



Evaluation of Dynamic Delivery Quality Assurance Process for Internal Target Volume Based RapidArc

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The conventional delivery quality assurance (DQA) process for RapidArc (Varian Medical Systems, Palo Alto, USA), has the limitation that it measures and analyzes the dose in a phantom material and cannot analyze the dosimetric changes under the motional organ condition. In this study, a DQA method was designed to overcome the limitations of the conventional DQA process for internal target volume (ITV) based RapidArc. The dynamic DQA measurement device was designed with a moving phantom that can simulate variable target motions. The dose distribution in the real volume of the target and organ-at-risk (OAR)s were reconstructed using 3DVH with the ArcCHECK (SunNuclear, Melbourne, USA) measurement data under the dynamic condition. A total of 10 ITV-based RapidArc plans for liver-cancer patients were analyzed with the designed dynamic DQA process. The average pass rate of gamma evaluation was $81.55 \pm 9.48\%$ when the DQA dose was measured in the respiratory moving condition of the patient. Appropriate method was applied to correct the effect of moving phantom structures in the dose calculation, and DVH data of the real volume of target and OARs were created with the recalculated dose by the 3DVH program. We confirmed the valid dose coverage of a real target volume in the ITV-based RapidArc. The variable difference of the DVH of the OARs showed that dose variation can occur differently according to the location, shape, size and motion range of the target. The DQA process devised in this study can effectively evaluate the DVH of the real volume of the target and OARs in a respiratory moving condition in addition to the simple verification of the accuracy of the treatment machine. This can be helpful to predict the prognosis of treatment by the accurate dose analysis in the real target and OARs.

Keywords: RapidArc, Delivery quality assurance (DQA), Internal target volume (ITV), ArcCHECK, 3DVH

Introduction

Many studies about Delivery quality assurance (DQA) methods have been conducted for the verification of the dosimetric accuracy of intensity modulated radiation therapy (IMRT).¹⁻⁴⁾ The standard protocol for IMRT DQA was established and performed according to the situation of clinical sites.⁵⁾ The conventional basic procedure for IMRT DQA can be summarized in two methods. One is the measurement of the dose at a specific point, and the other

is acquisition of the dose distribution in a two-dimensional (2D) plane or three-dimensional (3D) space using a film-irradiation or detector-array measurement. Then, the errors are analyzed by comparing the measured data with data calculated using a treatment planning system (TPS). Although similar methods are used in the DQA process for volumetric arc therapy (VMAT), such as RapidArc (Varian Medical Systems, Palo Alto, USA), the 3D detector array device is more suitable than a simple 2D plane detector regarding the characteristics of arc therapy.⁶⁻⁹⁾

The conventional DQA process has the limitation that it measures and analyzes the dose in a phantom material and not in the body of the patient. To overcome this problem, special tools were developed for the calculation of the dose distribution in the bodies of patients using the measurement data in the DQA process.^{10,11)}

Most cases of VMAT were for prostate, head, and neck cancer, where the organ motion can be excluded and the results of the corresponding DQA process under the normal static conditions can be applied and analyzed equivalently in the case of patient. However, the conventional DQA of VMAT in a static status cannot be analyzed properly for lesions in the lung and liver, where the respiratory motional effect cannot be excluded. Although the error of the conventional DQA for the motional lesions can be minimized using the respiratory gated method, the DQA for VMAT planned based on the internal target volume (ITV), which includes all of the target motional range, has difficulty properly analyzing the motional effect. The conventional DQA measurements in the static status can only verify the mechanical and dosimetric accuracy of the treatment machine and cannot analyze the dosimetric changes under the motional organ condition.

Although a moving phantom can be used to simulate the respiratory organ motion, the dynamic measurement data with a DQA device placed on the moving phantom cannot be analyzed properly without the accurate dynamic dose calculation by the TPS. Although dynamic dose calculations that consider the motional effect have been studied, no appropriate program has been developed for use in clinical sites.¹²⁻¹⁴⁾ Moreover, the dynamic measurement and comparison in the phantom condition do not provide meaningful results, because the analysis of the dynamic-dose change in the body of patient is more important in the prognosis evaluation of ITV-based VMAT. Certain tools are used to reconstruct the dose distribution in the patient using the DQA measurement data. When these tools are used for ITV-based VMAT, we should consider that the ITV and planning organ at risk volume (PRV) are the virtual expanded volume and develop a method to analyze the dose variation in the real volume of the target and organ at risk (OAR).

In this study, a DQA method was designed to overcome

the limitations of the conventional DQA process in the static condition for ITV-based VMAT. The dynamic DQA measurement device was designed with a moving phantom that can simulate variable target motions. The dose distribution in the real volume of the target and OARs were reconstructed with the measurement data under the dynamic condition. Then, to evaluate the designed DQA method, the dose-volume histogram (DVH) data of the real target and OARs were compared with the DVHs calculated in the ITV-based VMAT plan.

Materials and Methods

1. Preparation of ITV-based RapidArc plans

A total of 10 VMAT plans were created using the computed tomography (CT) data of liver cancer patients who were treated using the IMRT method. The IMRT was delivered with a gated method and planned with CT data and structures delineated on the 50% phase CT images which were reconstructed from four-dimensional (4D) CT data. The ITV and PRVs for this study were created based on the target and OARs created in the previous gated IMRT plan. The 4D CT data were acquired using a BrightSpeed CT scanner (GE Medical Systems, Milwaukee, USA), and the retrospectively reconstructed 10-phase CT data were transferred to the MIM program (MIM Software Inc., Cleveland, OH) to generate the ITV and PRV. The CTV and OAR contours in the 50%-phase CT for the previous gated IMRT plan were propagated to the other phase CT using a deformable registration algorithm, and all the contours from each phase CT were combined into final ITV and PRV.

The Eclipse TPS (Varian Medical Systems, Palo Alto, USA) was employed, and RapidArc was used as a VMAT method. The analytical anisotropic algorithm (AAA) was used as the dose-calculation algorithm, and a 6-MV photon beam was used for the planning. The PTV was created similarly to the ITV, and 10 RapidArc plans comprised two plans with two full arcs, four plans with one full arc, and four plans with two half arcs. The treatment-delivery machine was a Novalis Tx (Varian Medical Systems, Palo Alto, USA).

The prescription dose to the PTV was 50 Gy, and it was applied in 25 fractions. The optimization constraints for

the PTV were that the 95% isodose (prescription), 47.5 Gy surface had to cover 90% of the PTV and that no portion of the PTV could receive more than 110% of the prescription dose. The PRVs considered during the optimization were the liver, kidney, and spinal cord. The liver constraint was that the volume irradiated with >30 Gy should comprise <30% of the total volume. The kidney constraint was that the volume irradiated with >20 Gy should comprise <20% of the total volume. The dose limit to the spinal cord was 45 Gy.

2. Creation of DQA plans

A DQA plan for each RapidArc plan was prepared using an ArcCHECK (SunNuclear, Melbourne, USA) device. The mechanical and dosimetric accuracy of treatment machine was evaluated by comparing the measured data in the usual static condition with the data calculated by the TPS. The error was evaluated according to the pass rate calculated using the gamma evaluation method, with a 3% dose difference and a 3 mm distance-to-agreement criteria.

The new DQA process was designed for the analysis of the dosimetric changes under a respiratory target motional condition. Initially, the period and range of respiratory motion were recorded for all patients using movie data generated by 4D CT, and the same period and range were applied for operating the dynamic phantom to realize coincident respiratory conditions in each patient. The Dynamic Platform Model 008PL (CIRS Inc., Norfolk, VA), which can simulate respiratory motions, was used to apply the same respiratory motional effects in each patient

during the ITV-based RapidArc. In this study, a single motional range in the superior-inferior (SI) direction was measured and applied to the phantom simulation because the dynamic phantom could move in only one direction, and the greatest changes in the respiratory motion usually occurred in the SI direction.

The ArcCHECK was placed on the moving phantom as shown Fig. 1, and the dose delivered by the RapidArc plan was measured under the motional-target conditions for each patient. When the reference dose calculated using an original ArcCHECK CT image was used for the comparison analysis, the dosimetric error increased because the measurement was performed under the condition that the ArcCHECK was placed on several plates of the moving phantom. The beam attenuation and dosimetric changes

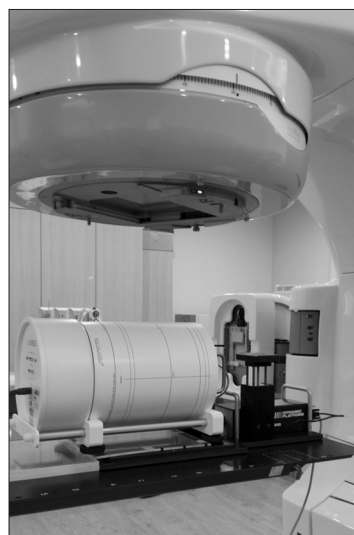


Fig. 1. ArcCHECK placed on the moving phantom for dynamic DQA process.

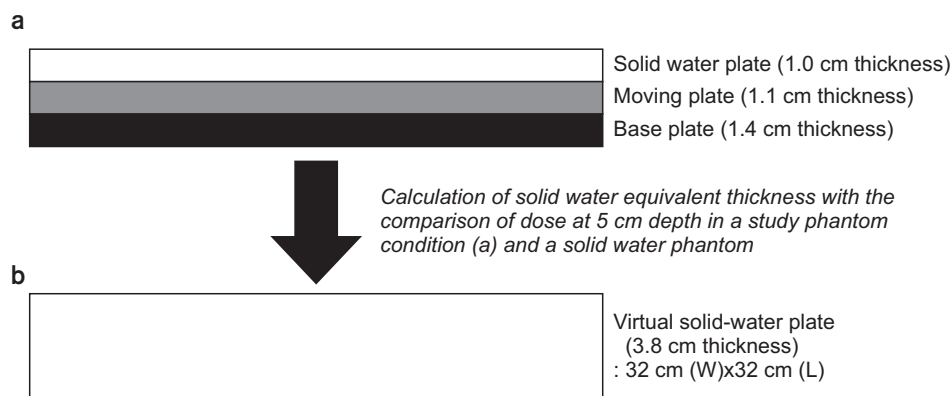


Fig. 2. Consideration of moving phantom plates in dose calculation: (a) Real structure of plates beneath ArcCHECK, (b) Virtual solid-water plate equivalent to three plates.

due to the plates beneath the ArcCHECK should be considered in the reference-dose calculation in the DQA planning process. The plates considered in this study were the base plate, the moving plate and the supporting plate, as shown in Fig. 2. A solid-water (SW) plate with a beam-attenuation effect equivalent to that of three plates was created according to the depth-dose measurement and thickness calculation. A virtual SW plate with the calculated thickness was inserted into the original ArcCHECK CT image and applied in the reference-dose calculation, which employed the same conditions as the measurement using

the moving phantom.

3. Patient dose calculation

The real dose distributions in the bodies of the patients were recalculated using the data measured by the ArcCHECK in the moving condition. A 3DVH (SunNuclear, Melbourne, USA) program was used for the recalculation of the dose in the patients. The virtual SW plate, which has an effect equivalent to that of the plates in the moving phantom, was applied to the CT of the patient to maintain

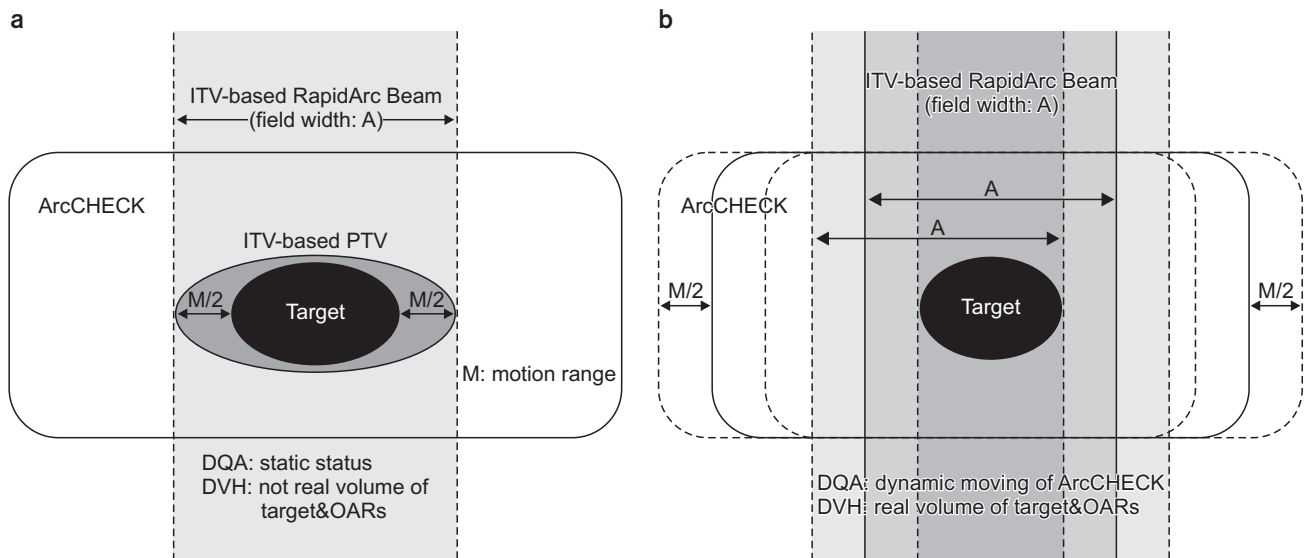


Fig. 3. RapidArc beam intensity which exhibit the same motion as the target and relatively equivalent condition of the target motion: (a) Real treatment condition in ITV-based RapidArc, (b) relatively equivalent condition by the application measured dose data using moving ArcCHECK.

Table 1. Volume comparison of target and OARs between ITV-based plan and Gated plan with information on the period and range of respiratory motion in each patient.

Patients	PTV [cm ³]		Liver [cm ³]		Lt-kidney [cm ³]		Rt-kidney [cm ³]		Respiration period [sec]	Respiratory motional range [cm]
	Gate-plan	ITV-plan	Gate-plan	ITV-plan	Gate-plan	ITV-plan	Gate-plan	ITV-plan		
A	642.0	711.2	1785.9	1965.9	238.8	270.2	196.8	221.2	8.5	1.7
B	273.8	327.8	1846.3	2073.9	145.8	170.7	141.9	155.7	5.0	1.8
C	49.5	58.7	1325.3	1471.7	161.3	191.5	153.0	174.5	5.5	1.3
D	61.9	86.6	965.3	1147.0	154.0	174.7	158.7	174.7	7.0	1.8
E	2021.9	2100.3	2506.2	2752.3	187.2	215.8	175.1	183.1	7.0	1.3
F	683.2	762.5	2005.1	2148.9	418.6	478.9	213.5	238.7	4.0	1.4
G	1133.9	1286.2	1453.4	1618.6	220.5	251.7	231.7	258.4	5.0	1.5
H	465.8	529.9	1326.1	1518.1	167.6	189.6	154.4	184.8	5.5	1.7
I	433.4	532.0	938.1	1115.9	201.2	239.9	165.2	199.5	7.0	1.8
J	440.6	527.8	1438.6	1726.8	147.5	190.4	156.2	196.8	6.0	1.2

the consistency between the measurement and calculation conditions. The structures for the target and OARs, which are delineated at 50%-phase CT, were applied instead of the ITV and PRVs in order to analyze the dose in the real volume of the target and OARs. The RapidArc beam intensity, which exhibited the same motion as the target, was realized with the measured data and assumed as a relatively equivalent condition of the target motion, as shown in Fig. 3. The DVHs of the real target and OARs were produced with a recalculated dose inside the patient and corrected in the real DVH values by excluding the effect of the virtual SW plate. To exclude the effect of the virtual SW plate, the dose difference between an original RapidArc and a RapidArc with a virtual SW plate was calculated in the Eclipse TPS. The difference was applied for the correction of the DVH values recalculated in the 3DVH program. The DVH values for the target and liver

were shifted as the dose difference corresponding to the 50% volume. The DVH of kidney was shifted as the dose difference corresponding to the 20% volume and the maximum dose difference was applied to the shift of the cord's DVH. The final corrected DVHs of the real volume of target and OARs under the respiratory moving conditions were analyzed by comparing the DVHs of the ITV and the PRVs calculated in an original ITV-based RapidArc plan.

Results

The ITV-based RapidArc plan volumes of the target and

Table 2. DQA results of the ArcCHECK measurement in a static condition.

Patients	A	B	C	D	E	F	G	H	I	J
Pass rate (%)	99.5	98.9	99.2	98.4	99.3	97.6	99.0	98.4	99.0	99.1

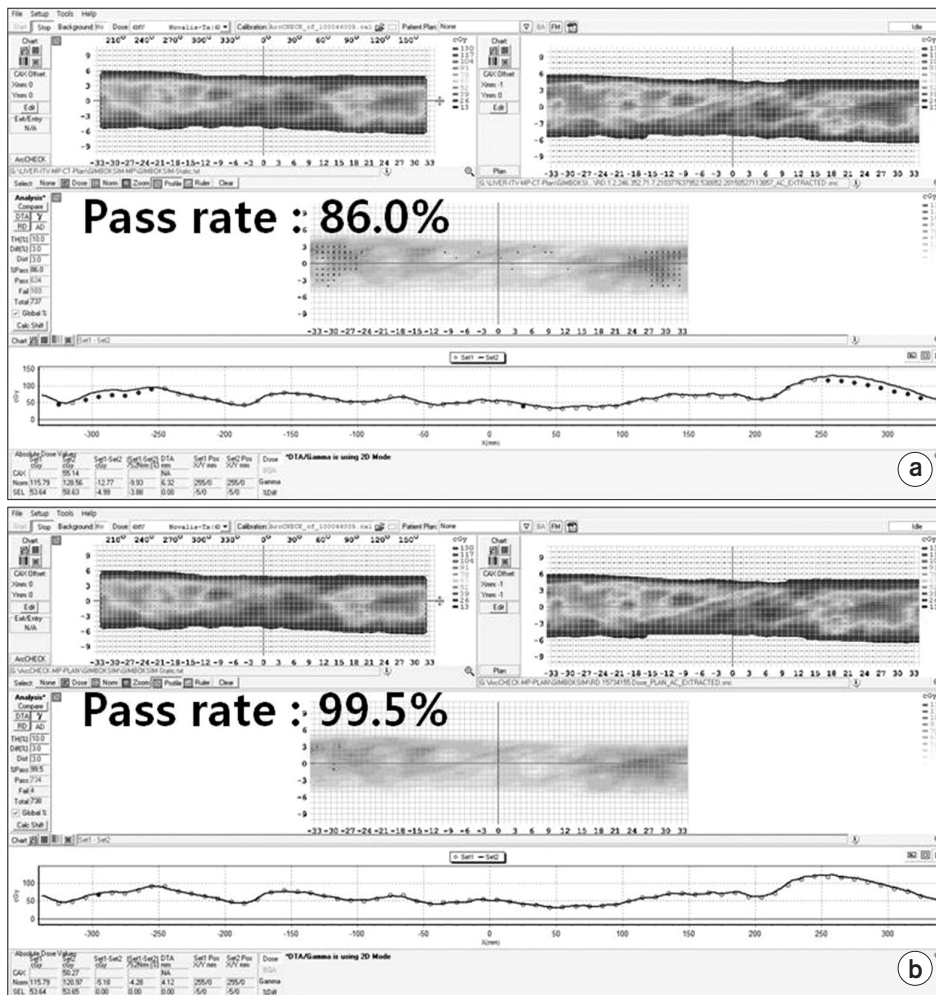


Fig. 4. Effect of moving phantom plates on the DQA error evaluation in patient (B): (a) Increased error due to the effect of the plates in moving phantom, (b) Reduce the error by the application of virtual solid-water plate in reference dose calculation.

Table 3. DQA error analysis according to the effect of virtual SW plate under the static and moving condition.

Patients	Pass rate in static condition (%)		Pass rate in moving condition & virtual SW plate apply (%)
	Not consider MP plate effect	Virtual SW plate apply	
A	89.1	99.2	79.7
B	86.0	99.5	75.3
C	88.7	99.5	81.8
D	88.7	99.5	73.7
E	70.3	99.1	91.1
F	74.5	96.8	85.1
G	82.2	100	95.8
H	85.5	97.6	67.6
I	82.3	99.3	92.7
J	83.7	98.4	72.7
Average±SD	83.10±6.26	98.89±0.99	81.55±9.48

OARs for 10 patients are listed in Table 1, along with the respiration periods and tumor motion ranges for each patient. The volume increase rate of the target and OARs compared with the volumes in 50%-phase CT for gated IMRT plans was confirmed.

The DQA results of the ArcCHECK measurement in a static condition are shown in Table 2. The average pass rate was 98.84±0.56%, which indicates the mechanical and dosimetric accuracy of the treatment machine.

Fig. 4 shows an example of the increased error due to the effect of the plates in the moving phantom in the static condition, when the plates were not considered in the reference dose calculation. The error can be decreased by employing the virtual SW plate in the dose calculation, as shown in Table 3. The average pass rate was 83.10±6.26% without considering the effect of the plates, and the average pass rate increased to 98.89±0.99% when the virtual SW plate was applied.

The average pass rate was 81.55±9.48% when the DQA dose was measured in the respiratory moving condition of the patient and the reference dose calculation with the application of the virtual SW plate. The increased error was inevitable in the comparison between the measured dose in the moving condition and the dose calculated in the static condition, indicating that the simple gamma evaluation of the dose data in the two different conditions was meaningless. To overcome this problem, the 3DVH program was used to calculate dose distribution in the patient under the moving condition. The dose measured

with a moving ArcCHECK was applied, and the dose in the real volume of the target and OARs was calculated, as shown in Fig. 5. The data for the 10 DVH cases show the calculated DVHs of the real target and OAR volumes according to the different respiratory motional patterns. The dashed lines in the DVH graph are the calculated values in the ITV-based RapidArc plan and show that variable dose differences can occur in the real volumes of the target and OARs under the moving organ condition.

Discussion

The conventional DQA method in a static condition for the ITV-based RapidArc has the limitation that it cannot analyze the dose variation in the real volume of the moving target and OARS but can only evaluate the mechanical and dosimetric accuracy of the treatment machine. In this study, the dynamically varying dose distribution was measured by the ArcCHECK placed on the moving phantom and was applied to the 3DVH program, which recalculated the dose inside the body of patient and analyzed the dose distribution of the real volume of the target and OARs to resolve the limitation.

When the calculated results for the 10 cases were compared with the corresponding reference ITV-based RapidArc plan, the calculated dose to a real target volume was slightly higher than the dose in the ITV-based RapidArc plan, except for one plan. Additionally, the dose differences in the real volume of the OARs varied according to the

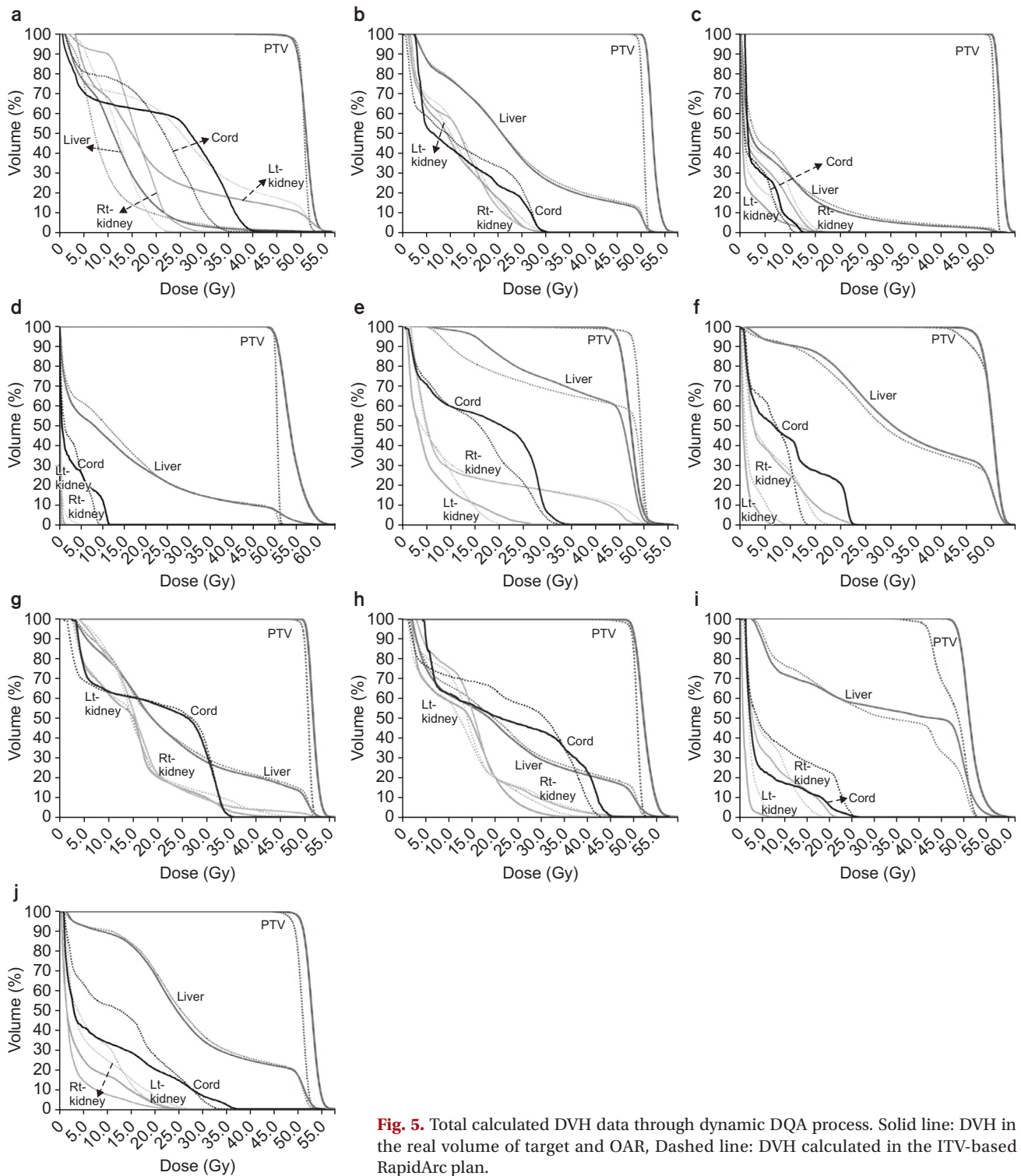


Fig. 5. Total calculated DVH data through dynamic DQA process. Solid line: DVH in the real volume of target and OAR, Dashed line: DVH calculated in the ITV-based RapidArc plan.

location of the target. Although the overall DVH exhibited a similar shape, a considerable change in the shape of the DVH was observed for some patients, including patient (a). The prescribed dose was planned for the ITV region,

yielding a high dose around the entire region of the ITV. The real target volume moving in the region of the ITV seemed to be sufficiently irradiated by the prescribed dose considering the relatively small volume compared with

the ITV, and we confirmed the valid dose coverage of a real target volume in the ITV-based RapidArc. The variable difference of the DVH of the OARs showed that dose variation can occur differently according to the location, shape, size and motion range of the target. This shows that dose analysis in the body of patients should be considered in ITV-based RapidArc in addition to the evaluation of conventional DQA results in the static condition.

The dynamic moving phantom used in this study could simulate the respiratory motion only in the SI direction, and further phantom study should be considered to simulate other motion directions, such as anterior-posterior and left-right, for further analysis of the motional effect.

In this study, a virtual SW plate was applied for the correction of the different conditions between the DQA measurement on the plates of the moving phantom and the original planning images in a real treatment couch table. Although the real dose should be calculated for the real couch table without the effect of the virtual SW plates, the 3DVH program used in this study could not exclude the virtual SW plate, as the consistency between the dose-measurement conditions and the separate dose calculation method for the removal of the effect of the virtual SW plate could not be designed in the 3DVH program. The difference was estimated according to the dose difference produced by applying the virtual SW plate to the dose calculation in the Eclipse TPS. The calculated dose in the 3DVH program considering a virtual SW plates was corrected by shifting a DVH dose curve with the acquired dose difference in the Eclipse TPS. This method involves a very simple estimation of the dosimetric change; a more detailed correction method should be investigated, and an additional analysis of the patient's dose change according to the period and range of respiratory motion should be performed.

Although the gating method to reduce the respiratory organ motional effect can be applied to the RapidArc, the possible dosimetric and mechanical error due to the stop-and-go motions of the heavy LINAC gantry can occur more than continuous treatment in the ITV-based RapidArc without the gating method.¹⁵⁻¹⁷⁾ Moreover, it should be considered that the gated RapidArc is difficult to apply to patients who cannot maintain a stable respiratory pa-

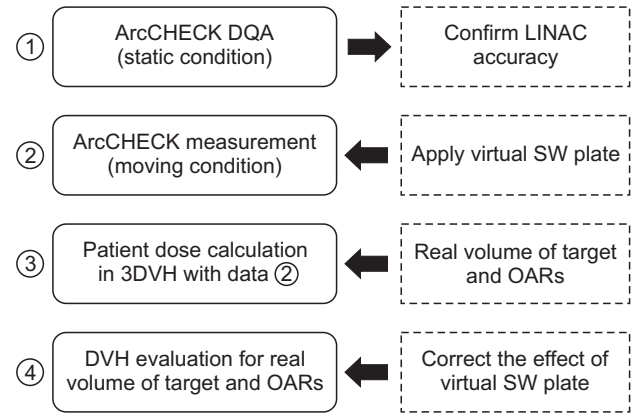


Fig. 6. Dynamic DQA process for ITV-based RapidArc designed in this study to evaluate DVH of the real volume of target and OARs.

tern. Thus, the RapidArc plan based on the accurately delineated ITV can be applied effectively for patients who have problems that are to be treated with the gating method.

The DQA process devised in this study, shown in Fig. 6, can effectively evaluate the DVH of the real volume of the target and OARs in a respiratory moving condition in addition to the simple verification of the accuracy of the treatment machine. This can be helpful to predict the prognosis of treatment by the accurate dose analysis in the real target and OARs.

Conclusion

The conventional DQA method in a static status for the ITV-based RapidArc, without a gating system, can only verify the mechanical and dosimetric accuracy of the treatment machine. An additional DQA method should be devised for evaluating the dosimetric characteristics in the real volume of the target and OARs under respiratory organ motion. The dynamic dose measurement using the moving phantom, which can simulate respiratory organ motions, and techniques employing the measured data to calculate the dose delivered to patients were devised in this study, and proper dose analysis was possible in the real volume of the target and OARs under the moving condition. The devised DQA process appears to be helpful for evaluating the real dosimetric effect of the target and OARs in the ITV-based RapidArc treatment.

Conflicts of Interest

The author has nothing to disclose.

Availability of Data and Materials

All relevant data are within the paper and its Supporting Information files.

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