Experience on Commissioning the first Halcyon Linear Accelerator in China

Bo Yang
Peking Union Medical College Hospital
Lang Yu
Peking Union Medical College Hospital
Zhiqun Wang
Peking Union Medical College Hospital
Bei Wang
Peking Union Medical College Hospital
Wenbo Li
Peking Union Medical College Hospital
Jie Zhang
Peking Union Medical College Hospital
Xin Zhang
Varian Medical System in China
Zhufeng Wu
Varian Medical System in China
Zongkai Zhou
Varian Medical System in China
Hui Sui
Varian Medical System in China
Ke Hu
Peking Union Medical College Hospital
Fuquan Zhang
Peking Union Medical College Hospital
Jie Qiu (qj_ww@139.com)
Peking Union Medical College Hospital https://orcid.org/0000-0002-1795-7998

Research

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Abstract

Objective: This study is aimed to establish a proper clinical commissioning procedure for the Halcyon 1.0 linear accelerator (linac) with pre-configured reference beam data (RBD) set and to ensure the commissioning results meet the clinical treatment requirements.

Methods: Four parts were carried out during the commissioning work on the first Halcyon linac in China, which were according to the characteristics of this linac, the experience of the acceptance tests and commissioning procedure of our existing linacs and treatment planning systems (TPS), reports of AAPM & IAEA and relevant publications with the choice of appropriate quality assurance (QA) tools and procedures. These four aspects were as follows: 1. Commissioning of the Halcyon linac; 2. commissioning of the Eclipse TPS; 3. QA and quality control (QA & QC) of the Halcyon linac; 4. QA & QC of the Eclipse TPS and developing the corresponding procedures.

Results: The 3D radius of the isocenter of gantry and collimator rotation from Winston-Lutz test was 0.64mm, the coincidence of the virtual isocenter and the treatment isocenter was quite well, and the maximum travel position deviation was 0.7mm. Percentage Depth Doses (PDDs) was 63.3% at 10cm at the reference setup and the tolerance was within 1%. The Machine Performance Check (MPC) results were within the relevant tolerance, and the gantry isocenter size measured from MPC test was 0.67mm. The pre-configured beam model data was in agreement with the measured data. In the process of rotation, the speed of gantry rotation and multi-leaf collimator (MLC) movement and the control of dose rate were all accurate with all deviations were controlled below 2%. The CT values of Surface and Interior of the carbon fiber treatment couch were -750HU and -950HU, respectively. All MPPG 5.a recommended regular field gamma compare tests met the requirements. The task group 119 test was also performed on Halcyon, the point dose difference for intensity-modulated radiation therapy (IMRT) and RapidArc techniques were -0.003 ± 0.011 and - 0.012 ± 0.006, respectively, with confidence limits of 0.025 and 0.024.

Conclusion: The measured data of the Halcyon linac are in good consistency with the pre-configured beam model data in Eclipse TPS. The commissioning results of the IMRT technique and the RapicArc technique are all within the tolerance ranges recommended by AAPM and relevant publications, which could meet the needs of clinical requirements. The pre-configured data can facilitate the commissioning work and the validation and replace fully collecting beam data, which will be the trend of the commissioning of linac in the future.

1. Introduction

Varian Halcyon linear accelerator (linac) is a newly designed model based on the Truebeam platform, which has the characteristics of conventional C-arm linac, CT machine and Tomography[1, 2]. The Varian Halcyon linac is designed with an enclosed, ring-mounted gantry and a 6 MV flattening filter free (FFF) beam, 800MU/min dose rate. Halcyon version 1.0 uses this dose rate for both treatment and image guidance. Given the safety features of enclosed gantry, the gantry can rotate with a maximum speed of 4 rpm. For Halcyon version 1.0, the maximum field size is 28 cm × 28 cm at isocenter, and equipped with a dual-layered, staked multi-leaf collimator (MLC)[3], the leaf width is 1 cm and the maximum movement speed is 5 cm/sec[4, 5].

The treatment workflow of the Halcyon linac is different from the conventional C-arm linacs[6]. For Halcyon, the patient (or physics QA equipment) is first positioned using lasers outside of the Halcyon gantry housing. The couch is then translated into the bore by a specific distance, moving the patient to the treatment position. Varian provides a Representative Beam Data set (RBD) for the Eclipse treatment planning system (TPS). The RBD should perform consistent verification in the commissioning program.

At present, relevant institutions at home and abroad have not yet released the clinical commissioning guidance of the Halcyon linac, we worked together with Varian and other relevant technical personnel, based on the reference reports of the American association of physicists in medicine (AAPM) and international atomic energy agency (IAEA), and relevant publications. After continuous efforts during the commissioning process, we developed a commissioning procedure for the Halcyon linac, which was the first experience in China. The purpose of this study was to establish an appropriate clinical commissioning procedure for Halcyon 1.0 linac with pre-configured RBD, thus ensuring that the commissioning results met the clinical treatment requirements.

2. Materials And Methods

2.A. Contents of Commissioning

The commissioning of Halcyon 1.0 linac mainly consisted of the following four parts: a) the commissioning for the Halcyon linac, b) the commissioning for the Eclipse TPS; c) the quality assurance and quality control (QA & QC) of the Halcyon linac;d) the QA&QC of the Eclipse TPS, and establish the corresponding procedures. All test methods are based on the guidance of AAPM, IAEA and relevant publications[7–14]. Due to the limitations of the mechanical structure and size of the treatment bore, users should pay special attention to the choice of QC devices. The QA tools used by our institution are displayed in Table I (linac QA) and Table II (TPS QA).

3. Key Points Of The Commissioning

3.A. Commissioning of the Halcyon linac

Unlike the conventional Installation Product Acceptance (IPA) of Varian C-arm linac, the IPA of Halcyon linac, besides MPC, does not involve some regular tests such as third-party mechanical test, 3D water tank test and image quality test. Although MPC covers radiation beam modeling, gantry angle, collimator angle, couch positioning accuracy and MLC positioning accuracy, they are all based on the QC equipment and methods provided by the vendor itself, which is not sufficient to support clinical treatment and the setup of baseline of QC procedures. The conducted comprehensive test of the following items, and the preformed tests were shown in Table I, which was according to our experience of the acceptance test of linacs, relevant reports of AAPM&IAEA, domestic and international publications[7, 9, 10, 13, 14] and the features of the Halcyon linac.

3.B. Commissioning of the Eclipse TPS

Based on the recommendation of AAPM MPPG 5.a[8], the commissioning of the planning system includes three parts: data collection, beam modeling and model validation. Since the Eclipse TPS of Halcyon linac is preconfigured with RBD data, which can replace the work of beam data collection and beam modeling, only model validation is necessary[15]. However, MPPG 5.a[8] recommended testing is listed as the regular testing for its clinical application. To improve the validation, the following tests were conducted according to our commissioning experience and relevant AAPM and IAEA planning system acceptance reports[8, 11, 12], which was displayed in Table II.

3.C. QA&QC procedure for the Halcyon linac

The Halcyon linac QA&QC procedure is designed on the basis of AAPM report[7, 14], relevant literature recommendation and the Halcyon linac commissioning baseline. At the meantime, requirements for fast test and quantitative analysis are considered. Given the features of the design of EPID and the importance of image quality in the workflow of QC, image quality is the focus of QA&QC. Compared with C-arm linac, the Halcyon linac has great differences concerning quantity and speed of daily patient treatment. The frequency of QA and QC should be changed. Currently, the same QC frequency of C-arm linac were performed only by following the recommended method of AAPM task group (TG) 142[14], including daily, monthly and annual tests. And the detail information of Halcyon linac QC was shown in Table III.

3.D. QA&QC Procedures for Eclipse TPS

Different from the conventional TPS, the machine parameters and beam data of Eclipse TPS for Halcyon linac cannot be modified, which could improve the safety of data and calculation. According to MPPG 5.a[8], only parts of its contents need to be tested randomly every year. Comparing the differences of calculation results, the deviation was controlled within 1%, and the annual tests were MPPG 5.a[8] regular data test, TG119 test[12], PSQA random test.

4. Results

4.A. Clinical Commissioning Results of the Halcyon Linac

All safety interlock checks operated normally to ensure radiation safety during linac operation. The highest radiation region of the vault was located at the back side of the linac, with a radiation level of 0.530usv/h, which was better than the national standard of 2.5usv/h, and the safety protection complied with relevant criteria[16].

The 3D radius of the isocenter gantry rotation was 0.69mm, and the maximum positioning deviation was 0.86mm at 225.The rotation radius of the collimator was 0.07mm, and the 3D radius of isocenter of the gantry and collimator was 0.64mm. The 3D radius of isocenter of the gantry and collimator was displayed in Fig. 1, all of which exceeding the acceptance standard of 1 mm.MLC had high accuracy in positioning, and the positioning accuracy was <1mm from 2cm×2cm to 28cm×28cm. The 0 indication of the gantry and collimator was 0.2, and the 0 deviation of the treatment couch<0.3mm. The extreme position of the treatment couch movement was -47.50cm-0cm, left and right -20.88cm -20.88cm, and 53.5cm-219cm in and out of the bed. The treatment couch moved in three-dimensional direction with accuracy <1 mm. All carbon fiber treatment couch had good rigidity. Under the load of 120 kg, the settlement was 1.7mm and the inclination angle was 0.7. The deviation between the treatment couch center and the field center gradually increased with the movement of the treatment couch, with the maximum deviation of 1.4mm. The virtual isocenter had good coincidence with the treatment center, with a maximum positioning deviation of 0.7mm. The EPID board was a fixed assembly. The maximum deviation between the four main directions and the radiation center was 0.2mm, which was better than the standard of 1mm for the C-arm linacs.

Under regular operation, for the Halcyon linac, the PDD10 was 63.3%, within the tolerance range of 1%, the PDD20/PDD10 was 0.542, which was softer than the conventional C-arm linac's 6MV beam quality. The symmetry of 10cm×10cm and 28cm×28cm radiation fields was 100.3%, the maximum radiation field depth was 10cm, and the average relative dose percentage at 10cm off axis was 78.83%. MU>2, dose rate linearity difference was within 1%, MU<2 linearity difference was within 2%. The output dose difference was within 0.1% at different angles and during rotation of the gantry. The absolute dose scale deviation was 3.7%, and the adjustment range was controlled within 5% of the default set value.

MPC results were all within the tolerance, and the isocenter size was 0.67mm, which was close to Doselab analysis results (0.64mm). The maximum deviation of treatment couch positioning was 0.14mm, and the maximum deviation of inner and outer isocenter was 0.21mm.

The predefined modeling data was in good agreement with the measured data. For PDD and off-axis ratio curves with different field sizes, the γ pass rate was greater than 99.5% using 1mm/1% analysis standard. The output factor was within the range of 1% except that the deviation of 2cm×2cm field was 1.2%.MLC measured penetration factor was 0.009%, DLG was 0.18mm, which was quite different from pre-defined data of 0.0047% and 0.1mm.

Rapidarc commissioning shows that the dynamic and static dose differences were within 0.1%, and the maximum deviation of DMLC dose was at 90°, 1.84%. The maximum positioning deviation of MLC in static of different angles and during rotation process was 0.6mm, which was better than the acceptance standard of 1mm. During the rotation process, the control of gantry speed, MLC movement speed and dose rate had good accuracy, and all deviations were controlled within 2%.

Image guidance was divided into 2D (High quality and Low dose) and 3D (High quality and Low dose) modes. See Table IV and Table V for image quality results and Table VI for image dose results. Fig.2 showed the 3D Image quality test results.

4.B. Commissioning Results of Eclipse TPS

According to the CT-SIM scanning conditions of different sites, four CT value-electron density conversion curves of head, chest, abdomen and pelvic cavity were created respectively, and the physical density range was 0.2-4.6g/cc. CT values of Surface and Interior of carbon fiber treatment couch were -750HU and -950HU respectively.

Concerning tests of MPPG 5.a[8], for 5.3 regular field, the dose differences of square fields and rectangular fields of different SSD were within 1%, except the point dose differences of 2cm×2cm field point was 1.7%. For 5.4 MLC small field, 5.5 cape field measurement, 5.8 oblique incidence and 7.2 intensity modulated MLC segments, the difference of point dose were all within 1%; For 5.6 the longest distance across the midline, 5.7 asymmetric field and minimum SSD, the different of point dose were within 2%, and the PDD and Profile curves of the above test results, 2mm/2%γ pass rate were all above 99.5%. 6.2 heterogeneous phantom test, Rapidarc and IMRT E-T-E test, the dose differences were 2.02% and 2.38% respectively, which exceeding the test standard of 3%.

In TG119 intensity modulation test[12], the point dose differences of IMRT and Rapidarc were -0.003±0.011 and-0.012±0.006 respectively, the confidence limits were 0.025 and 0.024, respectively. Arccheck surface dose test, the average passing rates of 3mm/3% and 2mm/2%γ were: 99.72% ±0.24,96.80%±1.17,99.70%±0.45 and 2%/2mm respectively, and the corresponding confidence limits were 0.75 and 1.19, 5.49 and 10.31, respectively. Portal Dosimetry test showed that the average pass rate of 2mm/2%γ was 98.80% ±0.01 and 96.60% ±0.02, respectively. The C-shape hard portal dosimetry test results were displayed in Fig. 3.

4.C. Results of QA&QC procedures for the Halcyon linac.

According to the characteristics of Halcyon linac and relevant publications of AAPM, three types of test were set up frequency, which were daily test, monthly test and annual test, respectively. The test consisted of six major parts, including dose test, mechanical test, image test, Rapidarc test, MPC and safety interlock test. The stability of test results would be reported in future articles.

4.D. Eclipse TPS QA&QC procedure results

The Eclipse TPS for the Halcyon linac was mainly tested based on MPPG 5.a[8]. Since the system has not yet reached the time of annual test, the results of annual tests will be reported in future articles.

5. Discussion

Different from other linacs, the Halcyon linac is provided with a standard data set and pre-configured TPS by the vendor. As we were not sure whether the intensity modulation results generated by the system could meet the clinical treatment requirements and comply with relevant international criteria. In order to validate the treatment accuracy of the workflow, the four commissioning procedures mentioned above were set up.

Compared with the conventional C-arm linacs, the Halcyon linac has fewer IPA test, and tests conducted by the three-dimensional water tank are replaced by the two-dimensional matrix. Although it has been reported in the literature that the two-dimensional matrix is similar with the three-dimensional water tank in terms of beam modeling test[17], [12] however, according to the recommendations of AAPM and international commission on radiation units and measurements, we still recommends to use the three-dimensional water tank for beam modeling test. The tests are relatively few. For example, whether it is necessary to add relevant tests such as regular mechanical isocenter and couch positioning accuracy to IPA, whether the testing contents and results of MPC can replace the testing tools of third parties, still needs further verification.

MPC is fast, convenient and covers a wide range of tests[18]. It mainly checks five parts: radiation beam modeling, gantry angle, collimator angle, couch positioning accuracy and MLC positioning accuracy[18]. However, Varian suggests that this test to be used as a comprehensive constancy check only, instead of replacing third-party QC tools. Recently, some international research institutions start to check if MPC and independent third-party QC tools can be replaced by each other, as the preliminary research results reports, some tests of MPC can be alternatives to some independent third-party QC tools[18, 2].

Varian provided beam data for Halcyon linac and pre-defined Eclipse TPS, reducing the time for data collection and modeling. Compared with the conventional TPS, Varian provides beam modeling data and pre-configued Eclipse TPS, which ensure the consistency and accuracy of data, eliminate the probability of errors on-site, and reduce the workload and time of commissioning for physicists[19]. In order to improve the working efficiency and accuracy during the commissioning process, it is suggested that for Halcyon Linac, Varian should provide the users with standard verification phantom, CT phantom image, electron density conversion curve and standard plan (such as TG119[12]) to further reduce the potential of errors and improve commissioning accuracy and speed. However, many physicists questioned the accuracy of this set of data. This set of data is different from the "golden standard" of the conventional C-arm linacs. The collection of this set of data is recommended by AAPM TG106 Report[10], and appropriate detectors, such as SNCEDGE detector and IBA CC13 detector, are selected for curve scanning with different field sizes, which can improve the accuracy of data collection. This method may also be the trend of the C-arm linacs commissioning in the future to reduce the systematic error caused by the differences of measuring equipment and physicists.

At present, the standard for the commissioning procedures of Halcyon linac and Eclipse planning system has not reached agreement yet. The commissioning tests, standard and methods are varied from hospital to hospital, with great differences. At present, most hospitals in China set up their own commissioning procedures based on IPA, relevant AAPM, IAEA reports and literature recommendations. The average commissioning time for a single energy is about one month. However, for Halcyon linacs, there is good consistency between different devices and comprehensive MPC analysis and other testing methods are available. Whether we need to conduct a full-scale test or only carry out spot checks on some key items needs to be verified by multi-center research.

Compared with the AAPM TG142 report[14], the Halcyon linac QA&QC skips the weekly check of MLC, due to the following three reasons: Firstly, the current new MLC's positioning accuracy and long-term constancy have been greatly improved compared with previous generations of MLC at the time the TG142 report[14] was issued. Secondly the monthly QA&QC test of Rapidarc technique has add extra test contents of MLC. Thirdly, if MLCs are not in good operation condition, the problem will reflect on the test result of the weekly PSQA testing.

MPPG 5.a[8] recommends that IROC credentialing test should be carried out before patients are treated. However, there are almost no hospitals in China to carry out this test before linacs are put into clinical use. Some hospitals may carry out IROC credentialing test as participating in some international research program. Absolute dose test is conducted by the Ministry of Radiation Safety for second check, the rest tests are all completed by hospital physicists themselves. If there are systematic errors during the commissioning process, it is difficult to detect the problems for most physicists. Therefore, if possible, it is recommended to participate in IROC credentialing test for further verification. We also call on relevant government ministries in China to organize and promote domestic credentialing test.

6. Conclusion

We established an appropriate clinical commissioning procedure for Halcyon1.0 linac. It is recommended to use the three-dimensional water tank for beam modeling test. The MPC test cannot replace the third-party QC tools, but only as a comprehensive constancy check. The participate in IROC credentialing test is an important supplement for commissioning. For hospital physicists, the main focus of the commissioning will be on the important features, such as, the high speed of gantry rotation and MLC motion, distance between virtual isocenter and treatment isocenter, and the pre-configured beam model, etc.

Declarations

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Conflict of interest disclosures:

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Research involving human participants and/or animals:

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Informed consent:

Not applicable. This study is an experience on commissioning the Halcyon linac.

Availability of data and material:

Data and material can be obtained upon request.

Ethical Statement:

The authors are accountable for all aspects of the work in ensuring that questions related to the accuracy or integrity of any part of the work are appropriately investigated and resolved.

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Tables

Table I

Test procedures, performed projects and measurement & QA tools for clinical commissioning of the Halcyon linac

Test procedures	Performed projects	Measurement Tools
Safety check	Door interlock, audio intercom, video monitor, radiation monitor, radiation on light, emergency switch, control buttons at console, anti-collision interlock	None
Radiation protection	Radiation level measurement of the vault	Ion chamber survey meter
Mechanical characterization	Gantry isocenter, collimater isocenter, isocenter of gantry and collimator, MLC field accuracy, gantry, 0 position check of collimator & couch, extreme position and accuracy of couch movement,couch rigidity check, coincidence of centers between couch and field, laser accuracy, deviation of centers of EPID and field, digital indicators’ offset of gantry and collimater	EPID, Doselab software and associated phantom, level bar, ruler, lead point and Penta Guide phantom
Radiation Beam Characterization	Radiation quality, symmetry and maximum field off-axis ratio, MU2 constancy, dose rate output constancy, MU linearity check, dose rate constancy under gantry rotation, output dose constancy under gantry rotation and gantry at different angles, profile constancy under gantry rotation and gantry at different angles, reproducibility test, daily/weekly constancy, constancy after high-dose irradiation, output volume and exposure field change relationship, surface dose, dose calculation and calibration	Blue Phantom^2 water tank，CC13，PFD，SFD，RFD chambers，solid water；1D water tank，FC65G ion-chamber，paralleled-plane chamber，electrometer，EPID，Doselab software
Machine Performance Check(MPC)	Isocenter size, isocenter projection (or MV Imager position) offset, MLC leaf positioning accuracy, MLC backlash, collimator rotational accuracy,Y field edges accuracy, absolute gantry positioning accuracy, relative gantry positioning accuracy, relative couch positioning accuracy (3 directions), virtual to treatment isocenter accuracy, couch shift accuracy, beam output change, beam uniformity change, cumulative gain change in ion chambers for MU1 and MU2	Drum phantom
Pre-configured modeling dosimetry check	Percentage Depth Doses (PDDs), output factors, profiles at different depth, MLC dosimetric leaf gap (DLG) & Transmission check	Blue phantom^2 3D, CC13, CC01, PDF, SFD and RFD ion chamber, FC65G ion chamber, electrometer
Rapidarc commissioning	Comparison of dynamic dose and static dose, dynamic multi-leaf collimator (DMLC) dose, DMLC positioning accuracy at different angles, DMLC positioning accuracy during gantry rotation, DMLC error during rotation, accuracy of dose rate control during rotation, gantry speed control accuracy during rotation, leaf speed control accuracy	EPID，Doselab，Build-up cap,FC-65G ion chamber, electrometer

Image Quality test	2D image: spatial resolution and density resolution, Scaling discrepancy, EPID dark field image, EPID image noise, EPID pixel value correction, EPID dose linearity, Mobius MC2 2D image doselab software automatic analysis, 2D / 2D image registration, image dose; 3D image: CT value accuracy, spatial resolution & density resolution, spatial position reconstruction accuracy, layer thickness reconstruction accuracy, CT value uniformity, image noise, automatic analysis using Catphan504 3D image doselab software, 3D / 3D image registration, image dose	EPID, Las Vegas phantom, Cube phantom, Doselab software and phantom, MVP phantom, Catphan CTP504 phantom, Penta Guide phantom

Table II

Test procedures, performed projects and measurement & QA tools for clinical commissioning of the Eclipse TPS

Test procedures	Performed projects	Measurement Tools
Setup of electron density curve	Correspondence between CT Value and Electron Density	CIRS CT-ED electron density conversion phantom
Modeling and Calibration of QC phantom	Arccheck, MVP phantom CT Scan, setup of phantom modeling	MVP phantom, CC13 ion chamber, electrometer, solid water, Arccheck
Treatment couch attenuation test	CT Value of treatment couch	Solid water, CC13 ion chamber, electrometer
MPPG 5.a recommending regular field tests	Modelling, tests of different SSD, square field, rectangular field, MLC small field, mantle field, cross-midline maximum, asymmetric field-small head rotation, oblique incidence, electron density curve confirmation, non-mean phantom point dose measurement with different technologies, extrapolation field 1cm x 2cm, intensity modulated field lightning field and banana field	Blue Phantom² three-dimensional water tank, CC13, CC01, PFD, SFD, RFD ionization chamber, FC65G ionization chamber, electrometer
Task Group 119 test	Different techniques, multi- target volume, prostate, head and neck, "C" target volume (easy-difficult) point dose and surface dose test and setup of confidence limit	MVP phantom, CC13 ionization chamber, electrometer, solid water, Arccheck
PSQA test	Three cases of each techniques of head, chest, abdomen and pelvic cavity, point dose and surface dose test and confidence limits setup	MVP phantom, CC13 ion chamber, electrometer, Arccheck, EPID
End to End (E-2-E) test	E-2-E test of different techniques, using CIRS chest phantom	CIRS chest phantom, CC13 ion chamber, electrometer

Table III
Frequency and test projects for the QA&QC of linac

Frequency	Test projects
Daily test	MPC, Rapidarc fixed plan PD test
Monthly test	Dose test, mechanical test, imaging test, Rapidarc test, MPC, safety interlock test
Annual test	Dose test, mechanical test, imaging test, Rapidarc test, MPC, safety interlock test

Table IV
Tests and Results of 2D Image Quality

Test projects	2D High quality	2D Low dose
Spatial resolution	0.44lp/mm	0.42 lp/mm
Density resolution	26.0%	26.1%
Scaling discrepancy	0.8mm	0.8 mm
Uniformity	98.9%	98.8%
CNR	42	9.8

Table V
Tests and Results of 3D Image Quality

Test projects		3D High Quality	3D Low dose
Spatial resolution		0.2lp/mm	0.27lp/mm
Density resolution		11%	9.3%
Scaling discrepancy		0.2mm	0.2mm
Uniformity		95.1%	93.2%
CNR		3.4	1.8
geometric distortion		0.3	0.4
CT value accuracy	Air	-883.8	-902
	PMP	-183.6	-179
	LDPE	-99.7	-110.5
	Polystyrene	-58.7	-58
	Acrylic	61.7	56
	Delin	282.8	262.1
	Teflon	938.2	896.8
Uniformity of CT values in different positions	center	96.2%	93.7%
	up	95.9%	93.6%
	down	95.9%	93.8%
	left	95.7%	93.7%
	right	96.6%	94.5%

Table VI
Image Dose Results under Different Modes and Maximum Fields.

Items	Field size	High quality	Low dose
MVCBCT	28cm×28cm	6.568	3.248
MV-MV	28cm×28cm	2.815	1.393

Figures

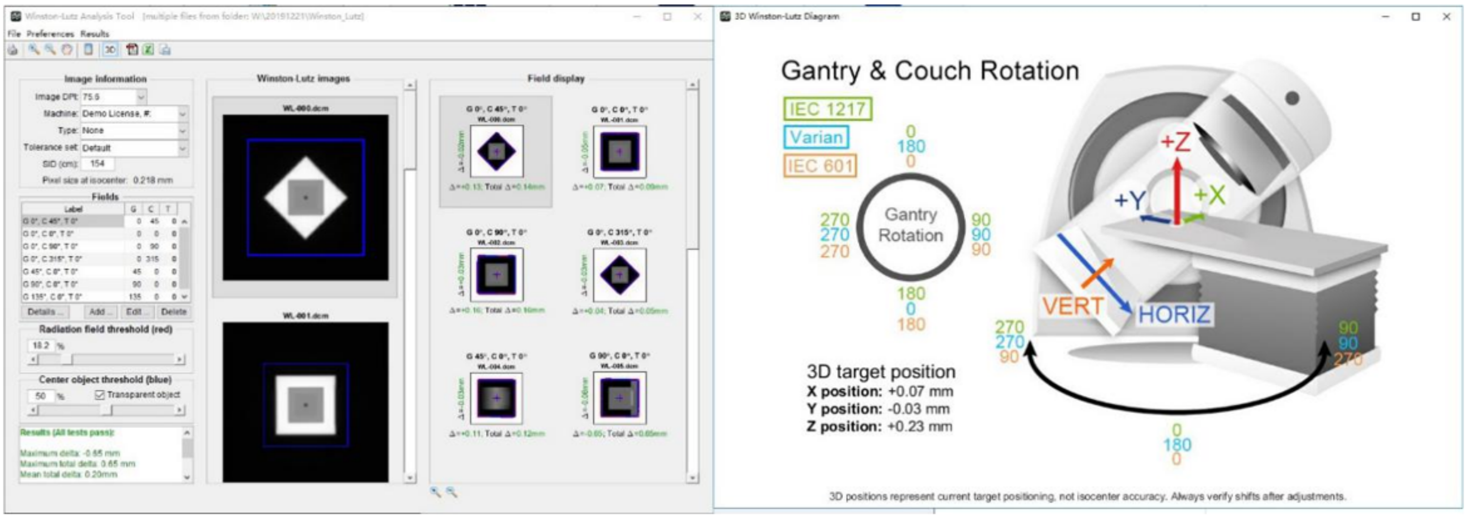

Figure 1

the 3D radius of isocenter of the gantry and collimator.

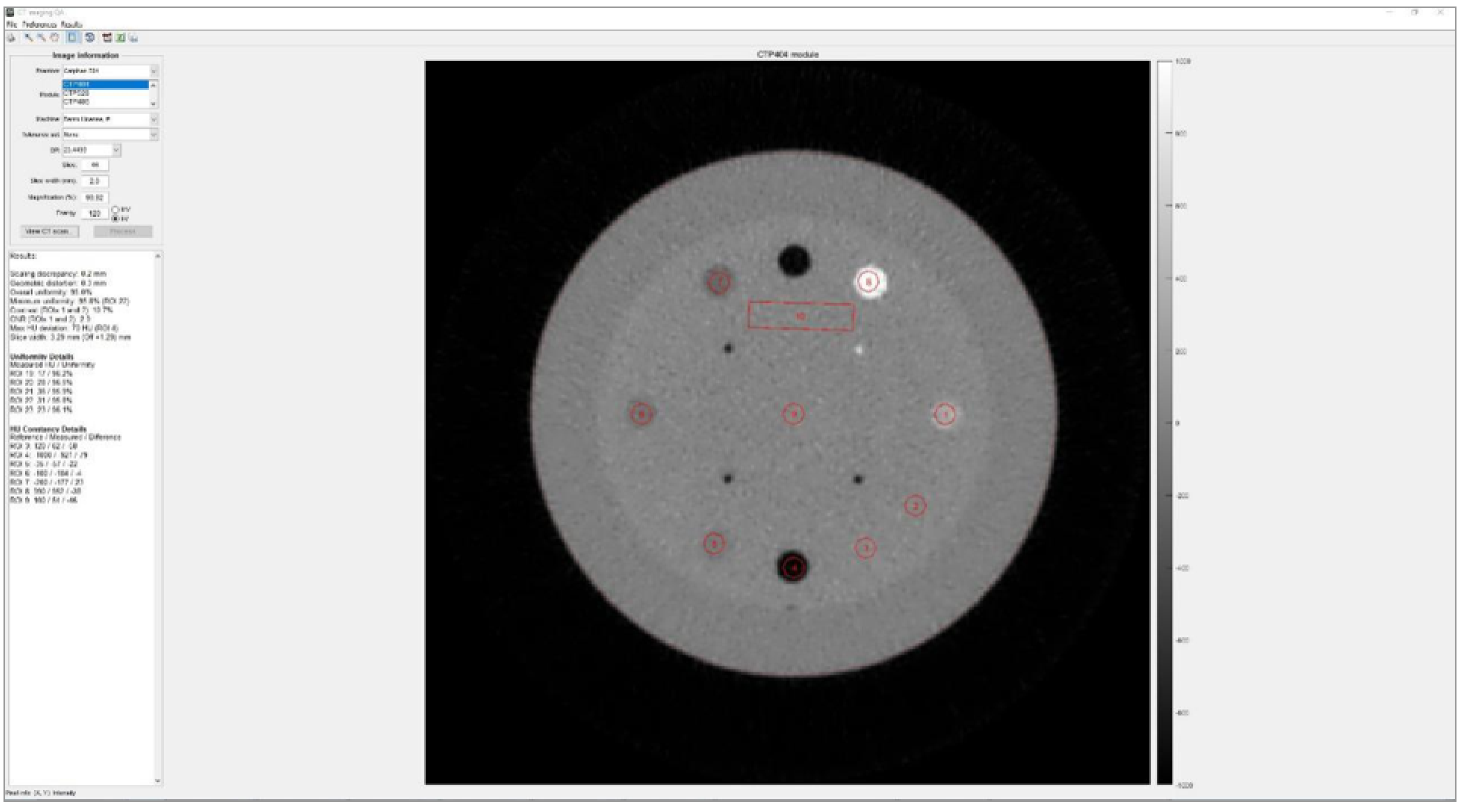

Figure 2

The 3D CBCT image quality test results.

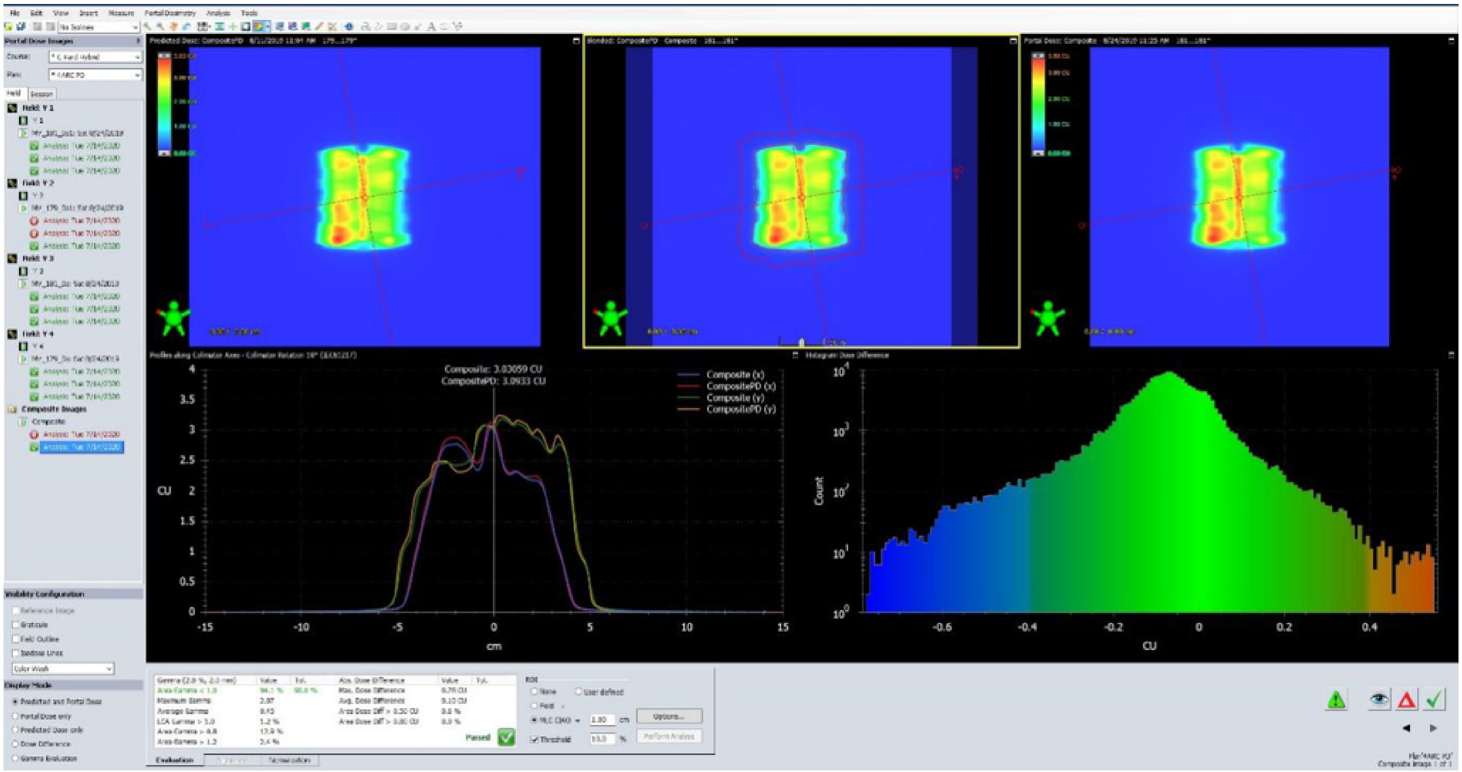

Figure 3

the C-shape hard portal dosimetry test results.