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Development of a Real-Time Internal and External Marker Based Gating System for Proton Therapy

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In respiratory-induced proton therapy, the accuracy of tracking system and beam controlling is more important than photon therapy. Therefore, a high accuracy motion tracking system that can track internal marker and external surrogate is needed. In this research, our team has installed internal and external marker tracking system at our institution's proton therapy system, and tested the scanning with gating according to the position of marker. The results demonstrate that the developed in-house external/internal marker based gating system can be clinically used for proton therapy system for moving tumor treatment.

Keywords: Proton therapy, Respiratory gating, Internal/external fiducials, Marker tracking

Introduction

In recent years, Proton therapy become widely introduced in many hospitals because of the superiority of the protons in sparing normal tissues due to the characteristic of sharp dose fall off the Bragg-Peak.[1-3] However, the drawback of the sharp dose fall off is that higher accuracy is required in the treatment than that in x-ray therapy.[4-6] In the cases of tumors located in the thorax and abdomen, respiratory motion introduces uncertainties into the process of calculating the range of proton beams. Therefore, more precise gating or tracking methods are needed for proton therapy.[7,8]

In order to incorporate the organ motion into the proton treatment aiming at reduction of the motion induced uncertainty, an internal-external motion monitoring and gating system was developed. For the system, the internal marker tracking algorithm was applied to the images from the biplane flat panel detector (FPD). The external marker tracking was performed by the 'Vicon' (Vicon Motion Systems Ltd, U.K.) system.[9] For the gating system with internal and external marker tracking, we merged each system's output data into one program, and named as 'co-registration algorithm'.[10] Through this algorithm, the proton beam could be activated when the external or internal markers were at the treatment range.

Materials and Methods

1. Internal marker tracking: biplane FPD and tracking software

The motion of an internal marker can be shown by fluoroscopic X-ray images. Our institution's proton therapy system has equipped the biplane FPD for verifying the position of the patients (Fig. 1). In this study, the FPD was used for capturing the image of internal marker with 8 frames/second in biplane direction and bypassing the images for marker tracking. The concept of finding the 3D coordinates of marker in biplane images was represented at Fig. 2. Through this concept internal marker tracking algorithm was developed. The derived 3D coordinates of internal marker were displayed on the right down of the monitor. A normal piece of clip was used for internal marker, because this was the phantom simulation.

2. External surrogate tracking: the Vicon system

For the external surrogate tracking, Vicon tracking system was adopted.[11] This system was used at our previous article.[10] This system can find out real time 3-D coordinates of each reflective marker's position. The 'Bonita 10' infra-red camera (Bonita, Vicon, Los Angeles, USA) has high resolution (1024×1024 pixels) and frame rates (250 Hz) . Through the 'Nexus' software (Vicon Nexus, Vicon Motion Systems, Oxford Metrics Group, U.K.) every single position of each markers are captured and exported to another application (Fig. 3).

3. Integration of internal and external marker tracking data

For the real-time tracking of internal target and external surrogate, the integration of the two independent system was needed. Therefore, the internal marker's 3D coordinates and external surrogates' 3D coordinates were gathered in one PC and displayed at one window. This

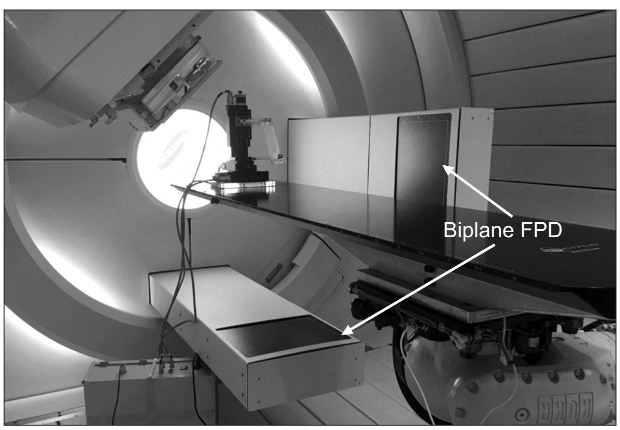


Fig. 1. The flat panel detectors (FPD) at the gantry of our institution.

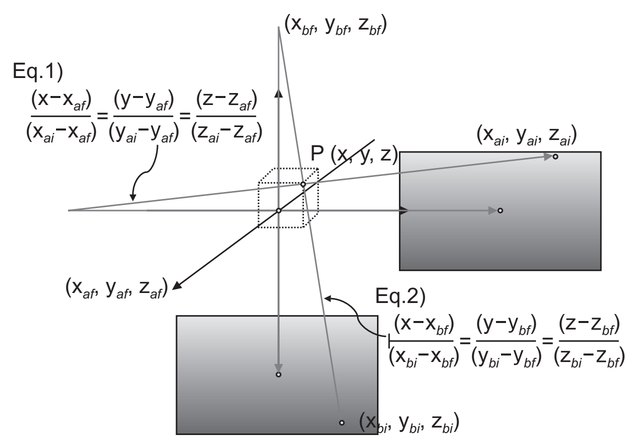


Fig. 2. The concept of finding the 3D coordinates of marker in biplane images (The two blue rectangles represent FPD's biplane images).

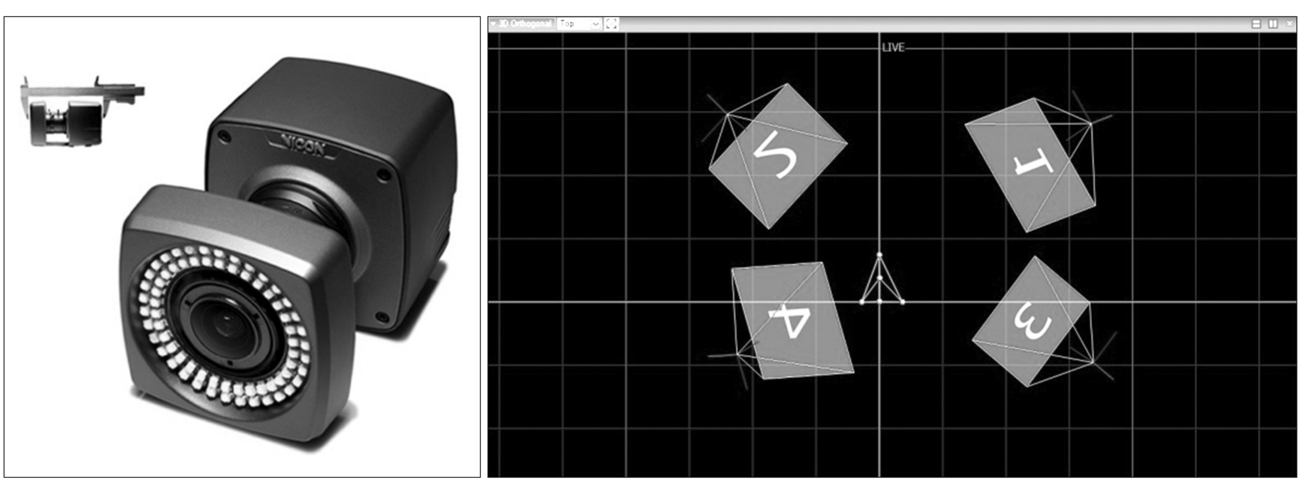
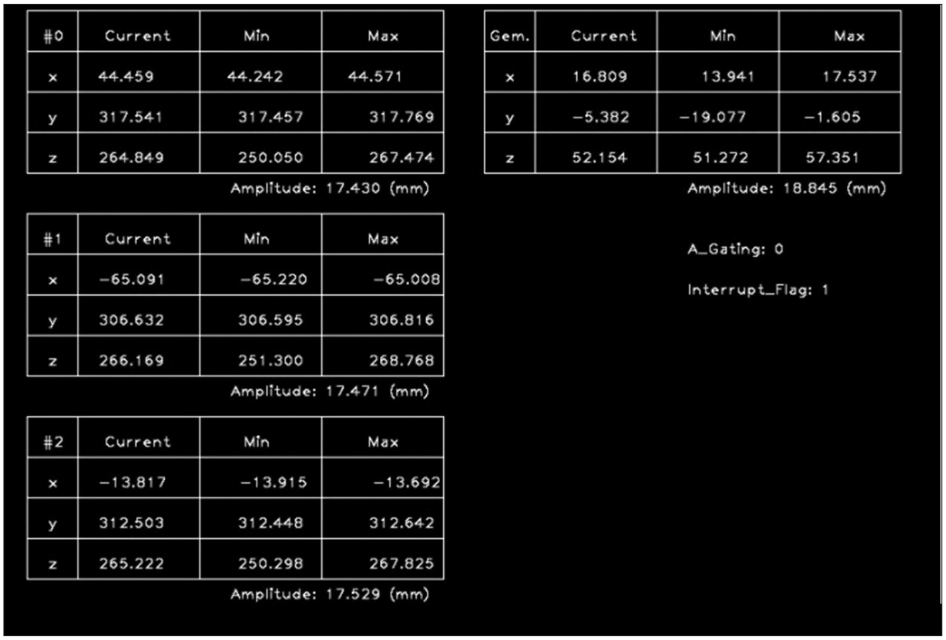


Fig. 3. The Bonita 10 camera (left) and the Nexus software (right).



#0	Current	Min	Max
x	44.459	44.242	44.571
y	317.541	317.457	317.769
z	264.849	250.050	267.474

Amplitude: 17.430 (mm)

#1	Current	Min	Max
x	−65.091	−65.220	−65.008
y	306.632	306.595	306.816
z	266.169	251.300	268.768

Amplitude: 17.471 (mm)

#2	Current	Min	Max
x	−13.817	−13.915	−13.692
y	312.503	312.448	312.642
z	265.222	250.298	267.825

Amplitude: 17.529 (mm)

Gem.	Current	Min	Max
x	16.809	13.941	17.537
y	−5.382	−19.077	−1.605
z	52.154	51.272	57.351

Amplitude: 18.845 (mm)

A_Gating: 0

Interrupt_Flag: 1

Fig. 4. The real time output status of the 'Co-registration Algorithm'. The boxes on the left side of the monitor show the coordinates of the three external markers, and the box on the right shows the 3D coordinates of the internal marker in millimeter scale.

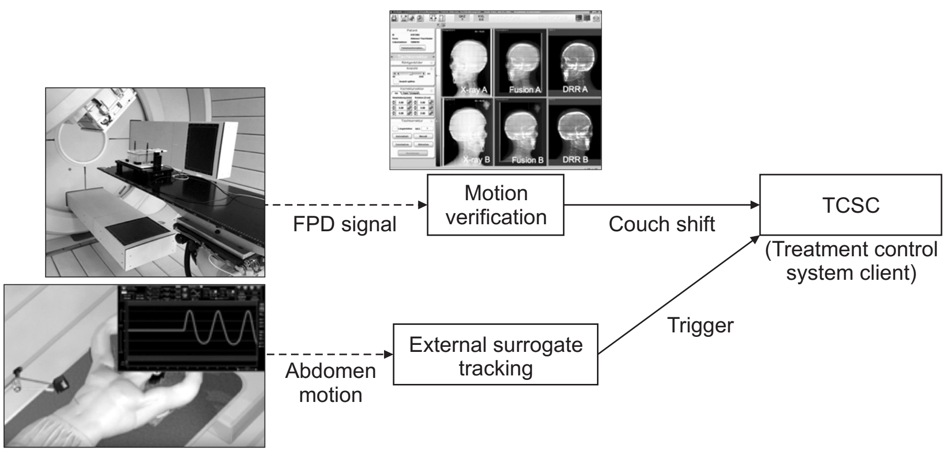


Fig. 5. Current proton therapy system at our institution.

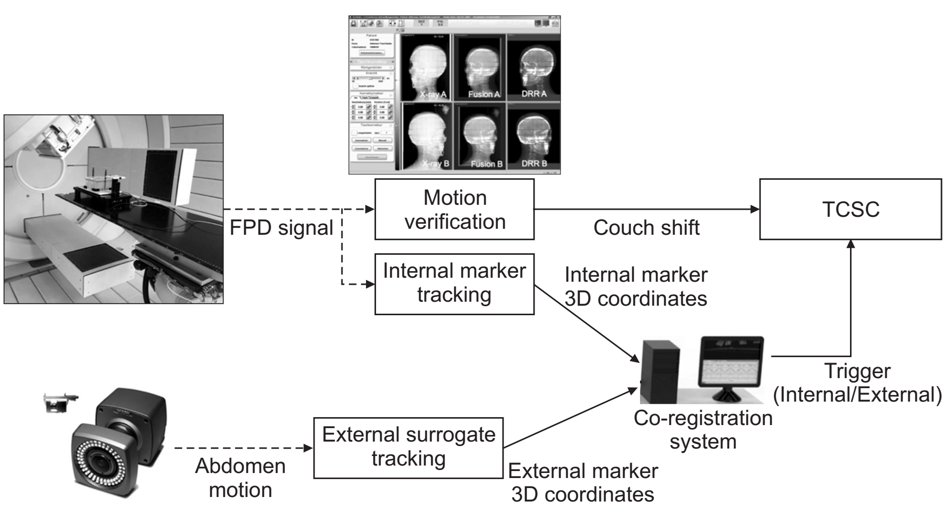


Fig. 6. Modified proton therapy system which is able to gate the beam based on external/internal marker's position.

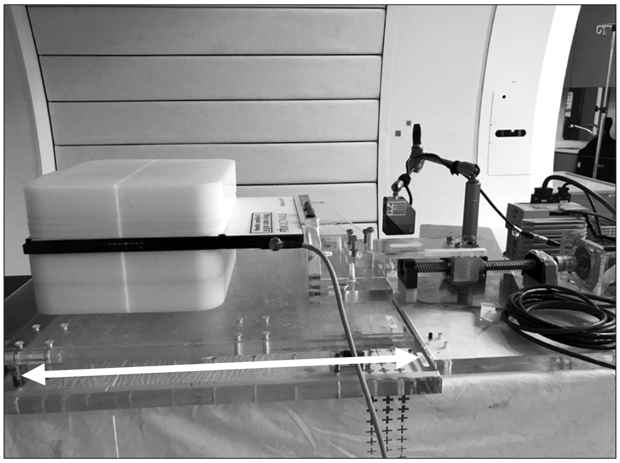


Fig. 7. A sliding motion phantom was placed on a couch for phantom simulation.

process was named as 'co-registration' system.[10] For the co-registration, firstly the coordinates of the three external markers with the Vicon system were imported to the 'co-registration computer'. Simultaneously, the internal marker data, captured with the FPD, were imported to the 'co-registration computer' through another TCP/IP socket, and thus, the 'co-registration computer' could import three external markers' coordinates data and internal marker's coordinate data simultaneously through the two TCP/IP socket. Here, every single position of one internal and three external markers can be exported to ASCII file, for further analysis. The display of monitoring of the 'Co-registration Algorithm' was presented (Fig. 4).

The next issue was let the proton beam export when

Statistics

Number of dose points	420
Evaluated dose points	146 (34.8%)
Passed	130 (89.0%)
Failed	16 (11.0%)
Result	89.0% (Yellow)

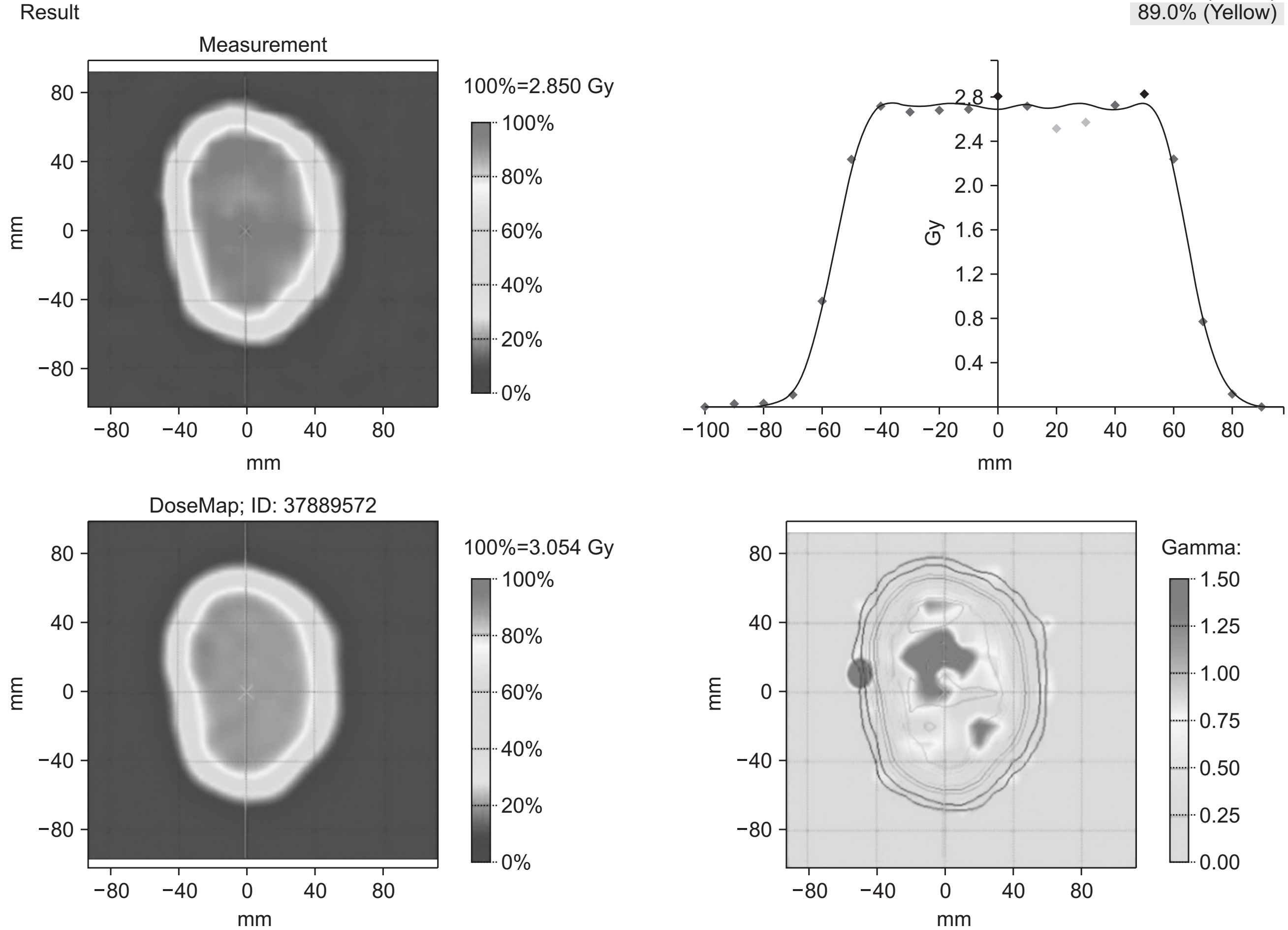


Fig. 8. The gamma analysis result for case 1 with the anzai external respiratory gating.

the location of the marker was within treatment range. Currently, our institution uses 'Anzai AZ-733V external respiratory gating system' (Anzai Medical, Tokyo, Japan) for scanning with gating treatment (Fig. 5). This system was modified to external and internal marker tracking system with adopting the developed algorithm (Fig. 6). To modify the system, some interface was made which can export the trigger signal from the 'co-registration' system to current treatment control system client (TCSC).

4. Phantom set-up

The experimental environment was set for scanning with gating at proton therapy room (Fig. 7). The 'Octatvius detector 1500' (PTW-Freiburg, Freiburg, Germany) is an air vented ionization chamber array with 1405 detectors in a 27×27 cm^2 measurement area arranged in a chaeckerboard pattern with a chamber-to-chamber distance of 10 mm in each row. The Octavius detector was placed on moving phantom for simulating a patient's movement. The moving phantom was moved sliding motion with sine wave.

For 2 liver cancer cases, the passing rate for 3%/3 mm gamma analysis were generated following the TG-119 instructions.[12] The maximum energy was 172.4 MeV, and the minimum energy was 88 MeV. The Spread-out Bragg peak was used with 25 modulation layers. The snout position was 25.32 and the air gap was 16.3 cm. The gating window was opened for 10% of the total phase. Firstly,

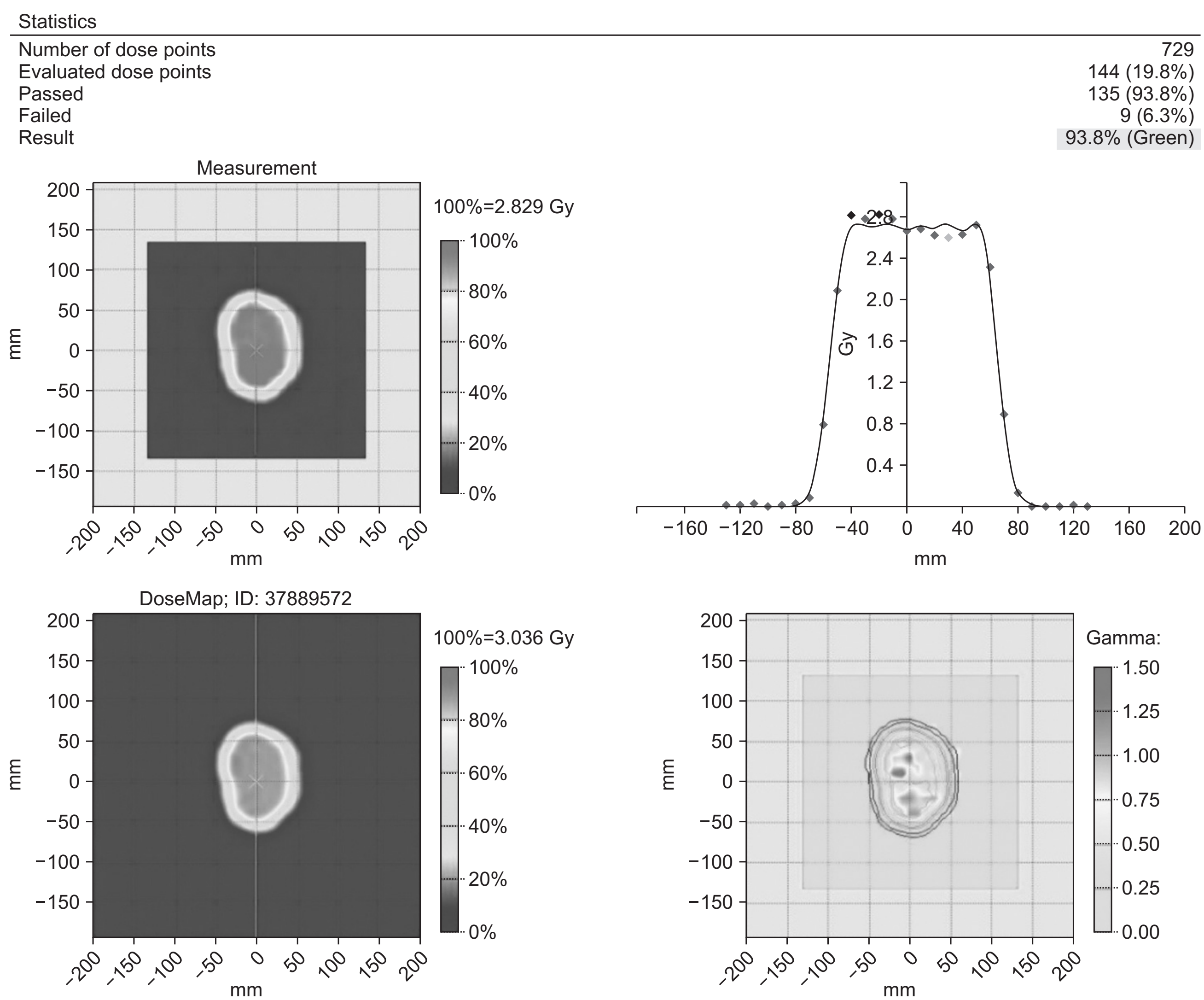


Fig. 9. The gamma analysis result for case 1 with the modified system's respiratory gating.

the 'Anzai external respiratory gating system' was used for reference, and then, the proposed system was used for gating. Finally, the gamma analysis was conducted for comparison.

Results and Discussion

The gamma analysis with anzai gating system was shown at Fig. 8. The low passing rate (89.0%) may be the effect of the moving phantom and gating mismatch. The gamma analysis with proposed gating system was shown at Fig. 9. The passing rate was 93.8% and it was a reasonable result for actual scanning with gating treatment.

The another case's results were shown at Fig. 10, 11. In this second case, anzai gating system showed better result. However, the proposed system was also affordable for using in gating treatment. The values of every cases were summarized at the Table 1.

Through these results, the scanning with gating performance was tested with our modified marker tracking system. In clinical usage, upper than 90% passing rate for 3%/3 mm gamma analysis is required. The proposed system meets the requirements and can be used for real treatment with further validation test.

In these experiments, external marker based gating was conducted. Actually, each internal/external marker based gating is available. However, the internal marker based tracking has some risk for damaging the proton therapy

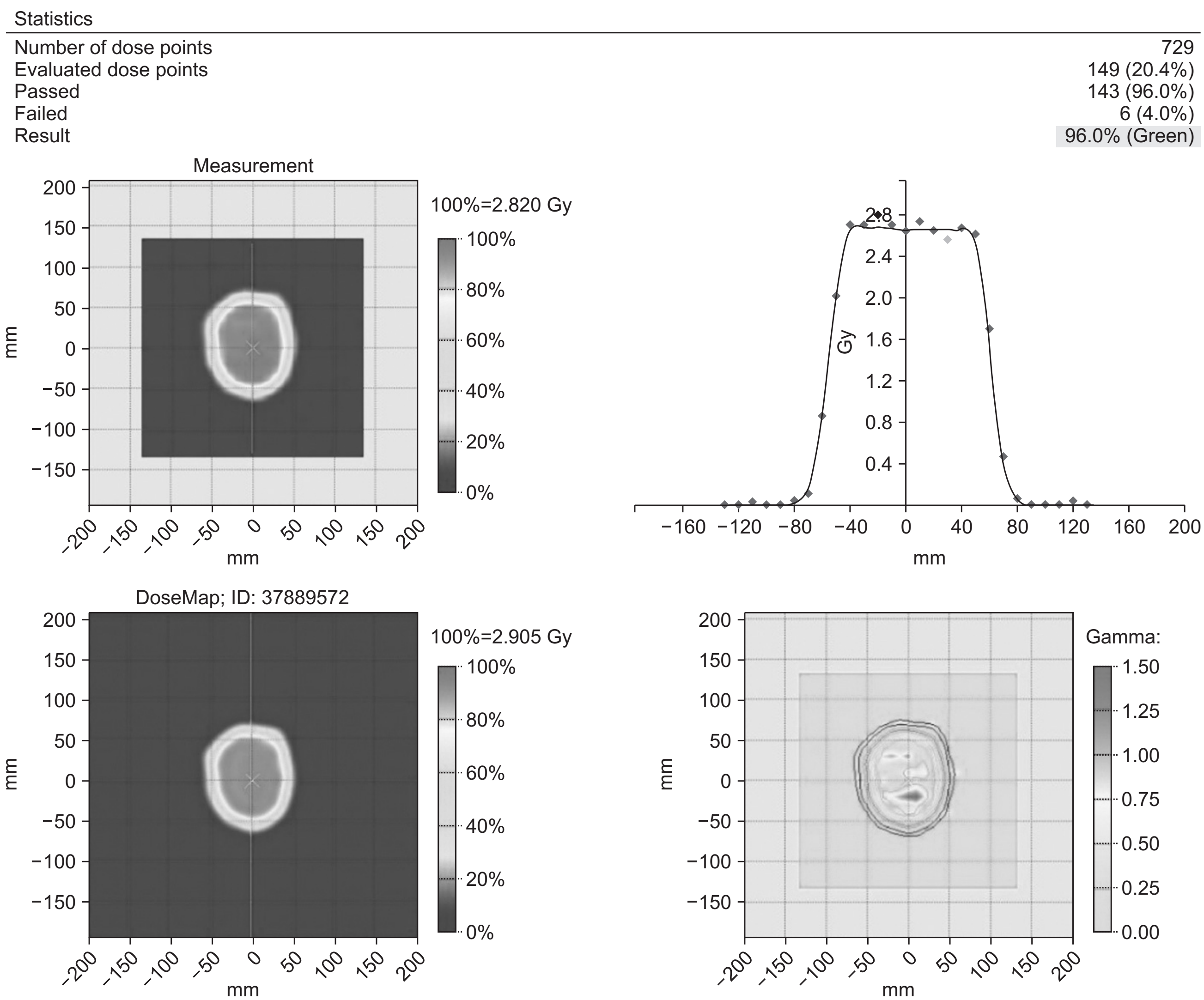


Fig. 10. The gamma analysis result for case 2 with the anzai external respiratory gating.

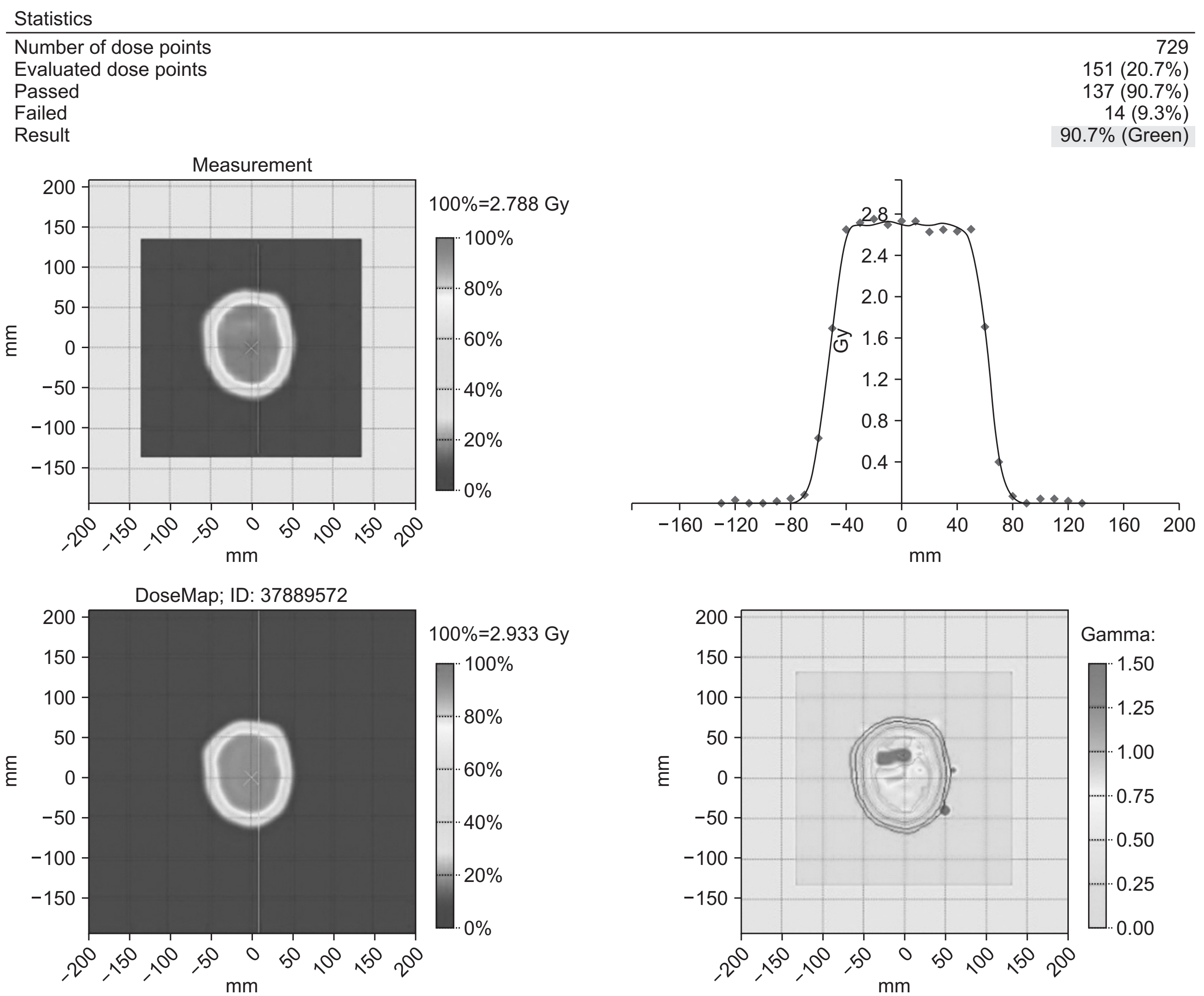


Fig. 11. The gamma analysis result for case 2 with the modified system's respiratory gating.

Table 1. The gamma analysis comparison table

Gating method	Passing rate	Absolute difference (arithmetic mean)
Plan 1		
Anzai gating	89.0%	0.056 Gy
Gating with proposed system	93.8%	0.047 Gy
Plan 2		
Anzai gating	96.0%	0.044 Gy
Gating with proposed system	90.7%	0.045 Gy

gantry. Therefore, we have plan for internal marker based gating experiment when spare FPD are ready (about next year). For the further study, intermittent internal marker position verification with FPD imagers, together with full-time external marker tracking is planned.

Conclusion

In this study, we developed a system that can track the internal and external marker simultaneously, and gating the proton beam according the position of the markers. The developed tracking software was interfaced to allow internal marker tracking with the images from a biplane FPD, while using the Vicon system to monitor external surrogates. With the continuous validation test, this gating system with internal and external marker tracking may be available for use in real treatment.

Acknowledgements

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Conflicts of Interest

The authors have nothing to disclose.

Availability of Data and Materials

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

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