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

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Abstract

Shanghai Proton Therapy Device (SAPT) represents the first domestically-developed 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 demanding 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 comparative analysis with measured results. Through finite element analysis of the rotating gantry using ANSYS and measurement of actual deformation via laser tracker, the accuracy requirements at the isocenter under typical operating conditions were validated and root cause analysis was performed, thereby confirming the reliability of the domestic rotating gantry.

Full Text

Study on the Isocentric Accuracy of the First Domestic 360° Compact Gantry for the Shanghai Advanced Proton Therapy Device

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Abstract

The Shanghai Advanced Proton Therapy Device (SAPT) represents China's first domestically developed proton therapy demonstration system. The rotating gantry constitutes a critical component of proton therapy installations, requiring

exceptional motion positioning accuracy and reliability. This study investigates the development and isocentric accuracy of the 360° rotating gantry installed at the Ruijin Proton Center, presenting comparative analyses with measured results. Through finite element analysis using ANSYS and deformation measurements obtained with a laser tracker, we validate the accuracy requirements at the isocenter under typical operating conditions and analyze the underlying causes, thereby confirming the reliability of this domestically produced rotating gantry.

Keywords: Proton therapy, Rotating gantry, Isocentric precision, Error analysis

1. Introduction

Proton therapy technology has emerged as a powerful tool in cancer radiotherapy, leveraging the unique Bragg Peak characteristic to precisely destroy tumor cells while maximizing protection of surrounding healthy tissue [1]. Since the world's first rotating gantry was established at Loma Linda University Proton Therapy Center in 1991 [6], international proton therapy technology has advanced rapidly, with researchers continuously improving gantry performance through structural innovation and optimization. As of August 2023, 113 proton therapy centers have been deployed globally. Notably, China's first domestically developed proton therapy demonstration facility—the Shanghai Ruijin Proton Therapy Center—has completed approximately 400 cases, with 75% treated in its rotating treatment room, demonstrating significantly enhanced treatment flexibility.

The rotating gantry serves as the core component enabling multi-angle precise irradiation, with its isocentric accuracy directly determining the spatial matching between the proton beam and tumor target volume. The isocenter represents the intersection of the gantry's rotational axis and the treatment head beamline, serving as the installation reference point in the treatment room. International standards require isocentric accuracy below $±1mm, withsomemanufacturersachieving <±$0.5 mm [7]. Mechanical precision is influenced by structural rigidity, drive mechanisms, and thermal deformation. For instance, the heavy-ion rotating gantry at Heidelberg, Germany, exhibits only 0.2 mm deformation per 1°C temperature variation due to its robust structural design [8].

Mainstream gantry structures include "drum-type" (e.g., Hitachi) and "truss-type" (e.g., IBA) configurations, with drive systems encompassing gear, chain, and friction transmission methods [9]. Lightweight design represents a significant trend, exemplified by the SAPT 180° rotating gantry, which reduced weight from 240 tons to 162 tons through topology optimization [10]. Modern systems increasingly integrate platform functionalities such as CBCT image guidance systems (e.g., Hitachi PROBEAT series) for three-dimensional pre-treatment positioning and real-time monitoring, along with respiratory gating systems and robotic positioning tables (e.g., Hitachi RGPT system) to accommodate dynamic tumor treatment requirements.

However, precision research for rotating gantries faces substantial challenges. The medical equipment precision standards (e.g., IEC 60601-2-1) are an order of magnitude stricter than industrial equipment, while clinical verification barriers exist as traditional measurement methods require system shutdown, conflicting with high utilization demands (the Ruijin Center treats over 10 cases daily). This study focuses on the SAPT 360° rotating gantry, proposing an optimized design strategy based on a "simulation-measurement" closed-loop analysis method. We employ finite element analysis (FEA) to construct mechanical models of critical gantry components, systematically quantifying the effects of rotational operating conditions and gravitational deformation on isocentric accuracy. Building upon this foundation, we innovatively introduce a high-precision measurement scheme using laser trackers to authentically replicate complex loading conditions in clinical treatment scenarios.

2. 360° Gantry System Design and Integration

The structural design of the rotating gantry primarily depends on the spatial parameters of the beam transport system. The SAPT 360° rotating gantry employs front and rear ring structures with cylindrical support, utilizing six rollers for the front ring and four rollers for the rear ring. The drive system utilizes motor-driven sprocket transmission, with both the transport line and counterweight fixed via steel structural supports. This configuration achieves a compact spot-scanning treatment head with a source-to-axis distance (SAD) of 2.3 meters, supporting motion management therapy in spot-scanning mode.

The gantry's longitudinal dimension is 7.6 m with a rotational radius of 4.2 m. The total weight is 136 tons, with the rotating portion accounting for 92.6 tons. The system achieves isocentric accuracy of $±$0.275 mm. Detailed parameters are summarized in Table 2 .

The 360° gantry system is deployed in the underground gantry room at the hospital's proton therapy center, which adopts a functional zoning design divided into treatment workspace and equipment operation & maintenance (O&M) zones. The treatment workspace integrates critical medical equipment including the treatment couch, CBCT system, laser positioning system, respiratory gating system, and control terminals [Figure 3: see original paper]. The equipment O&M zone forms an independent space physically separated from the treatment area, featuring an overhead bridge crane system for heavy equipment installation and maintenance, dedicated maintenance passages, collimator installation bases, comprehensive cable trays, and ventilation systems [Figure 4: see original paper]. To meet dynamic operational requirements, utilities are connected to the gantry main body through flexible cable trays, ensuring continuous stability of cooling circulation systems, power supply, and signal transmission.

3. Isocentric Accuracy Analysis

3.1 Simulation Methodology

The rotating gantry carrying the beam transport magnets must support dozens of tons of weight, necessitating comprehensive stress and deformation analysis of structural components across different orientations to ensure adequate stiffness and minimal deformation. Following construction of a three-dimensional gantry model with appropriate dimensional features in SolidWorks, we imported it into ANSYS Static Structural analysis module.

The finite element model [Figure 5: see original paper] employs 50 mm mesh size, generating 784,216 tetrahedral elements. Material properties are defined 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 gantry model, nonlinear constraints are applied throughout, with No Separation contact between large/small rolling rings and rollers (transmitting normal compressive and tangential forces while allowing small frictionless tangential movement) and Bonded contact for remaining components (simulating bolted connections). Rollers are configured with cylindrical supports.

In actual treatment conditions, the gantry remains static with only gravity and support reaction forces active. Simulation applies gravity vertically downward, with support reactions provided by small roller cylindrical supports. A deformation probe is placed at the isocenter point of the measurement fixture [Figure 6: see original paper]. Due to Z-axis symmetry in software calculations, only the 180° unilateral case is simulated. The vertical position is defined as 0° [FIGURE:6 left], with sequential 30° increments calculated until completing 180° measurement.

Simulation results yield isocentric accuracy data points for static positions from 0° to 180°, with each data point comprising XYZ coordinates in Cartesian space. An error sphere is constructed to envelop all data points, with the smallest such sphere defining the isocentric error radius, which approximates the isocentric accuracy [Figure 7: see original paper]. The simulation yields an error sphere radius of 0.25 mm.

3.2 Measurement Methodology

Measurement Procedure: 1. A mechanical fixture is attached to the treatment head with a laser tracker reflector placed at the fixture tip. 2. The theoretical isocenter represents a fixed point in treatment room space. Using the room's control network, the laser tracker guides the reflector to the isocenter position. 3. Multi-angle continuous rotation data acquisition measures the sphere position at 15° gantry intervals from -180° to +180°. 4. Repeatability testing validates measurement stability through reverse rotation and comparison of forward/reverse data differences. 5. Tracker data analysis examines sphere trajectory errors. The measurement site is shown in [Figure 8: see original paper].

Test Results: Measurement data produces an error sphere [Figure 9: see original paper] with a radius of 0.275 mm, representing the actual isocentric accuracy.

3.3 Comparison and Error Source Analysis

Displacement data comparison across XYZ directions [Figure 10: see original paper] reveals that simulated deformations are consistently slightly smaller than measured values, though curve trends align well. Structural deformation during rotation concentrates primarily in X and Y directions, with minimal Z-direction displacement. All three axes exhibit periodic variations correlating with gantry design and rotation mechanisms, with varying amplitudes reflecting directional differences in stiffness and stability.

X-direction deformation reaches minima at vertical positions (0°/180°) and maxima during 0-180° and 180°-360° rotation, peaking near 90° and 270°. Vertical and axial deformations exhibit maxima at 0° and 180° positions. Table 3 presents deformation values at critical angles.

Due to gravitational loading on the treatment head and transport line in the vertical direction, the large rolling ring experiences compression in Z-direction and tension horizontally, resulting in an elliptical “flattened” shape. Deformation magnitude increases as the rotating main body approaches vertical orientation. Y-direction displacement analysis shows significantly larger values during 180°-360° rotation compared to 0-180°, with maxima at 90° and 270° positions where stability requires closest attention. The gantry body, supported by rollers at two rolling rings and loaded with heavy mass at its top, behaves as a beam fixed at both ends, generating downward deformation at the inner sides of the rings and angular rotation at the ends. This rotation causes offset of the treatment head mounting base direction, partially compensated in the upper segment where gravity and deflection angle form acute angles. However, as rotation angle increases, particularly at 0-180° positions, isocentric offset increases accordingly. This deformation reveals insufficient support bearing stiffness, requiring improvement through crossed roller bearing replacement or dual-drive gear backlash elimination.

Multi-dimensional analysis of isocentric accuracy during dynamic rotation demonstrates high consistency between measured and simulated error distribution trends (correlation coefficient $R^2 \geq 0.92$), validating simulation model reliability. Simulation predicts overall isocentric accuracy of $±$0.25 mm versus measured $±$0.275 mm, representing <10% deviation and confirming effective reflection of actual mechanical performance. Notably, simulated Z-axis values are consistently smaller than measured data (average deviation 0.05 mm), attributed to unaccounted mechanical installation errors that should be eliminated through compensation.

Beyond gantry body deformation, comprehensive evaluation must assess additional error sources including radial runout errors of front and rear rings, coaxiality errors, and treatment head installation errors to ensure overall system precision and stability.

4. Conclusion

This study presents the development and isocentric accuracy analysis of China's first 360° compact rotating gantry for the SAPT proton therapy device. Key findings include:

1. Through integrated finite element analysis and laser tracker-based dynamic measurement, we quantified the influence of rotational operating conditions and gravitational deformation on the isocenter. Horizontal displacement minima occur at vertical gantry positions (0°/180°), with peak displacement (0.275 mm) near 90°/270° due to cantilever beam deflection effects, showing symmetric distribution. Vertical displacement, dominated by gravitational compression, exhibits extrema of $\pm$0.15 mm at 0°/180° orientations. Axial displacement shows asymmetry in the 180°-360° range (extrema $\pm$0.18 mm).

2. Qualitative analysis of isocentric accuracy during rotation and comparison of measured installation data with simulation results demonstrate consistent trends with minor deviations (simulated values generally smaller), confirming the rationality and reliability of both theoretical calculation and measurement methodologies. Measured data reveal that beyond gantry body deformation, treatment head installation offset errors require control through laser calibration fixtures.

The achieved isocentric accuracy of $\pm$0.275 mm, integrated with CBCT systems, represents advanced stability and reliability that meets treatment system requirements. This milestone in domestic high-end medical equipment development provides solid theoretical support for subsequent engineering applications, including multi-particle superconducting rotating gantry development, while establishing international leadership through ultra-high precision, innovative structure, and cost advantages.

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