Scientific Research Publishing
International Journal of Medical Physics, Clinical Engineering and Radiation Oncology, 2022, 11, 200-209
https://www.scirp.org/journal/ijmpcero
ISSN Online: 2168-5444
ISSN Print: 2168-5436

Evaluation of Patient-Specific Quality Assurance for Carbon Ion Radiotherapy Using Full Energy Scanning Method at QST Hospital

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How to cite this paper: Inomata, A., Katsumata, M., Lee, S.H., Suzuki, Y., Nakajima, T., Furuichi, W., Yamaoka, K., Yamamoto, A., Mizuno, H. and Kohno, R. (2022) Evaluation of Patient-Specific Quality Assurance for Carbon Ion Radiotherapy Using Full Energy Scanning Method at QST Hospital. *International Journal of Medical Physics, Clinical Engineering and Radiation Oncology*, **11**, 200-209.
https://doi.org/10.4236/ijmpcero.2022.114017

Received: September 26, 2022
Accepted: November 27, 2022
Published: November 30, 2022

Abstract

Purpose: Patient-specific QA (PSQA) measurements for carbon ion radiotherapy (CIRT) are critical components of processes designed to identify discrepancies between calculated and delivered doses. We report the results of PSQA conducted at the QST Hospital during the period from September 2017 to March 2018. **Methods:** We analyzed PSQA results for 1448 fields for 10 disease sites with various target volumes, target depths and number of energy layers. For the PSQA, all the planned beams were recalculated on a water phantom with treatment planning software. The recalculated dose distributions were compared with the measured distributions using a 2D ionization chamber array at three depths, including 95% of the area of the prescription dose. These recalculated dose distributions were evaluated using the 3%/3mm gamma index with a passing threshold of 90%. **Results:** The passing rates for prostate, head and neck, and bone and soft tissue were 96.8%, 99.3%, and 91.7%, respectively. Additionally, 94.7% of lung plans with low energy beams passed. Overall, the CIRT in the QST Hospital reached a high passing rate of more than 95%. Although the remaining 5% failed to pass, there was no dependence between measurement depth and disease sites in these failures. **Conclusion:** Using PSQA measurements, we confirmed consistency between the planned and delivered doses for CIRT using the full energy scanning method.

Keywords

Carbon Ion Radiotherapy, Full Energy Scanning, Patient-Specific Quality Assurance, Gamma Index

1. Introduction

Carbon ion radiotherapy (CIRT) with the passive beam method using the Heavy-Ion Medical Accelerator in Chiba (HIMAC) at the QST Hospital (formerly the National Institute of Radiological Sciences (NIRS) Hospital) began in 1994 [1]. CIRT with the scanning beam method [2], which is currently used in treatments, was started in 2011 at the QST Hospital. So far, treatments for more than 12,000 patients have been successfully carried out with carbon ion scanning beams at the hospital.

Since the scanning irradiation technique is a sophisticated method to deliver a highly conformal dose to the tumor volume, patient-specific quality assurance (PSQA) is necessary to validate the individual plan generated by the treatment planning system (TPS) and its delivery from the scanning beam delivery system [3] [4]. The QST Hospital has been carrying out the PSQA as a dosimetric verification for a hybrid raster-scanning method before therapeutic irradiation [5]. However, these PSQAs were verified for only 122 patients with 470 fields. Moreover, these patients were being treated for only four kinds of disease sites: prostate, bone and soft tissue, head and neck, and uterus.

Currently, more than 800 patients per year are being treated at the QST Hospital with carbon ions, not by using the previous hybrid raster-scanning method, but by using a new full-energy depth scanning method, which was initiated in 2015 [6]. The main targets for the treatment are: prostate cancer, bone and soft tissue, head and neck, lung, liver, pancreatic tumors, and retreatment of post-surgical locally recurrent rectal cancer [1]. Hence, many tumors for various sites have been treated by using the full-energy depth scanning method, and many PSQA results have been made for various sized tumors treated by the new method. However, their PSQA results had never been evaluated completely.

In this study, we summarize recent PSQA results from the QST facility obtained for more patients and more disease sites than previously reported. We analyzed PSQA results for 1448 fields of a total of 324 patients covering 10 different treatment sites, in order to ensure the safety of the CIRT treatment plans validated from the gamma index.

2. Materials and Methods

2.1. Patient Characteristics

From September 2017 to March 2018, we performed the PSQA procedure for 1448 treatment fields and 10 treatment sites of 324 patient treatment plans. **Table 1** summarizes the numbers of patients and fields by disease site. These data

Table 1. Summary of patient statistics.

Disease site	Number of patients (%)	Number of fields
Bone and soft tissue	50 (15.4)	217
Esophagus	10 (3.1)	49
Head and neck	38 (11.7)	270
Liver	17 (5.2)	33
Lung	26 (8.0)	94
Lymph node	7 (2.2)	25
Pancreas	34 (10.5)	127
Prostate	112 (34.6)	444
Rectum	26 (8.0)	163
Uterus	4 (1.2)	26

were obtained in accordance with the Declaration of Helsinki. The institutional ethics review board of the QST approved this study (number 19-023). The most treated site was the prostate and the second most was the bone and soft tissue. The number of fields depended on the disease site.

2.2. Full Energy Scanning Method and Treatment Planning

Each field was delivered by the full energy scanning method. The pencil beam was laterally scanned to get a lateral irradiation field with orthogonal scanning dipole magnets and then it was longitudinally scanned by the energy change through the accelerator itself [2]. In the case of the QST facility, a 201-step energy pattern in the full energy scanning method could change the energy ranging from 430 to 56 MeV/n. One energy step corresponded to a range shift of 2 or 3 mm and <100 ms was taken for 1 slice change. This provideda modulated dose delivery with beam-scanning velocities of 100 and 50 mm/ms at the isocenter. The accuracy of the scanned beam position was less than ±0.3 mm. The scanning magnets were controlled as a function of the spot weight detected by the dose-monitoring system.

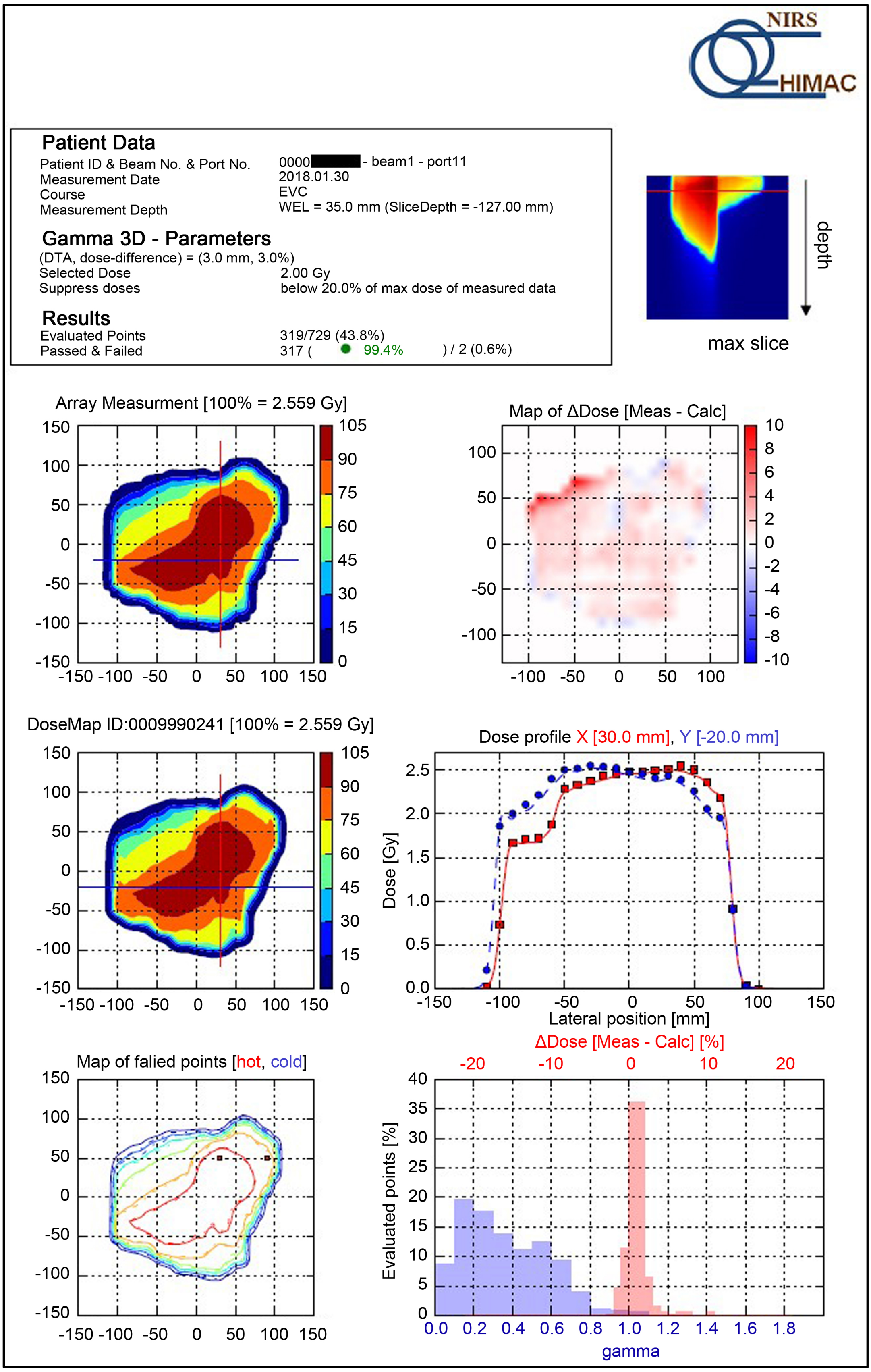
The beam scanning path and the deposit dose in each spot have been precisely determined in treatment planning to deliver the dose distribution planned. Treatment plans were designed with the treatment planning software XiDose (Elekta AB, Sweden). The XiDose was developed as part of our collaboration with Elekta AB for scanned carbon ion radiotherapy [7]. The analytical pencil beam algorithm with the trichrome beam model [8] in XiDose was adopted for patient dose calculations. Plans were developed using the single field uniform dose (SFUD), multiple field sequential optimization (MFSO) which sequentially optimizes multiple treatment fields, and intensity-modulated carbon ion radiotherapy (IMIT) which simultaneously optimizes multiple treatment fields. The numbers of treatment fields for the SFUD, MFSO, and IMIT were 1075, 272 and 101, respectively.

2.3. Patient Specific Quality Assurance Evaluation

The PSQA was performed prior to therapeutic irradiation. After making the treatment plan, the dose distribution was measured using the Octavius Detector 729 XDR (PTW Freiburg, Germany) which is a two-dimensional detector array with 729 equally spaced ionization chambers with a size of 0.5 × 0.5 × 0.5 cm^3 and a distance of 1 cm center-to-center and covering an active area of 27 × 27 cm^2. In this measurement, we also used the accordion-type water phantom "AVWP" (Accelerator Engineering Corporation, Chiba, Japan) for which the water-equivalent depth was freely adjustable from 30 to 300 mm (**Figure 1**). Each field was measured at three different depths: depth at the isocenter, and depths at proximal and distal parts within the planning target volume (PTV), which were predetermined in the treatment planning. We determined the measurement depths such that the region of 90% of the prescribed dose in the QA plan had an area of more than 2 cm × 2 cm.

The dose distributions were then compared with the dose distribution recalculated via the TPS for depth in the water. For comparison, gamma index analysis [9] was performed using the Shintiryoutou QA System (Penguin System Co., Ltd., Ibaraki, Japan). **Figure 2** is a typical PSQA report. The measured two-dimensional

Figure 1. Photo of the AEC accordion-typewater phantom (AVWP).



Patient Data

Patient ID & Beam No. & Port No. 0000[redacted]- beam1 - port11
Measurement Date 2018.01.30
Course EVC
Measurement Depth WEL = 35.0 mm (SliceDepth = -127.00 mm)

Gamma 3D - Parameters

(DTA, dose-difference) = (3.0 mm, 3.0%)
Selected Dose 2.00 Gy
Suppress doses below 20.0% of max dose of measured data

Results

Evaluated Points 319/729 (43.8%)
Passed & Failed 317 (● 99.4%) / 2 (0.6%)

Array Measurment [100% = 2.559 Gy]

Map of ΔDose [Meas - Calc]

DoseMap ID:0009990241 [100% = 2.559 Gy]

Dose profile X [30.0 mm], Y [-20.0 mm]

Map of falied points [hot, cold]

Figure 2. An example of a patient's QA report prepared by the Shintiryoutou QA system.

doses at the three different depths were compared with the dose at the same depths calculated by XiDose and evaluated by using the gamma index where dose tolerance and distance-to-agreement criteria were set to 3% and 3 mm. The clinical criterion required that more than 90% of the points evaluated via the gamma index must have a passing rate less than 1. Passing rate in this study was defined as the portion of passed irradiation fields which meets the clinical criterion for all irradiation fields of each disease site.

The PSQA results for 324 patients and for 1448 fields were analyzed to evaluate the validity of the PSQA criterion. First, the passing rates for each disease site were evaluated, and the percentages of the gamma index passed for the PTVs at all measurement depths were evaluated. Then, in order to understand the beam energy dependence of the passing rates for each site, we evaluated target depths in water for the failed plans, and the dependence of the passing rates for each site on the number of beam energy layers (scanning beam energy steps).

3. Results and Discussion

Table 2 summarizes passing rates for bone and soft tissue, esophagus, head and neck, liver, lung, lymph node, pancreas, prostate, rectum, and uterus. Average passing rate was 95.6%. It was clear that the CIRT in the QST Hospital had reached a high passing rate of more than 95%. Passing rates for the lymph node and liver were somewhat low, 88.0% and 90.9%, respectively. The number of failed treatment fields for the SFUD, MFSO and IMIT were 56, 3 and 4, respectively. Namely, failure rates of treatment fields for each irradiation method were only 5.2% (56/1075), 1.1% (3/272) and 3.9% (4/101). As a result, there were no differences in failure rates for the treatment fields among irradiation methods.

When the clinical criterion was not satisfied, medical physicists reviewed the PSQA result for the failed plan. For the QA plan with a steep depth-dose gradient, if necessary, the evaluation depth of the QA plan was shifted 1 - 2 mm back and forth for measurement again, and medical physicists re-analyzed the

Table 2. The passing rates for the ten disease sites considered in the study.

Disease site	Passing rate (%)
Bone and soft tissue	91.7
Esophagus	100.0
Head and neck	99.3
Liver	90.9
Lung	94.7
Lymph node	88.0
Pancreas	91.3
Prostate	96.8
Rectum	96.3
Uterus	96.2

result. Thus, they confirmed the phantom setup, the operation of the radiation detector, and the QA plan to investigate reasons for its failure. Finally, those failed results could be passed by the additional measurements with the 1 - 2 mm shift.

Figure 3 shows a scatter plot of gamma index passing percentages for PTVs at all measurement depths. Overall, 98.4% of the measurement depths had passing percentages greater than 90%. We could observe the tendency of the gamma index passing percentages for PTV sizes from this figure. Particularly, we also could confirm the trend for smaller PTV sizes. We expected that the number of elements measured from the 2D ionization chamber array would be small, if the tumor was small. Therefore, if one element failed, the gamma index passing rate would deteriorate significantly.

However, for 255 measurement depths for a small PTV size of less than 30 ml, there were 253 passing measurements. Of these, the smallest size and field were a volume of about 4 ml and a field of about 4 cm^2 for retreatment of prostate cancer. Since the minimum field size was 4 cm^2 (as 2 cm × 2 cm), the point doses were adequately measured. Namely, the passing rate was 99.2%, and this meant that the dose calculation algorithm in the TPS reproduced the measurements of carbon ions very well. The TPS defines the carbon ion beam spread as a three-Gaussian model, and it has been reported that results for this model agree well even for a small target [7]. In conclusion, we found that the PSQA results had no dependence on PTV size.

Figure 4 shows target depths for the failed treatment plans for all disease sites, except for the esophagus. Three measurement depths and failed depths are also shown in this figure. Depending on the site, it was obvious that each treatment

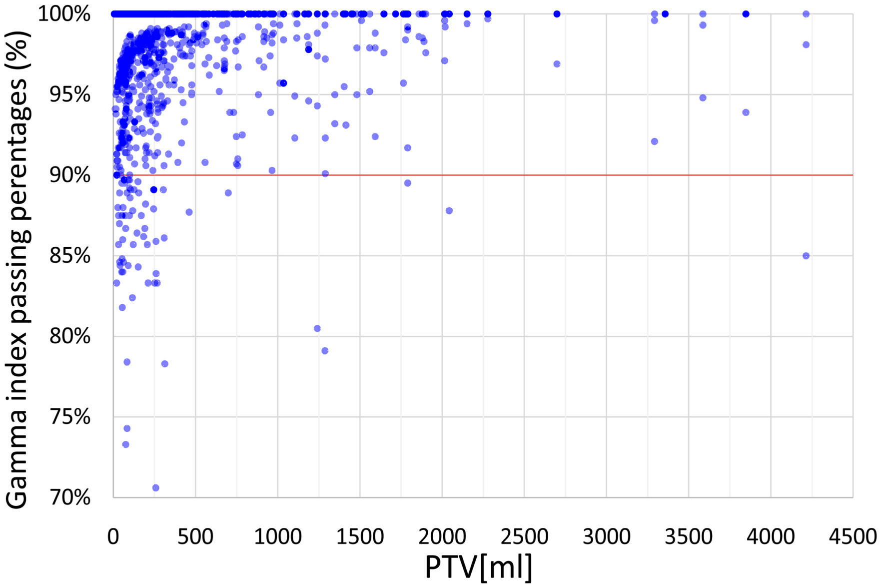


Figure 3. A scatter plot of gamma index passing percentages for PTVs at all measurement depths. The red horizontal line is the clinical pass criterion for the gamma index used in the QST Hospital.

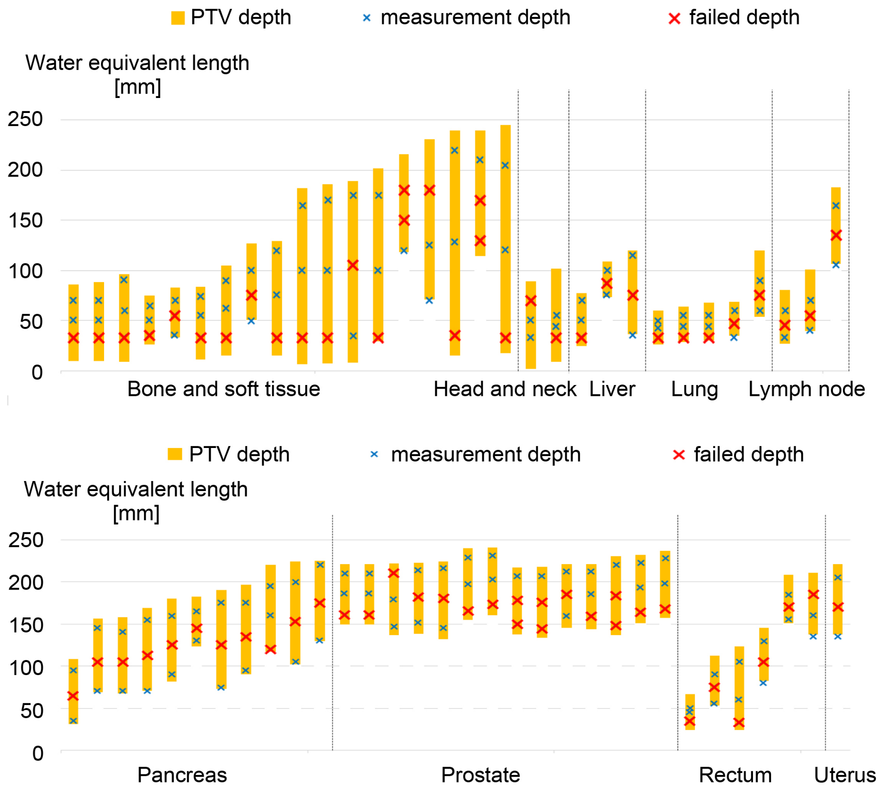


Figure 4. PTV depths for the failed treatment plans of the nine disease sites considered. Blue and red x marks indicate measurement depth and failed depth, respectively.

plan had various target depths. On the other hand, we could not find any simple tendency in the failed depths for each disease site.

The numbers of passed and failed measurement depths were 4276 and just 68. Their mean depths were 115.3 ± 62.3 and 106.3 ± 59.5 mm, respectively. Generally, PSQA measurements have been carried out at various measurement depths according to the target depth. Since carbon ions have the highest spot weight in the deepest part of the target through optimization that planned the clinical dose to the target, we had expected the failed depth would depend on the measurement depth for various targets. However, although half of the failed depths were the depths of the isocenter in the plans, we could not find a specific failed depth for treatment plans.

The number of energy layers used for passed or failed plans for tendisease sites is shown in **Figure 5**. Although many scanning beam energy layers for each site were used in the CIRT, we could not observe any difference for the boxes (*i.e.*, the interquartile range) between passed and failed plans. Namely, we found no dependence on the number of energy layers for the failed plans.

In this study, measured dose distributions were analyzed using the PSQA criterion, which was the 3%/3mm gamma index with a passing threshold of 90%. The overall passing rate was significantly high 95% for this criterion. No dependence on the disease sites, the PTV sizes and the number of energy layers was also found for the failed plans. We could confirm the accurate delivery dose for

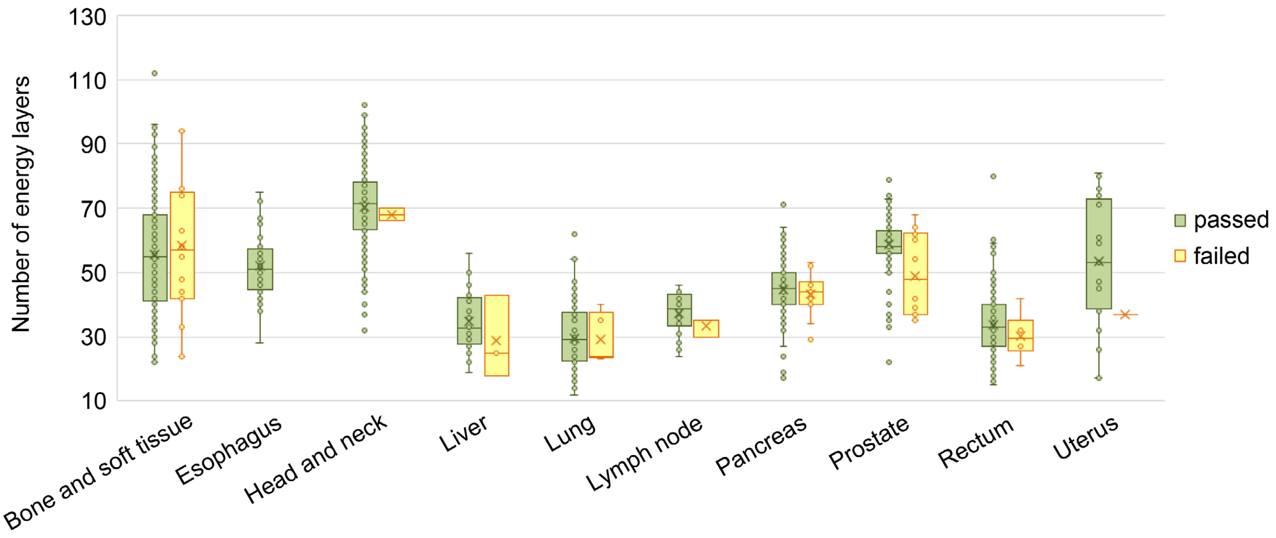


Figure 5. The number of energy layers used for passed or failed plans for the ten disease sites considered. The boxes represent the interquartile range, which is defined as the range of the 25% to 75% of the values. The whiskers represent the range of data that are within 1.5 times the interquartile range from the edge of the box. Outliers outside this range are represented as open circles. The solid lines in the middle of the boxes indicate the median values.

the CIRT and the reasonability of the criterion in the PSQA procedure.

On the other hand, about 800 patients/year and 50 patients/day have been treated by the CIRT at the QST Hospital. Moreover, the number of patients continues to increase every year. In order to treat more patients, we need to simplify the PSQA procedure. Actually, the PSQA measurements with three repeated irradiations at three measurement depths take 15 min for one treatment field. Namely, since the number of fields per one patient is more than two, it takes a lot more time to carry out the PSQA measurements per one patient. Li *et al.* [10] have reported that the treatment log file in a spot scanning system was precise enough to serve as a quality assurance tool to monitor variation in spot position and MU value. Using the log file in the CIRT can be expected to reduce the PSQA measurements time.

4. Conclusion

We analyzed the results of PSQA for CIRT using the full energy scanning method at the QST Hospital from September 2017 to March 2018. The overall passing rate was 95% for the criterion of the PSQA, which was the 3%/3mm gamma index with a passing threshold of 90%. In addition, we found that there was no dependency on disease sites or targets in these passing rates. Consequently, utilizing the PSQA measurements, we confirmed consistency between the planned and delivered doses for CIRT using the full energy scanning method.

Acknowledgements

This work was supported by JSPS KAKENHI Grant Number JP19K08188.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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