

# Design of a Motion Simulation System to Assist Respiratory Gating for Radiation Therapy

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## Research

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# Abstract

## Background

Stereotactic ablative radiotherapy (SABR) aims to deliver high doses of radiation to kill cancer cells and shrink tumors in less than or equal to 6 fractions. However, organ motion during treatment is a challenging issue for this kind of technique. We develop a control system via Bluetooth technology to simulate and correct body motion during SABR.

## Methods

Radiation doses were analyzed, and the radiation damage protection capability was checked by external beam therapy 3 (EBT3) films irradiated by a linear accelerator. A wireless signal test was also performed. A validation was performed with 8 previously treated patient respiratory pattern records and 8 healthy volunteers.

## Results

The homemade simulation system consisted of 2 linear actuators, one movable stage with a maximal moving distance of 6.5 cm x 12.5 cm x 5 cm to simulate the respiratory pattern of 8 patients precisely with a median error of 0.36 mm and a maximal motion difference of 1.17 mm, and 3.17 and chipset transited signals to display them as a waveform. From the test with 8 volunteers, the chip could detect deep respiratory movement up to 3 cm. The effect of the chip on a radiation dose of 400 monitor units (MUs) by 6 MV photons and 200 MUs by 10 MV photons showed high penetration rates of 98.8% and 98.6%, respectively.

## Conclusions

We invented a tubeless and wireless respiratory gating detection chip. The chip has minimal interference with the treatment angles, good noise immunity and the capability to easily penetrate a variety of materials. The simulation system consisting of linear actuators also successfully simulates the respiratory pattern of real patients.

## Background

Stereotactic ablative radiotherapy (SABR) aims to deliver high doses of radiation to kill cancer cells and shrink tumors in less than or equal to 6 fractions<sup>(1)</sup>. However, both intrafraction and interfraction movements are issues that must be overcome due to the fact that they may reduce the precision and increase the radiation toxicity and even reduce the tumor control rate<sup>(2-6)</sup>. This problem can be improved

by commonly used methods, including applying image guidance during radiation therapy (RT) <sup>(6), (7)</sup> and reducing respiratory motion <sup>(8)</sup>. Several techniques currently used in clinical settings might reduce respiratory motion, including gating, active breathing coordination (ABC), the deep-inspiration breath hold technique, and surface image guided RT <sup>(9), (10)</sup>. However, several or dozens of pipelines and several transceivers around the patient might be needed to use the above techniques, which will interfere with the implementation of certain beam angles and noncoplanar beams. High-dose rate beam delivery, such as FLASH, may be an alternative solution but is only available in animal experiments and may not be suitable for larger tumors <sup>(11), (12)</sup>. Therefore, it is a worthwhile investment to develop RT with minimum pipelines.

Wireless signal transmission, such as the Bluetooth technique, has been widely used in clinical scenarios <sup>(13), (14)</sup>. However, interference between the device transmissions in a high-energy radiation environment is sometimes observed <sup>(15)</sup>.

Our study attempts to develop a chip that can sense respiratory motion precisely and work well in a high-radiation environment and a motor system with linear actuators that can simulate the respiratory pattern of real patients and help physicists perform a motion simulation to assist respiratory gating for RT.

## Results

### Smart Chip and the Simulation System

The homemade simulation system consisted of 2 linear actuators and one movable stage with a maximal moving distance of 6.5 cm (left-right) x 12.5 cm (posterior-anterior) x 5 cm (superior-inferior). The magic chip size was 3 x 4 x 2 cm, and the simulation system size was 50 x 27 x 30 cm. The stage movement rate was as follows: 1000 mm/min for the X axis and 2000 mm/min for the Z axis. The calibration system is shown in Fig. 1A, and the simulation system is shown in Fig. 1B.

### Patient Simulation and Detection

To validate the simulation, we tested 8 patients with metastatic adrenal gland lesions treated by SABR with a respiratory pattern record for gating control at our institute. The respiratory patterns were extracted, and the simulation motor factors were adjusted to fit the respiratory curve. We collected 13 respiratory points for each patient for a comparison, and the maximum error for a total of 104 points was 1.17 mm. The total mean difference between the patients' data and our simulation results was 0.36 mm. The patient simulation results are shown in Fig. 2.

### Volunteer respiratory pattern detection.

Eight volunteers were enrolled to validate the smart chip function. Each volunteer's respiratory pattern was detected successfully. Interestingly, even the deep respiratory pattern could also be detected well by our smart chip; the results are shown in Fig. 3.

## Interference Results

The percent depth dose of the beam data after 6 MV and 10 MV photon radiation was measured as shown in Fig. 4. The effect of the chip on the radiation dose of 400 MUs by 6 MV photons and 200 MUs by 10 MV photons showed high penetration rates of 98.8% and 98.6%, respectively.

## Discussion

Our homemade smart chip can sense respiratory motion precisely with an error less than 1 mm and can work well in a high-radiation environment; in addition, the motor system can simulate the respiratory pattern of real patients well even for deep breathing situations.

Motion reduction is an issue for SABR, and several suggestions and guidelines have been applied for lung cancers (16), (17). Some techniques, such as ABC, SDX, and surface imaging techniques, offer possible solutions to reduce the motion interference. However, all of the above techniques require the installation of extra facilities, and multiple lines and tubes are needed to set up the above systems. Moreover, the estimation of the position of a tumor may vary with the use of different respiratory monitoring systems and individualized systems (18), (19). Our system offers a wireless, continuous, and precise way to detect respiratory motion and an auxiliary system to supplement the above techniques, which might be helpful for better target delineation.

Radiation interference was observed in previous studies (15). Our chip has a high penetration rate of up to nearly 99%. Almost no dose interference will broaden the application of this system. It is worth aiming for further applications in a prospective study.

Our study also has some limitations. The lack of data from prospective studies or animal studies reduces persuasive power of our results. The whole simulation system did not pass Food and Drug Administration (FDA) tests. However, to the best of our knowledge, our smart chip and simulation system offer a chip-based, convenient, and precise solution to assist respiratory gating for RT.

## Conclusions

We invented a tubeless and wireless respiratory gating detection system. The system has minimal interference with the treatment angles, good noise immunity and the capability to easily penetrate a variety of materials. The system also successfully simulates the respiratory pattern of real patients.

## Methods

### Chip Design and Calibration System

The smart magic chip included the following materials: 1) a small chip with a size of 3 cm x 4 cm x 2 cm that can sense six degrees of freedom (6DOF) of movement; 2) one 3 V 160 m Ah button cell battery; and

3) a signal transmission and reception system built by Bluetooth technology. The chip calibration system was modified from an IBA (former Scanditronix Wellhofer) blue phantom WP 700.

### **Robotic 4D Stage and Control Configurations**

The motion correction simulation system with 6DOF included a motion stage and a control computer (LabVIEW, National Instruments, Austin, TX, USA). The stage was made by 3D printing . A translation of the left-right (x), superior-inferior (y), and anterior-posterior (z) axes and a rotation of the pitch (about the x axis) around a pivot point at the base of the platform could be applied.

### **Experimental Verification of the 4D Linear Actuator**

We performed a volunteer study and employed data from previously treated patients to test the system. The 8 volunteers were asked to rest in a comfortable supine position on a head support without the use of a mask or additional immobilization. With Alice PDx (Alice PDX; Philips Respironics, Best, The Netherlands), We further tested 8 patients who received adrenal SABR from 2014 to 2018 via a gating technique to verify our system. The accuracy of the compensation was verified in both studies.

### **Radiation Dose Evaluation and Management**

Radiation dose interference was also verified by a Linac accelerator Synergy® (Elekta, Crawley, UK). We delivered 400 MUs by 6 MV photons and 200 MUs by 10 MV photons with a field size of 10 cm x 10 cm to depths of 0 cm, 0.5 cm, 1.5 cm, 2.5 cm, and 5.5 cm. GAFCHROMIC® EBT3 films were used to analyze the dedicated dose and determine the amount of interference.

## **Declarations**

### **Ethics approval and consent to participate**

The study has been approved by our institutional review board (201809064RINA).

### **Consent for publication**

This research has no limitation for publication.

### **Competing interests**

The authors declare that they have no conflicts of interest.

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### **Authors' contributions**

JKW and YJW was responsible for drafting the article and for analysis and interpretation of the data. FMH was involved in the management of the patients. SHC was involved in data acquisition and analysis and interpretation of the data. SHL was involved in data acquisition. All authors read and approved the final manuscript.

### Availability of data and material

Experimental data and complementary examinations are available from the corresponding author on reasonable request

### Acknowledgements

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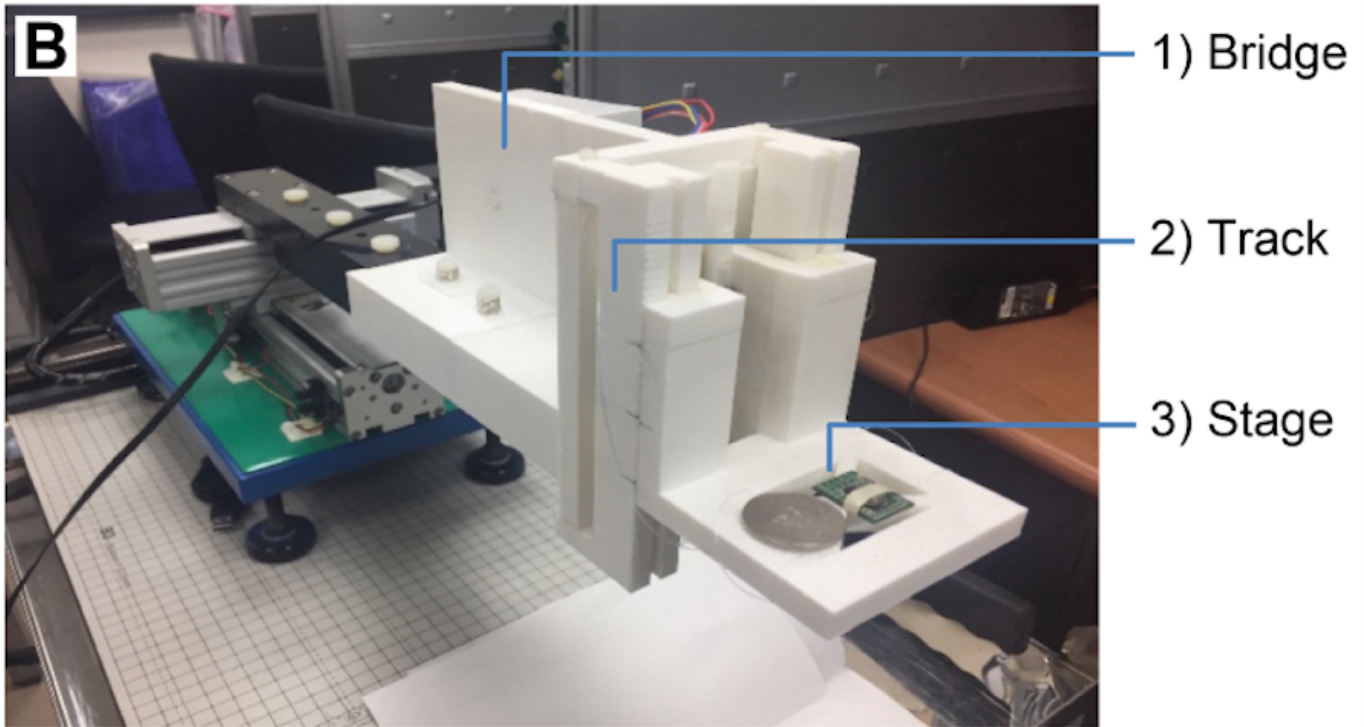
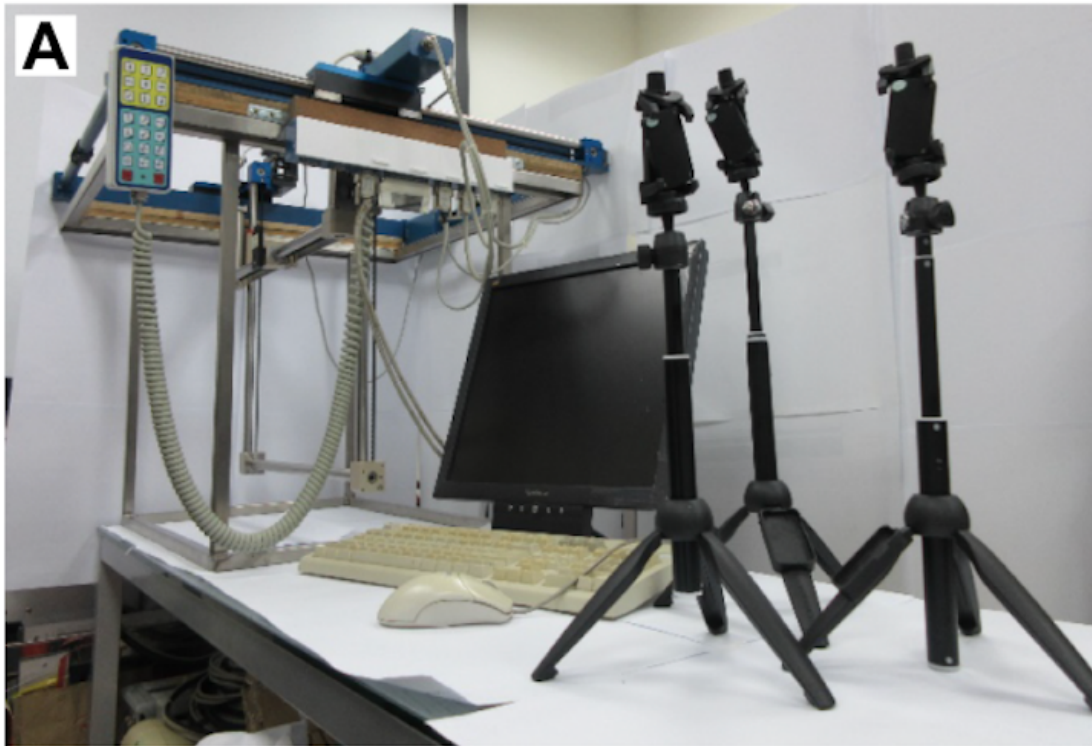
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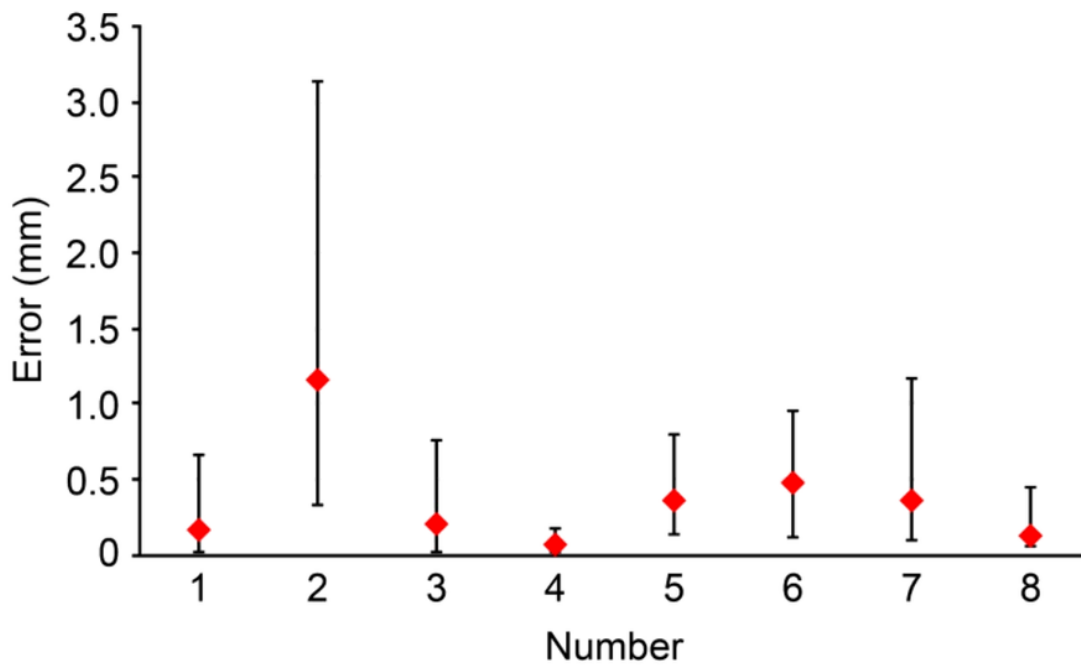
## Figures



**Figure 1**

(A) Modified calibration system and (B) homemade motion simulation system.





Red point: mean error.

Figure 2

The patient simulation results.

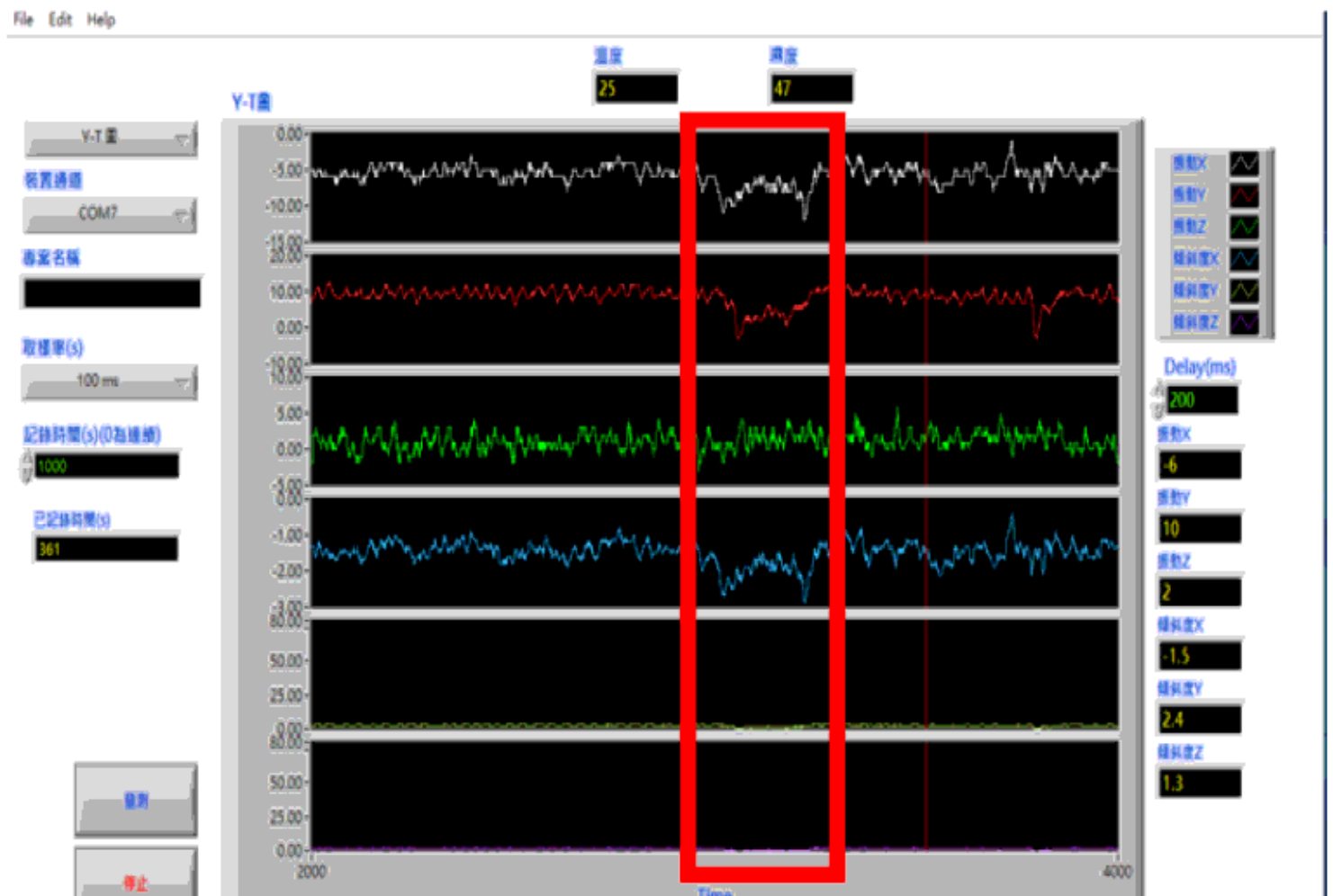


Figure 3

Smart chip function validation by volunteer respiratory motion pattern detection.

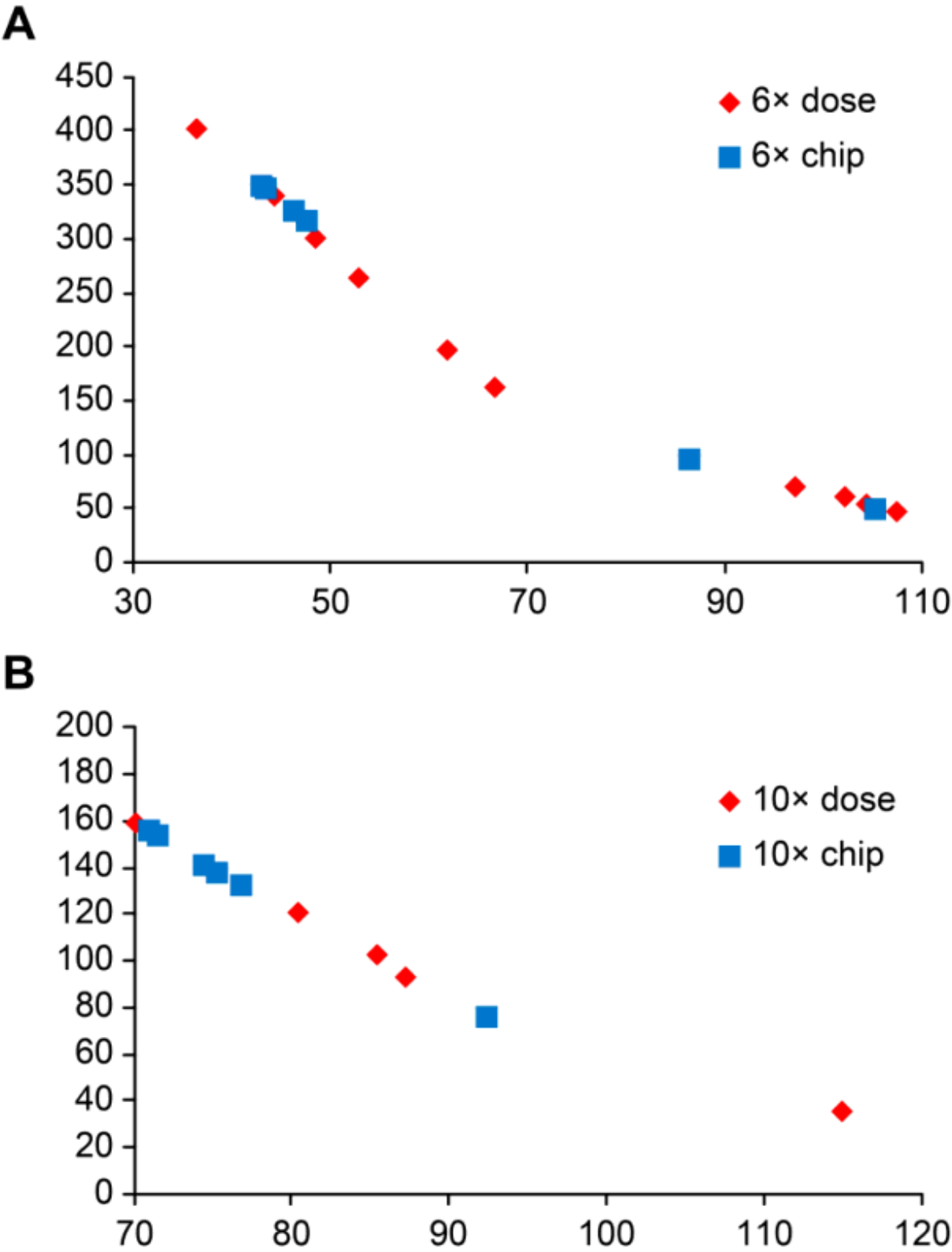


Figure 4

Radiation dose interference: (a) penetration status in the 6 MV environment and (b) penetration status in the 10 MV environment.