therefore, good agreement of the measured dose with the ionization chamber/ArcCHECK-3DVH dose was obtained.

There are limitations to this study. The accuracy of our log file–based method was evaluated for a prostate VMAT with a comparatively simple plan optimization and delivery site. In more complex plans such as in the head and neck VMAT, highly modulated treatment beams can be generated using complex leaf and gantry motions. Therefore, even if XVMC dose calculation was applied in our log file–based method, spatial resolution of leaf and gantry positions recorded on log file or the recording interval time could have affected the accuracy of our log file–based method in more complex plans such as the head and neck VMAT.

Conclusion

In this study, we developed a log file–based method that uses an Elekta log file and an XVMC dose calculation implemented in the Monaco TPS. Our data show that the accuracies of the log file–based dose and ionization chamber/ArcCHECK-3DVH dose for leaf misalignment in the cases of both phantoms and patients were in good agreement with each other.

Declaration of Conflicting Interests

The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

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