Impact of log file source and data frequency on accuracy of log file-based patient specific quality assurance

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Abstract

Performing phantom measurements for patient-specific quality assurance (PSQA) adds a significant amount of time to the adaptive radiotherapy procedure. Log file based PSQA can be used to increase the efficiency of this process. This study compared the dosimetric accuracy of high-frequency linear accelerator (Linac) log files and low-frequency log data stored in the oncology information system (OIS). Thirty patients were included, that were recently treated in the head and neck (HN), brain, and prostate region with volumetric modulated arc therapy (VMAT) and an additional ten patients treated using stereotactic body radiation therapy (SBRT) with 3D-conformal radiotherapy (3D-CRT) technique. Log data containing a single fraction were used to calculate the dose distributions. The dosimetric differences between Linac log files and OIS logs were evaluated with a gamma analysis with 2%/2 mm criterion and dose threshold of 30%. The original treatment plan was used as a reference. Moreover, DVH parameters of $D_{98\%}$, $D_{50\%}$, and $D_{2\%}$ of the planning-target volume (PTV) and dose to several organs at risk (OARs) were reported. Significant differences in dose distributions between the two log types and the original dose were observed for PTV $D_{98\%}$ and $D_{2\%}$ ($r < 0.001$) for HN cases, PTV $D_{98\%}$ ($r = 0.005$) for brain cases, and PTV $D_{50\%}$ ($r = 0.015$) for prostate cases. No significant differences were found between the two log types with respect to $D_{50\%}$. The root mean square (RMS) error of the leaf positions of the OIS log was approximately twice the RMS error of the Linac log file for VMAT plans, but identical for 3D-CRT plans. The relationship between the gamma pass rate and the RMS error showed a moderate correlation for the Linac log files ($r = -0.58$, $p < 0.001$) and strong correlation for OIS logs ($r = -0.71$, $p < 0.001$). Furthermore, all doses calculated using Linac log files and OIS log data had a GPR >90% for an RMS error < 3.3 mm. Based on these findings, a tolerance limit of RMS error of 3.3 mm for considering OIS log based PSQA was established. Nevertheless, the OIS log data quality should be improved to achieve adequate PSQA.

Keywords: Patient specific quality assurance; Log file; Oncology information system

1 Introduction

Verifying the planned and delivered dose is a key aspect in a radiotherapy quality assurance (QA) program. With the introduction of fluence-based precision radiotherapy techniques, measurement-based dose verification became a standard process for patient-specific quality assurance (PSQA) [1,2]. The purpose of measurement-based verification is to ensure that the dose calculation of the treatment planning system (TPS) is consistent with measurements and that the treatment plan transfer was successful. These measurement-based QA procedures,

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however, are very time-consuming and require extensive resources.

To overcome these limitations, independent dose calculation (IDC) has been proposed for PSQA, which has become an accepted procedure [3,4]. One promising solution as input data for IDC are Linac-based log files [5]. For example, independent dose calculation based on Linac model and dose kernel-based calculation or Monte Carlo simulation usually uses the planning parameters and control point data of the original treatment plan to generate the photon fluence [6,7]. Linac log files can replace those data as an input source of secondary dose/MU calculation in showing a good agreement ($r = 0.98$, $p < 0.001$) for cross-validation with ion chamber measurements for phantom and patient geometries [8]. Evaluation between measurement and non-measurement-based PSQA has also been carried out with relatively small dosimetric differences [9–11]. The workload associated with adaptive radiation therapy (ART) might even require new PSQA routines based on IDC [12]. For online ART, automated QA procedures are even a prerequisite and log files are an obvious data source for PSQA [10,13].

As for any other calculation-based procedures, input data source and data quality are of utmost importance. Although the concept of log file based IDC, or PSQA in general, has been the subject of several studies, quality aspects related to log file source and data structure have not been evaluated in great detail, especially for Elekta linacs. In this type of machine, log files are archived inside the backup utility with a resolution of 25 Hz. General patient information (e.g. name of the patient, medical record number, date of birth) are not provided in the log file. In addition, log file data with a lower rate at 4 Hz are accessible via the iCom interface. A recent study reported that dosimetric output of IDC based on 4 Hz log files and treatment planning system (TPS) based dose calculation were in good agreement [14]. A new approach for receiving log file data is to query the Oncology Information System (OIS) database for the recorded treatment. Although the resolution of these treatment data is less than 4 Hz, the advantage is that the data is already referenced to the patient and no additional interface to the Linac is needed. Additionally, this process can be highly automated starting from patient selection to retrieval of the data, calculating the root mean square error as well as dose calculation and evaluation using the dose volume histogram (DVH) and eventually also the gamma analysis.

The aim of this work was to provide the proof of principle that dose calculation based on OIS log can be performed. An additional aim was to assess the dosimetric accuracy of the high resolution Linac log files and the OIS log files by using the same dose engine to avoid any systematic impacts from the dose calculation procedure.

2 Materials and methods

2.1 Patients and TPS

In total, a cohort of forty patients consisting of ten patients for each head and neck (HN), brain, and prostate cancer cases treated with VMAT as well as ten stereotactic body radiation therapy (SBRT) patients treated with 3D-CRT. One fraction was evaluated for all investigated cases. Four additional fractions of five HN cases were included to assess the inter-fraction variation of the data. Treatment planning was performed with RayStation Version 11 (RaySearch Laboratories AB, Stockholm, Sweden). Table 1 shows an overview of the investigated indications, fractions, and calculation parameters. All plans were delivered by an Elekta Versa HD Linac (Elekta AB, Stockholm, Sweden). Target dose prescription for the VMAT cases was to the median dose ($D_{50\%}$) according to ICRU recommendations [15]. For the SBRT cases the prescription was defined at the 65% iso-dose line covering 99% of the planning target volume (PTV). The OIS Mosaiq (Elekta AB, Stockholm, Sweden) was used to store and retrieve all treatment-related information.

2.2 Linac log files

The log files of the Versa HD Linac record various delivered beam parameters such as control points, Linac state, dose rate and cumulative MU, gantry rotation, wedge status, collimator angle, table position, jaws, and leaves position with a frequency of 25 Hz. The Linac log files can be retrieved using the backup utility in service mode. It contains the log information of eight days, which is compressed into a single zip file. For this study the file was decompressed, and the binary format .trf (treatment record file) was subsequently converted to a .xml format using Elekta Treatment Recorder Converter Tool. Control points, cumulative MU, gantry and collimator angle, jaw position, and multi-leaf collimator (MLC) position were the main parameters to create an RT plan based on the log file data. The XML file was converted into a readable matrix for each for each treatment.

2.3 OIS log

Mosaiq stores all patient-related information inside the Radiation Oncology network. It contains essentially the same information as the Linac log files. However, the OIS log file information has a lower sampling frequency than Linac log file, i.e., only one data point per control point is stored. Using the Standard Querying Language (SQL), the treatment parameters can be accessed from the Mosaiq database.

Table 1
Number of patients and beam parameters used in this study.

Site	Number of patients	Technique	Arcs/ beams	Dose grid (mm^3)	Number of fractions evaluated
HN	5	VMAT	2 full arcs	3 × 3 × 3	25
	5	VMAT	2 full arcs	3 × 3 × 3	5
Brain	4	VMAT	2 partial arcs	2 × 2 × 2	4
	6	VMAT	2 partial arcs and 1 non-coplanar partial arc	2 × 2 × 2	6
Prostate	4	VMAT	2 partial arcs	3 × 3 × 3	4
	6	VMAT	1 partial arc	3 × 3 × 3	6
Lung	10	SBRT	7–8 static beams	2 × 2 × 2	10

2.4 Data preparation and data-post-processing

Both Linac log files and OIS logs were used as input for dose recalculation with the clinical TPS. A copy of the original treatment plan was created in the TPS using the scripting capabilities. Next, the following parameters of the original plan data were replaced by the respective log file data: MU per segment, maximum MU, jaw position, collimator angle, and MLC position. The gantry angle became a reference parameter for the log-based plans because of the limitations of the TPS, which requires a fixed gantry angle separation of 2°. Therefore, the information in the Linac and OIS logs was re-sampled to meet these limitations. For Linac log files with a high sampling frequency, re-sampling was carried out by selecting the data points closest to the planned gantry ±0.2°. To analyze the actual plan-based sampling frequency, the time difference between the gantry angles defined in the original treatment plans was measured using the high resolution Linac log files. Typically, three to nine data points surrounding the planned gantry angle were averaged and used as control point data.

Unlike the Linac log file, the OIS log file only had 1 data point for each control point available. Two-point interpolation between the delivered n gantry angle and n+1 gantry was applied to predict the closest data to the planned gantry angle. In case the information of two gantry points was not between the planning gantry angle, a 3-point interpolation was used in this case as seen in Fig. 1. All log-based treatment plans were recalculated with the same calculation parameters as the original plans.

2.5 Evaluation and analysis

The dose distribution for both types of log-based treatment plans were compared to the original treatment plans. The dosimetric evaluation was based on DVH. More specifically, PTV parameters such as $D_{98\%}$, $D_{50\%}$ and $D_{2\%}$ (calculated dose at 98%, 50%, and 2% of volume) were extracted from DVH. For consistency, the same DVH parameters were evaluated for the SBRT plans despite the different type of prescription. For OARs, serial organs were the focus of this study and the following DVH parameters were extracted: $D_{1\%}$ and D_{max} (dose at 1% volume and maximum dose) and additional contra lateral parotid mean dose $D_{50\%}$ were extracted as well. For prostate cancer, $D_{1\%}$ of the bladder and the rectum organ were observed. The relative differences of the dosimetric parameters were statistically evaluated by applying a paired student t-test. A p-value < 0.05 was considered statistically significant.

3D gamma index analysis was performed using the Verisoft software (PTW, Freiburg, Germany) by applying a 30% threshold. The analytical criteria applied to all cases were 2 mm distance to agreement (DTA) and 2% dose difference (DD) with respect to the local dose. An additional analysis was carried out by evaluating the deviations of the logged data to the planned data at each point of the MLC position. Differences in delivery and planning positions were evaluated for all MLC segments using the root mean square (RMS) error of the leaf positions. The following equation was used to determine RMS leaf error

$$RMS = \sqrt{\frac{\sum_{f=1}^{F}\sum_{c=1}^{C_f}\sum_{l=1}^{L_{f,c}}\left(x_{log,f,c,l} - x_{TPS,f,c,l}\right)^2}{\sum_{f=1}^{F}\sum_{c=1}^{C_f}\sum_{l=1}^{L_{f,c}}1}} \quad (1)$$

where x_{TPS} and x_{log} are the position of a leaf l in the control point c of each field f for the TPS and log data, respectively. Note that only the leaves in the treatment field were considered. F is the number of fields, C_f is the number of control points of field f, and $L_{f,c}$ is the number of leaves in the treatment field for field f and control point c. The denominator is the sum of all leaves in the treatment field of the whole treatment plan.

In this work, the RMS leaf error was evaluated for each treatment and correlated with the gamma index evaluation of the respective dose distribution. The Pearson correlation coefficient r was evaluated; and r was defined as weak,

moderate, and strong for $r < 0.4$, $r = 0.4$–0.7, and $r > 0.7$, respectively.

3 Results

3.1 Raw data

Concerning the sampling frequency, the average time and standard deviation between each control point (2° gantry angle) estimated using the Linac log files were 0.8 ± 0.3 s, 0.8 ± 0.5 s and 0.6 ± 0.4 s for HN, brain, and prostate cases, respectively. Note that the control points sampling rate is not constant during a treatment. The average standard deviations of the control point sampling rate per beam were 0.3 s, 0.5 s, and 0.4 s for HN, brain, and prostate cases, respectively. It needs to be highlighted that this control point sampling rate is the same for the Linac log files and the OIS logs. Based on the estimated delivery time reported by the TPS, the average time between control points of the original treatment plans were 0.8 ± 0.3 s, 0.9 ± 0.4 s and 0.5 ± 0.1 s for the HN, brain, and prostate cases, respectively.

Fig. 2 shows a representative example of monitor unit per segment for one arc. The MU per segment of the TPS had a constant value of 2.04 MU, however the delivered MU per segment fluctuated. Linac log file and OIS log result showed different MU per segment, but on average the delivered MU for this irradiation were 2.04 MU ± 0.50 MU and 2.04 MU ± 0.71 MU, respectively. Futhermore, compared to the MU per control point of the treatment plan, the deviation of the average MU per segment for all evaluated logs was on average 0.02% and 0.05% for Linac log files and OIS logs, respectively. The results of this raw data examination also indicated the existence of data poverty in the OIS log sampling. For instance, at the 23rd and 134th control points of Fig. 2, the MU of OIS log reached zero. However, the MLC was moving at this time as shown in Supplementary Fig. S.1. This crashed the dose calculation in the TPS. Therefore, the 3-point interpolation was used in these cases.

3.2 Dose comparison

Treatment plans based on Linac and OIS log files were created from one fraction then multiplied by the number of fractions for each patient. Fig. 3 shows as an example DVH for one each HN, brain, and prostate cancer case. The main differences in the DVH were found in the PTV. For the HN case the PTV of the Linac log file- and the OIS log-based dose distribution showed differences in the high and low dose regions of the target ($D_{98\%}$ and $D_{2\%}$) with significant difference ($p < 0.001$). However, an insignificant difference ($p = 0.34$) between Linac log files and OIS logs was found to the prescription dose value ($D_{50\%}$). The dose at the PTV for the brain case differed more in the high dose region compared to the low dose region. Moreover, a significant difference ($p = 0.005$) was observed in brain PTV

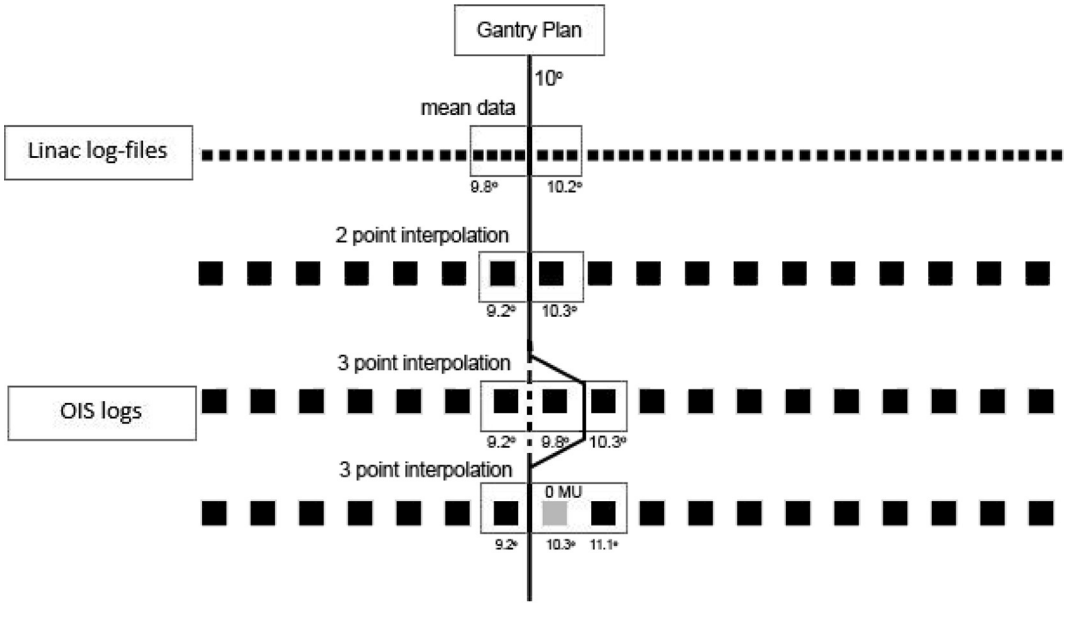

Figure 1. Resample method of Linac log file and OIS log. The black square represents the data stream of log information. An example of 10° gantry angle is shown in the solid lines. The Linac log file averages the log data of information from 9.8 to 10.2 treated gantry. The OIS log were postprocessed applying one of the following 3 options: 1) 2 point interpolation when 10° of gantry angle is between the log information, 2) 3 point interpolation when the OIS log does not sandwich 10° of gantry plan, the algorithm collects next segment's data, and 3) 3 point interpolation when 10° of gantry angle is in between the OIS log information but 0 MU was found in the data.

$D_{98\%}$. In addition, the dose volume for prostate case had a relatively similar dose for all regions even though a small offset in the mean dose of PTV with a significant difference ($p = 0.02$) between Linac and OIS log was observed. For all cases, the DVH resulting from the Linac log file-based dose calculation tended to be closer to the DVH of the TPS compared to the DVH derived from OIS log-based plans. In contrast, the dose difference of PTV was insignificant for all dose metrics of the lung SBRT cases. The average results of dosimetric differences are summarized in Supplementary material Table S.1.

The Pearson correlation between MU fluctuation and dose difference showed no correlation. The r-values for Linac-$D_{98\%}$, OIS-$D_{98\%}$, Linac-$D_{2\%}$, and OIS-$D_{2\%}$ were 0.04, −0.07, −0.25, and 0.08, respectively. The graph for this correlation is shown in the Supplementary material Fig. S.2.

Concerning OARs, statistically significant differences between original dose distributions and the ones based on log files were seen only in HN cases in the spinal cord and brainstem for D_{max}. Although the dosimetric difference in OAR of the brain cases was generally not significant, the standard deviation of OIS log-based dose distributions was higher than for Linac log file-based ones.

Fig. 4 shows the gamma pass rate (GPR) with the criteria of 2%/2 mm local gamma indices as a function of RMS error. The gamma pass rates were systematically lower for the OIS logs compared to the Linac log files as seen in Supplementary material Table S.2. The results showed that all investigated OIS and Linac log plans with an RMS error lower than 3.3 mm had a GPR higher than 90%. The linear regression between RMS and GPR showed a moderate and strong correlation with an r-value of −0.58 and −0.71 for Linac log files and OIS log, respectively. Both regression model correlation showed statistical significance with $p < 0.001$.

The log-based re-calculation for five HN patients was done for five fractions to estimate the inter-fraction variation of both data sources. We found that the standard deviation of the GPRs of all fractions were 0.1% and 1.2% for the Linac log files and OIS-logs, respectively. The GPRs between Linac log files and OIS log showed a strong correlation with $r = 0.76$, $p < 0.001$ as shown in Supplementary material Fig. S.3. The GPRs of all VMAT treatments of Linac log files and OIS log were found to be moderately positively correlated $r = 0.64$, $p < 0.001$.

4 Discussion

This study developed a method to recalculate radiotherapy plans using high-resolution Linac log files and OIS-based logs. Due to resampling to control point data, frequencies ranging from 1.2 Hz to 1.7 Hz can be reconstructed. It is still reasonable to work with this kind of data as the original instructions given to the linear accelerator are also given in terms of control points. The estimated time interval between control points of the original treatment plan and the reconstructed treatment plans agreed within the respective standard deviations. Therefore, a reasonable dose reconstruction is possible as shown in this work and by others. Katsuta et al. converted high resolution Linac log files to RT plans, recalculated them in a TPS, and then compared the results with ArcCHECK measurements in prostate cases. The dosimetric difference in PTV between the log file and ArcCHECK was 1.0% ± 0.9% [8]. These results are consistent with our study, indicating an average range of deviations between −0.8% to 0.6% for the prescribed dose between RT plan and Linac log files based ones as seen in Table S.1. Han et al. and Noh et al. retrieved lower frequency log files via the iCom interface and processed them with third-party software such as Mobius3D, MobiusFX, and ArcCHECK. Their results showed that the comparison of the 4 Hz Linac log file with the TPS was in good agreement with a gamma pass rate higher than 90% for machine QA, chest, and HN cancer [11,16]. However, after implementing log file-based QA, treatment plans might no longer be measured independently. Therefore, comprehensive machine QA, beam commissioning, and a comparison of measurement vs non-measurement PSQA before clinical implementation with various complexities have to be done to avoid the PSQA failure [17]. Additionally, a set of consistency patients and randomly selected treatment plans should be measured as part of a regular QA process [5,18].

The analysis of the DVH parameters showed that the $D_{50\%}$ of the PTV calculated using the OIS log plans of the entire patient population was not significantly different from the prescribed dose, see Table S.1. A substantial difference (>5%) was only found in spinal cord $D_{1\%}$ and D_{max} for the OIS log due to the limited number of voxels and the steep dose gradient in this region. Note that analysis of DVH parameters is always dependent on the relative positions between the PTV and OARs and selecting appropriate thresholds for DVH parameters is therefore not straight forward. The fluctuating MU per control point (Fig. 2) did not correlate with the dosimetric difference between Linac log files and OIS logs to the TPS. Other studies have shown that small MU errors have a small impact on the dose distribution because the errors can cancel out on average [19]. This agrees with the finding that the average MU per control point for both Linac and OIS log files were identical within the calculated standard deviations compared to the TPS.

Based on the recommendations of the AAPM TG-142, a leaf position tolerance of 1 mm and a maximum RMS error of 3.5 mm for IMRT [20] should be employed as a threshold for QA purposes. Leaf position accuracy in this study

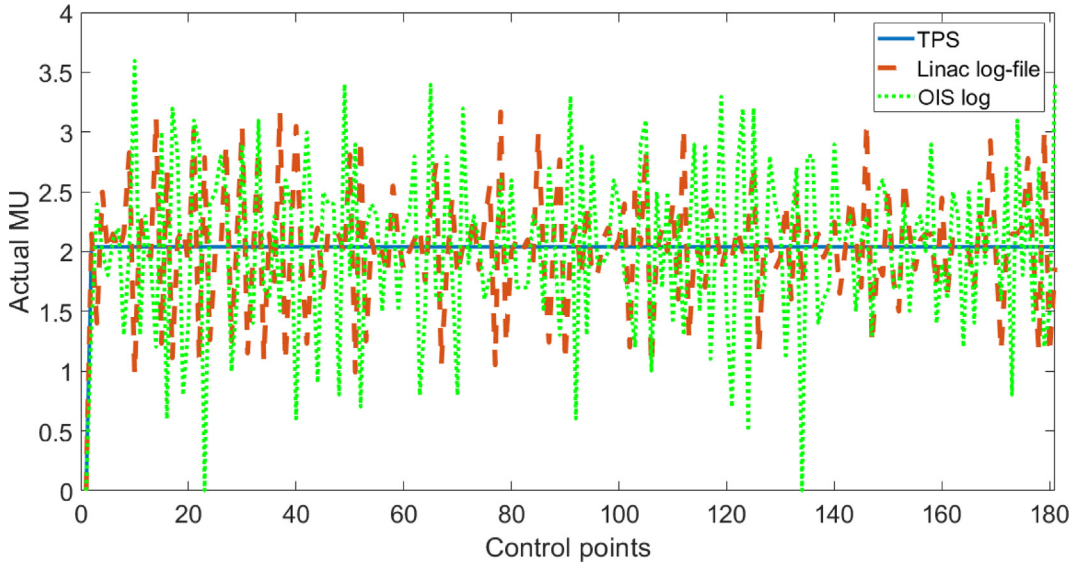

Figure 2. Raw monitor unit per control point for one arc. Blue line corresponds to TPS, red line to Linac log file, and green line to OIS log. The RMS leaf error in this sequence was 1.8 mm and 3.2 mm for Linac log file and OIS log, respectively.

exceeded the recommendation of AAPM TG-142 due to the dynamic nature of the delivery technique. However, these results are in good agreement with Kabat et al., who found that the position tolerance value for dynamic leaf would be higher than 1 mm deviation. As a result, the dynamic treatment allowed a deviation exceeding 1 mm up to 80% of the treatment duration [5]. VMAT QA testing has also been conducted experimentally using EPID and detector arrays for a leaf position error up to 1 mm on all MLCs and compared with the gamma index with the criteria of 2%/2 mm. The results showed a lower gamma pass rate for HN and brain cancer cases with an MLC bank error compared to the error-free treatment. These findings showed that the leaf position error was susceptible to the dosimetric output in the VMAT planning [21,22]. The findings supported the notion that the RMS increase resulting from leaf position errors led to a decrease in the GPR. For measurement-based PSQA, AAPM TG-218 reported that the universal tolerance and action limit of GPR for IMRT with 3%/2 mm criteria should be higher than 95% and 90%, respectively [2]. In contrast, calculation-based QA is not affected by uncertainties arising from an experiment setup, Linac output, and detector calibration. Consequently, tighter acceptance criteria could be applied to calculation-based QA, provided that the data quality is sufficient. In Fig. 4, we employed the 30% threshold and a stricter GPR criterion of 2%/2 mm which gives more information on the agreement between doses.

Based on our findings, the RMS error evaluation can be used for PSQA using either Linac log files or OIS logs. OIS based dose calculation had excellent agreement with the original plans for static treatments shown in the SBRT with 3DCRT technique. VMAT plans generally produced larger RMS errors and showed lower GPR. This effect was more pronounced for more complex cases such as HN cases but showed acceptable results for the majority of cases. The applicability of the OIS logs for QA purposes is also supported by the correlation between the OIS log and Linac log file calculations.

Using the RMS error allows a straightforward selection of patients for experimental verification and a reduction of the experimental workload. Based on these results, the following workflow could be implemented: If the RMS error is larger than 3.3 mm the treatment plan should be measured. If the RMS is lower than 3.3 mm and the GPR is lower than 90% the treatment plan should also be measured. If the RMS is lower than 3.3 mm and GPR is higher than 90% the measurement can be omitted. The current workflow can be completed within 5 minutes. Possible ways to improve efficiency further is the direct integration of the software code including the gamma analysis directly into the TPS.

There are limitations to this work. The evaluation of Linac log files and OIS logs recalculation was performed on a limited number of patients using Elekta and RayStation equipment. Including more patients would further enhance the statistical confidence of the data. Expanding the concept to other vendors, provided the necessary scripting interfaces are available, could improve the generalizability of the analysis and offer valuable insights. To study the influence of acceleration and deceleration of the moving parts of the MLC even higher sampling rates than the currently

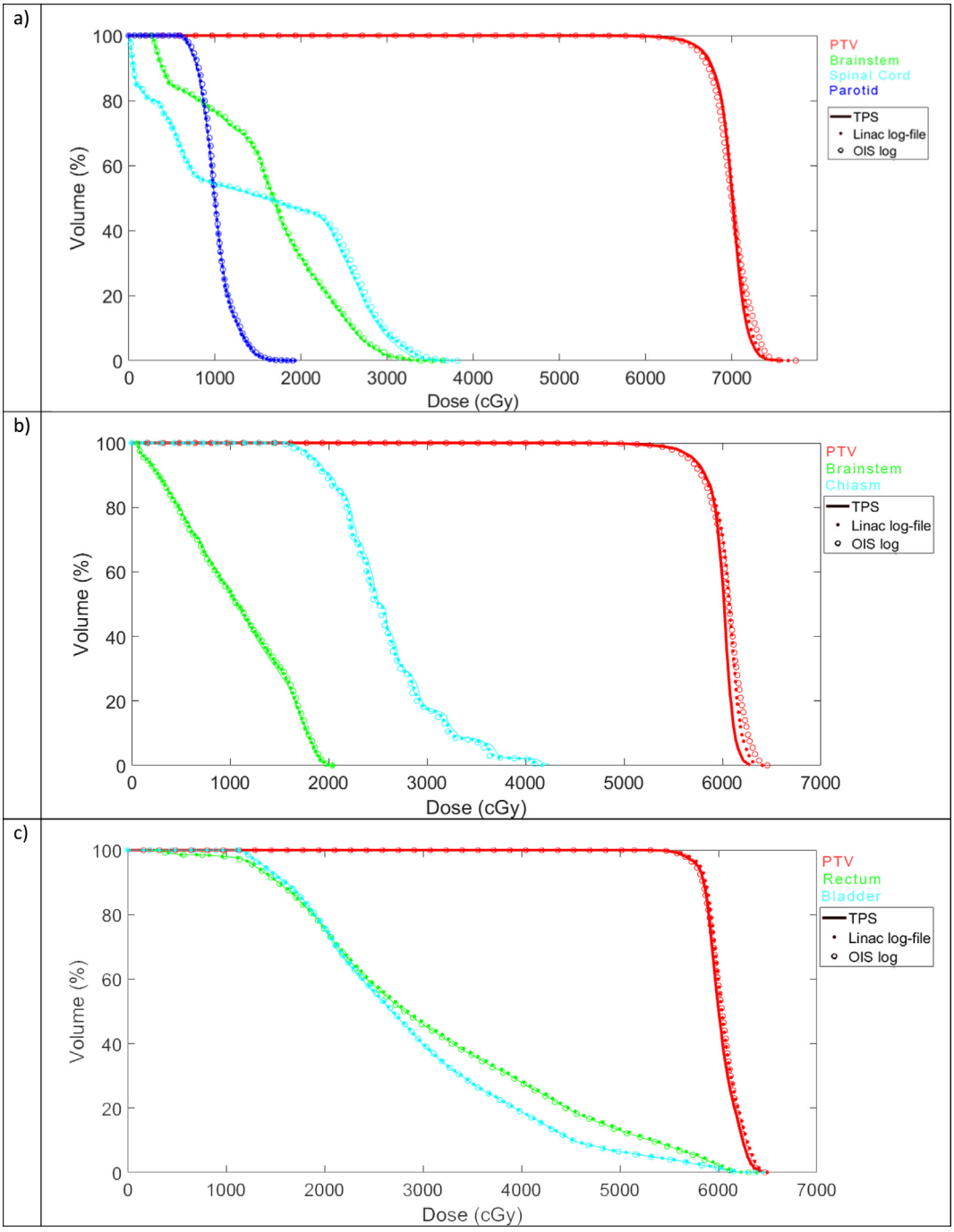

Figure 3. A typical DVH of TPS (solid line), Linac log file (solid dot), and OIS log (hollow dot) of a) head and neck, b) brain, and c) prostate case. Only the PTV (red) and the several OARs with consideration to upmost clinical interest are shown.

available would be desirable. Consequently, the maximum number of control points which can be used for dose calculation has to be increased. In this work we were limited by the restriction of the TPS which only allowed a fixed gantry angle difference between control points of 2°. Moreover, the resampling using linear interpolation between recorded gantry angles on OIS logs is a possible source of error. In this study, we tried to show that it is in principle possible to use the treatment record data for dose reconstruction. A more sophisticated way to interpolate the raw data is out of the focus of this work and will be investigated in the future.

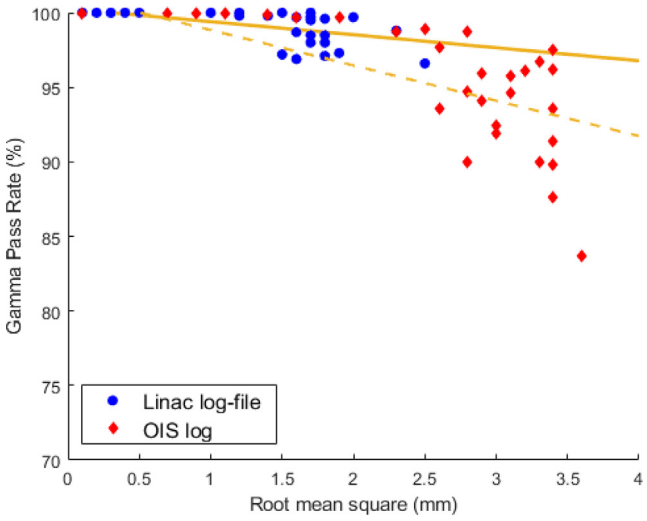

Figure 4. Root mean square vs gamma pass rate of Linac log file and OIS log with criteria 2%/2 mm and dose threshold 30%. The gamma pass rate start falling below 90% at RMS of 3.3 mm. Linear regression fitted of Linac log files (solid line) and OIS logs (dashed line) to RMS with correlation $r = -0.58$ and $r = -0.71$, respectively.

Generally, the raw data quality of the OIS logs should be improved to increase the accuracy of the OIS log-based dose calculation for applications beyond PSQA such as dose accumulation in an adaptive radiotherapy workflow. One example of necessary improvements is the presence of segments with zero MU recorded by the OIS while absent in the Linac log files. Apparently, the delivered MU of these segments were added to the next segment. This assumption is supported by the fact that the total recorded MU and the average MU per control point of the OIS logs and Linac log files were consistent with the planned parameters. The reason for this behavior could be that the OIS data sampling is done in an asynchronous way. Moreover, this asynchronous sampling might also affect the MLC data that led to lower quality of OIS log dose recalculation compared to the Linac log files.

5 Conclusion

Our study demonstrated the dosimetric difference between high-frequency Linac log files and OIS log-based dose calculation for PSQA. The Linac log files and OIS logs agreed well with the prescribed dose. The data quality of the OIS logs is lower compared to the Linac log files, which is also visible in the lower accuracy of the total dose distribution calculated using the OIS logs. Nevertheless, OIS logs can still be used for PSQA to catch coarse errors and reduce the workload of experimental plan verification by implementing a 3.3 mm RMS error threshold and a GPR higher than 90% using a 2% / 2 mm 30% dose threshold acceptance criterion. However, an improvement of the data quality of OIS logs is necessary.

Data Availability Statement

The code used to extract the data is distributed by the authors as open-source. The patient data can be made available on request due to privacy/ethical restrictions.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.zemedi.2023.05.006.

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