Study on Isocentric Accuracy of the 360° Compact Rotating Gantry of the First Proton Therapy System (SAPT)

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Abstract

The Shanghai Proton Therapy Device (SAPT) is the first domestic proton therapy demonstration system. The rotating gantry constitutes a critical component of the proton therapy apparatus, achieving an isocentric accuracy of ±0.275 mm that surpasses international mainstream equipment, thereby requiring high motion positioning precision and reliability. This study presents the development of the 360° rotating gantry at Ruijin Proton Center and investigates its isocentric accuracy through comparison with measured results. Finite element analysis of the gantry was conducted using ANSYS, while actual deformation was measured using a laser tracker. The accuracy requirements at the isocenter under typical operating conditions were validated, root cause analysis was performed, and the reliability of the domestic rotating gantry was verified.

Full Text

Study on the Isocentric Precision of the First Proton Therapy Device (SAPT) 360° Compact Gantry

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Abstract

Background: The Shanghai Proton Therapy Device (SAPT) represents China' s first domestically developed proton therapy demonstration system. The gantry, a critical component of proton therapy equipment, achieves an isocentric accuracy of ±0.275 mm—surpassing international mainstream devices and demanding exceptional motion positioning precision and reliability. **Purpose:** This study provides reference for understanding how gantry structure affects treatment accuracy under varying rotation angles. **Methods:** We present the development progress of the 360° gantry installed at the Ruijin Proton Center, investigate its isocentric accuracy, and compare simulation with measured results. Using ANSYS static structural analysis, we performed deformation analysis of the gantry' s central point, measured actual deformation with a laser tracker, plotted error spheres, determined accuracy at the isocenter under typical working conditions, and analyzed root causes. **Results:** Qualitative analysis of isocentric point accuracy during gantry rotation, combined with comparison between installed measurement data and simulation results, shows consistent trends but certain deviations (simulated values generally smaller), indicating theoretical calculations approximate but do not identical match measured results. However, the rationality and reliability of the simulation method are fully verified. **Conclusions:** Simulation results demonstrate that the gantry structure' s stiffness, strength, and stability are excellent, providing solid theoretical support for subsequent engineering applications. The successful development of China' s first 360° gantry marks not only a milestone in the localization of high-end medical equipment but also achieves leading international standards with ultra-high precision, innovative structure, and cost advantages.

Keywords: Proton therapy, Gantry, Isocentric precision, Error analysis

Introduction

Proton therapy technology has become a "new weapon" in cancer radiotherapy due to its unique Bragg Peak characteristic, which precisely destroys tumor cells while maximizing protection of surrounding healthy tissue [1]. Since the world' s first rotating gantry was built at Loma Linda University Proton Therapy Center in 1991 [2], international proton therapy technology has rapidly advanced, with researchers continuously improving gantry performance through structural innovation and optimization. As of August 2023, 113 proton therapy centers have been deployed globally. Among them, China' s first domestically developed proton therapy demonstration system—the Shanghai Ruijin Proton Therapy Center—has significantly enhanced treatment flexibility with its 180° rotating treatment room, accumulating approximately 400 clinical cases with rotating treatment room cases accounting for 75% of the total. International manufacturers have developed distinctive gantry designs with continuous breakthroughs in precision and functionality, driving proton therapy toward greater precision and efficiency.

1. Gantry Isocentric Precision

The isocenter is the intersection point of the gantry' s rotation axis and the treatment beam line, serving as the equipment installation reference point in the treatment room. This metric represents the core indicator for evaluating rotating gantries and directly impacts treatment accuracy. Most international rotating gantries require isocentric precision better than ±1 mm, with some manufacturers achieving rotation accuracy better than ±0.5 mm [3]. Mechanical precision is influenced by structural stiffness, drive methods, and thermal deformation. For example, the German Heidelberg heavy ion rotating gantry, due to its robust structural design, experiences only 0.2 mm deformation per 1°C ambient temperature change [4].

2. Structure Types and Drive Methods

Mainstream gantry types include "drum-type" (e.g., Hitachi) and "truss-type" (e.g., IBA), with drive methods encompassing gear, chain, and friction transmission systems [5]. Lightweight design trends are significant; for instance, the Shanghai Proton Therapy Device' s 180° rotating gantry weight was reduced from 240 tons to 162 tons through topology optimization [6].

3. Integrated Platform Functions

Modern gantries incorporate CBCT image guidance systems (e.g., Hitachi PROBEAT series) to enable three-dimensional pre-treatment positioning and real-time monitoring, enhancing target accuracy. Auxiliary technologies such as respiratory gating systems and robotic positioning tables (e.g., Hitachi RGPT system) further adapt to dynamic tumor treatment requirements.

The rotating gantry is a critical component in particle therapy equipment, enabling the treatment head to rotate around the patient for precise tumor irradiation. Its structure must accommodate the beam transport line layout, delivering high-quality particle beams to the patient through deflection and correction magnets [7-9]. As the core component enabling multi-angle precise irradiation, the gantry' s isocentric precision directly determines the spatial matching between the proton beam and tumor target. However, nonlinear factors such as mechanical deformation under dynamic loads and cumulative bearing clearance errors make existing static calibration methods insufficient to meet the stringent submillimeter precision requirements of clinical therapy. Current precision research for rotating gantries faces several challenges: ultra-precision requirements where medical equipment standards (e.g., IEC 60601-2-1) are an order of magnitude higher than industrial equipment; and clinical verification barriers where traditional measurement methods require shutdown for inspection, conflicting with high utilization demands of treatment equipment (e.g., Ruijin Center treats more than 10 cases daily).

This study focuses on the central rotating gantry of the Shanghai Ruijin Proton Therapy Device, proposing an optimization design strategy based on a "simulation-measurement" closed-loop analysis method. Using Finite Element Analysis (FEA) technology, we constructed mechanical models of key gantry components to systematically quantify the impact of rotation conditions and gravitational deformation on isocentric precision. Building upon this, we innovatively introduced a high-precision measurement scheme based on laser trackers to realistically reproduce complex load conditions in clinical treatment scenarios. Through closed-loop comparison of simulation predictions and measured data, we validated the effectiveness of this method in improving gantry isocentric precision and operational stability, providing theoretical support for the development of particle therapy device rotating gantries while expanding the clinical adaptability boundaries of high-precision radiotherapy equipment.

summarizes key technical indicators and dimensional accuracy of comparable international equipment.

Table 1. Statistical table of main rotating gantry parameters [10-13]

Manufacturer/Institution	Weight	Drive Method	Isocentric Precision
US Loma Linda			0.8 mm
Belgium IBA			0.5 mm
Japan Hitachi			0.35 mm
US Varian			0.275 mm
Switzerland PSI Gantry II	C-frame		
China Shanghai Proton Device 360° Gantry	Ø10.5 m / Ø9.5 m / 10.9m		

360° Rotating Gantry System Design and Integration

The structural design of the rotating gantry primarily depends on spatial parameters of the transport system, with its morphological characteristics serving as a functional carrier adapted to the length and orientation of the transport line. The system achieves a compact spot-scanning treatment head with a Source-Axis Distance (SAD) of 2.3 meters, supporting motion organ treatment in spot-scanning mode.

[Figure 1: see original paper] shows the SAPT rotating gantry structure. [Figure 2: see original paper] illustrates the layout of physical elements in the transport line for proton beam transmission. The rotating gantry has a longitudinal dimension of 7.6 m, rotation radius of 4.2 m, total weight of 136 t, rotating part weight of 92.6 t, and isocentric precision of ±0.275 mm. Detailed parameters are listed in .

Table 2. Main parameters of the 360° rotating gantry

Parameter	Specification
Isocentric precision	<±0.5 mm (design), ±0.275 mm (achieved)
Transport line radius	<3.98 m (design), 4.205 m (achieved)
Transport line displacement	<7.8 m (design), <1.2 mm (achieved)
Rotation gantry total weight	<100 t (design), 92.6 t (achieved)
Angle resolution	<0.05° (design), 0.01° (achieved)
Angle repeatability	<0.2° (design), 0.006° (achieved)

The gantry body adopts front and rear ring structures with cylindrical support. The front ring uses six roller supports, while the rear ring uses four roller supports. The drive method employs motor-driven sprocket transmission. Both the transport line and counterweight are fixed through steel structure supports.

The 360° rotating gantry system is deployed in the underground level of the hospital proton therapy center (Gantry room). The area adopts functional zoning design, divided into two core regions: treatment workspace and equipment maintenance area. The treatment workspace is the patient activity area, integrating key medical equipment including treatment couch, CBCT system, laser positioning system, respiratory gating system, and control terminals [Figure 3: see original paper]. The equipment maintenance area forms an independent space through physical separation from the treatment area, equipped with a cross-regional bridge crane system at the top to ensure hoisting and maintenance operations for heavy equipment. Dedicated maintenance passages are arranged along the walls, equipped with collimator installation bases, integrated wiring trays, and ventilation pipelines.

To meet the dynamic operation requirements of the rotating gantry, media such as water, electricity, and gas are dynamically connected to the gantry main body through flexible cable trays, ensuring continuous and stable operation of the cooling circulation system, power supply, and signal transmission. The core function of this gantry system is to precisely execute treatment plan instructions, achieving multi-angle precise irradiation of lesion tissue through multi-dimensional rotation around the isocentric axis [14].

[Figure 4: see original paper] shows the maintenance area of the 360° rotating gantry.

Isocentric Precision Simulation Method

The rotating gantry carrying the beam transport line must support dozens of tons during operation, necessitating stress and deformation analysis of structural elements in different orientations to ensure proposed structural stiffness and precision. After constructing the 3D gantry model with corresponding dimensional features in SolidWorks, we imported it into ANSYS static structural analysis module.

[Figure 5: see original paper] shows the established finite element model of the 360° rotating gantry. The model employs solid elements. To save computational resources, a mesh size of 50 mm was adopted, dividing into 784,216 elements and 1,541,836 nodes. Tetrahedral elements were used throughout. Materials were analyzed as structural steel with elastic modulus of 2×10^{11} Pa, Poisson' s ratio of 0.3, and density of 7.85×10^{3} kg/m^{3}. Based on the simplified 360° gantry model, nonlinear constraints were applied, with "No separation" contact between large/small roller rings and small rollers. This contact can transmit normal compressive forces and tangential forces, allowing normal non-separation and small-deformation frictionless tangential motion. Other component contacts were "Bonded" to simulate bolt connections. Small rollers and guide rollers were configured with cylindrical supports.

Simulation method: Under actual treatment conditions, the gantry is static with only gravity and support reaction forces. Therefore, simulation set gravity vertically downward. For model simplification, cylindrical supports of small rollers provided support reaction forces for the rotating gantry. As shown in [Figure 6: see original paper], deformation probes were set at the isocentric point of the measurement fixture to measure deformation. Due to symmetry of software simulation results about the Z-axis, only unilateral 180° cases were simulated. The gantry' s vertical state was defined as 0° (left side of [Figure 6: see original paper]), rotating 30° increments clockwise about the Y-axis, with calculations performed at each position until completing 180° measurement.

Isocentric Precision Measurement Method

1. **Measurement method:**
   (1) Connect mechanical fixture to treatment head, placing laser tracker reflector at fixture tip.
   (2) The theoretical isocentric point is a fixed point in treatment room space. Using the treatment room control network, the laser tracker guides reflector position adjustment to the isocentric point.
   (3) Multi-angle continuous rotation data acquisition: measure and record sphere position, then rotate gantry every 15°, measuring at each position until completing ±180° measurement.
   (4) Repeatability testing to verify measurement result stability.
   (5) Reverse rotation: measure and record data at each position, compare (3) and (4) to obtain forward/reverse rotation data differences.
   (6) Analyze tracker data to examine sphere trajectory error. Measurement site photo shown in [Figure 8: see original paper].

Test Results

Using measurement data to create error sphere, as shown in [Figure 9: see original paper], the measured error sphere radius is 0.275 mm.

Simulation results: Obtained isocentric precision under static conditions from

0-180°. Each data point consists of XYZ coordinates in Cartesian coordinate system. The smallest sphere enveloping all data points is called the error sphere, shown in [Figure 7: see original paper]. The error sphere radius represents the isocentric point error radius, approximately equivalent to isocentric precision. The simulation result yields an error sphere radius of 0.25 mm.

[Figure 7: see original paper] shows the simulation data error sphere. [Figure 9: see original paper] shows the measured data error sphere.

Isocentric Precision Comparison and Error Traceability

Comparing displacement data in XYZ three directions, as shown in [Figure 10: see original paper], simulation deformation is slightly smaller than measured data, but curve trends basically match. During rotation, significant structural deformation changes concentrate in X and Y directions, with minimal Z-direction displacement. XYZ displacements all show periodic changes consistent with gantry design and rotation mechanism. Deformation amplitudes differ among directions, reflecting varying gantry stiffness and stability. X-direction deformation shows minimum values when gantry is vertical, with larger values appearing during 0-180° and 180°-360° rotation processes, peaking near 90° and 270° with increasing then decreasing trends. Vertical and axial deformation maxima appear at 0° and 180° positions—when the gantry is vertical.

shows deformation at key angles.

Table 3. Deformation at key angles

Measurement	First Test	Second Test

Due to gravity acting vertically on treatment head and transport line, the large roller ring experiences compression in Z-direction and tension in horizontal direction. Both large and small roller rings exhibit a "flattened" elliptical shape. Deformation in these directions is larger when the transport line and treatment head assembly is closer to vertical. Gantry deformation at 90° can be referenced in [Figure 11: see original paper].

[Figure 10: see original paper] compares simulation and measured data. Y-direction displacement analysis reveals significantly larger displacement during 180°-360° rotation than 0-180°, with maximum values at 90° and 270°, indicating these positions require maximum stability attention. Viewed from the side, the gantry body is supported by rollers at two roller rings, with its structure visualized as a beam loaded at its top, causing downward deformation along gravity direction at inner sides of both roller rings. Fixed beam ends cause rotation, shifting treatment head mounting base direction. In the upper segment, this offset is partially compensated as gravity direction forms acute angles. However, as rotation angle increases, particularly at 0-180° positions, isocentric point offset increases. This deformation causes minute deviation of treatment head mounting base direction relative to radial vertical direction, triggering isocentric point displacement and exposing insufficient support bearing stiffness—requiring replacement with cross-roller bearings or dual-drive gear backlash elimination to improve rigidity.

Multi-dimensional analysis of isocentric precision during gantry dynamic rotation reveals high consistency between measured and simulation data in error distribution trends (correlation coefficient R^2 0.92), validating simulation model reliability. Simulation predicts overall gantry isocentric precision of ±0.25 mm, while measured results show ±0.275 mm—deviation rate <10%, indicating the model effectively reflects actual mechanical performance. Notably, simulation values are generally smaller in Z-axis direction (average deviation 0.05 mm), presumably due to unaccounted mechanical installation errors that should be eliminated after compensation.

During actual installation and testing, besides gantry body deformation as primary error source, comprehensive evaluation of other potential isocentric error sources is necessary, including radial runout error, coaxiality error between front and rear rings, and treatment head installation error, to ensure overall system precision and stability.

Conclusions

This paper presents the development and isocentric precision study of China's first domestic proton therapy device (SAPT) 360° compact gantry. First, regarding mechanical structure design, we introduced the development status, employing a combined method of finite element analysis and laser tracker-based dynamic measurement to quantify impacts of rotation conditions and gravitational deformation on the isocentric point. Second, through isocentric precision analysis, horizontal displacement is minimal at gantry vertical positions (0°/180°), peaking near 90°/270° due to cantilever beam deflection effects (0.275 mm), showing symmetric distribution. Vertical displacement is dominated by gravitational compression, showing extreme values of ±0.15 mm at 0°/180° positions. Axial displacement shows asymmetry in 180°-360° range (extreme value ±0.18 mm).

Through qualitative analysis of gantry rotation isocentric precision and comparison between installed measurement data and simulation results, both show consistent trends with certain deviations (simulation values generally smaller), demonstrating theoretical calculation and measurement method rationality and reliability. Measured data reveals that besides gantry body deformation, treatment head installation offset errors require control through laser calibration fixtures.

Most international rotating gantries require isocentric rotation accuracy better than ±1 mm, with some manufacturers achieving better than ±0.5 mm. Isocentric precision affects image guidance and treatment accuracy. Improving precision is crucial for ensuring radiation beams precisely focus on tumor targets while avoiding damage to surrounding healthy tissue. The gantry' s isocentric precision reaching ±0.275 mm, integrated with CBCT system, demonstrates advanced stability and reliability, meeting treatment system requirements and providing solid theoretical support for subsequent engineering applications such as multi-particle superconducting rotating gantry development.

Note: Figure translations are in progress. See original paper for figures.