

DESIGN AND CONSTRUCTION

OF A RESPIRATORY MOTION PHANTOM FOR TESTING THE TARGETING ACCURACY OF THE CYBERKNIFE SYSTEM WITH THE SYNCHRONY® RESPIRATORY TRACKING SYSTEM

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Abstract

Tumor moving due to respiration during the radiation treatment process is difficult to manage. Without management for respiratory motion, the critical organs may receive a high radiation dose with decreasing target dose. Synchrony® respiratory tracking of the Cyberknife system provides the unique possibility to do real-time patient and tumor motion tracking.

An in-house respiratory motion phantom was designed and constructed for testing the targeting accuracy of the Synchrony® system. To simulate target and skin respiratory motions, an in-house respiratory motion phantom (17 × 45 × 15 cm³) made of acrylic was created. Inside the phantom, there were two parts; the mechanical part is composed of a cam and a slash cut pipe driven by a gear motor with 12 VDC to move the tumor and skin motion platform. The electrical part consists of AC to DC switching connected to an adjustable voltage regulator for supplying the gear motor. The amplitude and respiratory rate of the phantom were calibrated and evaluated using the Varian Real-Time Position Management (RPM) system. Then the phantom was used to test the targeting accuracy of the Synchrony® system by varying the amplitude of skin motion, respiratory rate, and tumor motion distance.

The phantom can be moved along the superior-inferior (SI) directions (tumor motion) with the distances of 15, 25, and 35 mm and moved along the anterior-posterior (AP) direction (skin motion) from 0 to 15 mm. The respiratory rates can be varied from 0 to 30 cycles/min. The maximum standard deviation of amplitude and the respiratory rate in the phantom were 0.22 mm and 0.089 sec/cycle, respectively. The targeting error of the Synchrony® system is less than 1.0 mm. The skin motion amplitude, respiratory rate, and tumor distance do not affect the targeting accuracy of the system.

KEY WORDS : Respiratory motion phantom/ Cyberknife/ Synchrony respiratory tracking system / Targeting accuracy

I. INTRODUCTION

Tumors in the chest and abdomen moved due to respiration during radiation treatment process is difficult to manage [1,2,3,4]. Without compensation for respiratory motion, the healthy tissue may receive a high radiation dose and the dose to the target is decreased. Synchrony® respiratory tracking of Cyberknife system provides the real-time tumor tracking of the patient and tumor motion based on the movement of the fiducials (internal markers) in the tumor and respiratory signal (from LEDs marker on the patient's skin surface) and moves the linear accelerator dynamically with the target [5]. For the quality control of the tracking system, a respiratory motion phantom is needed [6,7,8].

II. MATERIALS AND METHODS

A. Design and construction of the in-house respiratory motion phantom

The respiratory motion phantom model was designed to be able to simulate respiratory motion signal and tumor motion.

The acrylic plates with 5 mm thickness were used for fabricating an external part of the phantom and 3 mm for the skin motion platform (Fig. 1a) and holding the gear motor and also supporting two long sides of the phantom. The nuts and bolts were used to join every part together. The size of the phantom is $17 \times 45 \times 15$ cm³.

Inside the phantom, there are mechanical and electronic parts. The mechanical part is made of 3 mm thickness acrylic plate which consists of a skin motion platform (Fig. 1a), a tumor motion platform (Fig. 1b), slashed PVC pipes with 15, 25, and 10 mm long (Fig. 1c), and cam (Fig. 1d). One end of slashed pipe is attached with the cam and another end attached with the tumor motion platform (Fig. 1e) by using four nuts and bolts to move the platform in superior-inferior (SI) direction with the same length of the pipe. (The tumor motion platform can move by push of slash cut pipe and pull with tourniquet). Moreover, another side of the cam is attached with the gear motor to rotate the cam for moving the skin motion platform in AP and tumor motion platform in SI direction. The construction of the phantom is shown in Fig. 1f.

The electronic part is composed of an adjustable voltage regulator circuit which was assembled according to the circuit diagram illustrated in Fig. 2. The switching power supply converts the 220 VAC to 13.8 VDC and transfers the DC current to the adjustable voltage regulator circuit for driving gear motor with variable velocity adjusted by voltage regulator circuit.

The ball-cube phantom with Gafchromic film was scanned using axial mode, 120 kVp, and 1.5 mm slice thickness. A treatment plan was generated with the goal of 80% isodose line of 6.5 Gy conforming the outer surface of the acrylic ball target (left=31.75 mm, anterior=31.75 mm and superior = 31.75 mm) as shown in Fig.4.

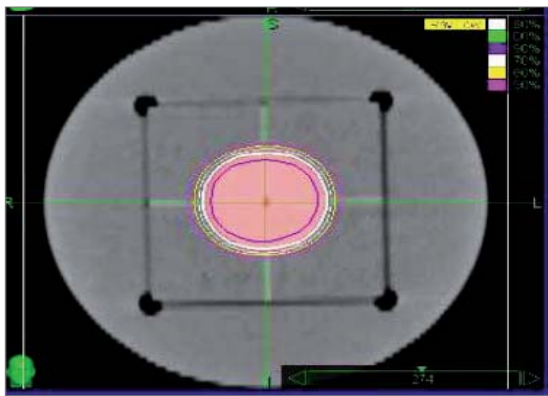


Fig.4 The 80% isodose line (white line) of 6.50 Gy covers the outer surface of ball target (pink circle)

Then the ball-cube with two pieces of unexposed Gafchromic film was placed on a piece of a 5 cm thick Styrofoam and then placed on the top of the tumor motion platform of respiratory motion phantom as shown in Fig.5.

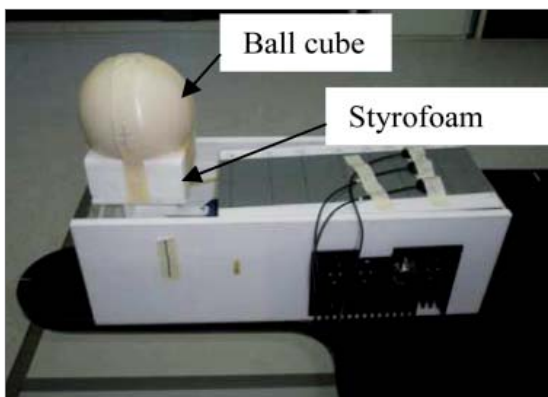


Fig.5 The setup of the in house respiratory motion phantom and ball cube

The phantom was exposed with the moving various parameters to verify and study the correlation of amplitude of skin motion of 6, 7.5, 9, 12 and 15 mm, respiratory rate of 5, 10, 15, 20, 25 and 30 cycle/min and moving tumor distance of 15, 25 and 35 mm.

The exposed and also unexposed films were scanned at the same time using a flatbed transparency scanner. During scanning, the anterior edge of the film was on the top and the left/superior edges were on the left of the image. Then the scanning images were analyzed using End to End (E2E) Film Analysis 2.0 Software tool as shown in Fig.6. All results of the centroid of dose distribution (total targeting error) were calculated. All total targeting errors of the centroid of dose distribution for each parameter group were analyzed by using one way ANOVA (Analysis of Variance).

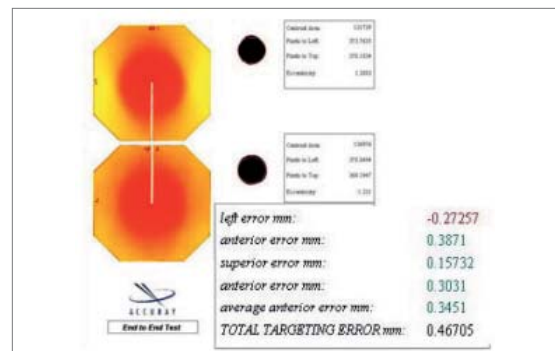


Fig.6 The centroid analysis E2E software in total targeting error (mm)

III. RESULTS

The respiratory phantom was constructed. It can be moved in two directions, supero-inferior with 15, 25 and 35 mm distances by tumor motion platform movement and antero-posterior in the range of 0 to 15 mm by moving the skin motion platform.

By adjusting the voltage regulator, the respiratory rate can be varied from 0 to 30 cycles per minute. The phantom is shown in Fig.7.

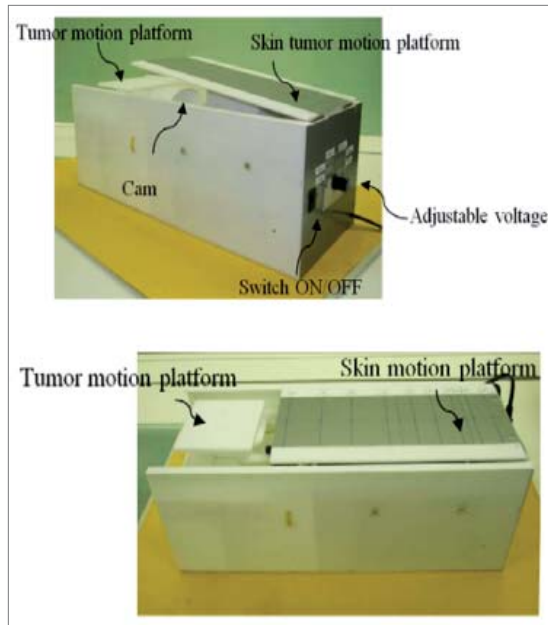


Fig.7 The completed in-house respiratory motion phantom

The maximum standard deviation of the amplitude of skin motion for the precision test is 0.22 mm. Also the maximum standard deviation of the respiratory rate is 0.089 seconds per cycle. The data in detail are shown in table 1 and 2, respectively.

Table 1 The standard deviation of amplitude position (mm) of the respiratory motion phantom

Setting value	Mean reading $\pm$ SD	Range (Min-Max)
6.0	6.0 ± 0	-
7.5	7.6 ± 0.22	7.5 - 8.0
9.0	9.0 ± 0	-
12.0	12.0 ± 0	-
15.0	15.0 ± 0	-

Table 2 The standard deviation of respiratory rate (sec/cycle) of the respiratory motion phantom

Setting value		Mean reading	Range
Cycle/min	Sec/cycle	$\pm$ SD	(Min-Max)
5	12	11.98 ± 0.045	11.9-12
10	6.0	6.04 ± 0.089	6.0-6.2
15	4.0	4.0 ± 0.07	3.9-4.1
20	3.0	3.0 ± 0.0	-
25	2.4	2.4 ± 0.07	2.3-2.5
30	2.0	2.0 ± 0.0	-

The total targeting errors with various amplitudes of skin motion, respiratory rates and tumor motion distances are shown in table 3, 4 and 5, respectively.

Table 3 Total targeting errors (mm) of various amplitudes of skin motion for 15 cycles/min respiratory rates and 25 mm tumor motion

Amplitude (mm)	No.			Mean $\pm$ SD	
	1	2	3		
6	0.40	0.94	0.75	0.70	± 0.27
7.5	0.31	0.65	0.34	0.43	± 0.19
9	0.55	0.33	0.77	0.55	± 0.22
12	0.45	0.63	0.57	0.55	± 0.09
15	0.75	0.78	0.98	0.84	± 0.13
Mean $\pm$ SD				0.61	± 0.22

Table 4 Total targeting errors (mm) of various respiratory rates for 7.5 mm amplitude of skin motion and 25 mm tumor motion

Respiratory rate(cycle/min)	No.			Mean $\pm$ SD	
	1	2	3		
5	0.53	0.37	0.61	0.50	± 0.12
10	0.61	0.28	0.33	0.41	± 0.18
15	0.31	0.65	0.34	0.43	± 0.19
20	0.25	0.46	0.33	0.35	± 0.11
25	0.79	0.32	0.583	0.56	± 0.24
30	0.83	0.37	0.55	0.58	± 0.23
Mean $\pm$ SD				0.47	± 0.18

Table 5 Total targeting errors (mm) of various tumor distances for 7.5 mm amplitude of skin motion and 15 cycles/min respiratory rate

Tumor distance(mm)	No.			Mean $\pm$ SD	
	1	2	3		
15	0.83	0.68	0.752	0.75	± 0.08
25	0.31	0.65	0.34	0.43	± 0.19
35	0.73	0.72	0.45	0.63	± 0.16
Mean $\pm$ SD				0.61	± 0.19

The mean values of the total targeting errors for the skin motion amplitude, respiratory rate and tumor motion are 0.61 ± 0.22 mm, 0.47 ± 0.18 mm and 0.61 ± 0.19 mm, respectively. By using the ANOVA statistical test to analyze the total targeting errors, there are no significant differences for the skin motion amplitudes from 6 to 15 mm (p-value = 0.1717, 95% CI), respiratory rate from 5 to 30 cycles/min (p-value = 0.5961, 95% CI) and tumor motion from 15 to 35 mm (p-value = 0.099, 95% CI).

IV. DISCUSSIONS

The in-house respiratory motion phantom was constructed and evaluated using the Varian RPM system. The phantom consists of two platforms for two directions of motion: superior to inferior with the distances of 15, 25 and 35 mm and anterior to posterior from 0 to 15 mm. The respiratory rate can be varied from 0 to 30 cycles per minute.

The measurement values in the standard deviation of amplitude of skin motion and respiratory rate indicated that the stability of the respiratory motion phantom is fairly stable and acceptable with maximum standard deviation of 0.22 mm amplitude and 0.089 seconds/cycle respiratory rate. This is due to stable voltage supplying to the gear motor. However, the problem of the respiratory motion

phantom is the heat from the gear motor and the adjustable voltage regulator circuit which could be broken if it moves for a long period of time. This problem may be solved by moving the heat sink outside the phantom.

According to the evaluation of targeting accuracy of Cyberknife with Synchrony® respiratory tracking system, although, the amplitude of skin motion, respiratory rate and tumor distance are varied in human standard range, the Synchrony® system has sufficient performance for moving treatment target with the maximum error of 0.61 ± 0.22 mm. The result agrees with the other studies, three Cyberknife centers [9] with the error of 0.7 ± 0.30 mm and Wong et al [10] with the error of 0.82 ± 0.27 mm. Consequently, the total system error of the Cyberknife system with Synchrony® respiratory tracking system could be ensured with error less than 1.0 mm.

V. CONCLUSION

From this study, the respiratory motion phantom was designed and constructed. The performance of the phantom was calibrated and evaluated using the Varian RPM system. The results show sufficient accuracy and stability. After evaluation, it was used to test the targeting accuracy of the Cyberknife system with the Synchrony® respiratory tracking system.

This phantom is very useful and convenient tool for independently testing the targeting accuracy of the Synchrony® respiratory tracking system.

The maximum targeting error of the Synchrony® respiratory tracking system tested by this respiratory motion phantom is 0.61 ± 0.22 mm. By using

ANOVA statistical test, it is found that the targeting accuracy of this system does not depend on amplitude of skin motion, respiratory rate and tumor motion distance (p-value > 0.099, 95% CI).

The testing of the Cyberknife with the Synchrony® respiratory tracking system using the respiratory motion phantom shows that it is suitable for clinical treatment with only a sub-millimeter error.

VI. References

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