Performance assessment of a programmable five degrees of-freedom motion platform for quality assurance of motion management techniques in radiotherapy

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Compliance with ethical standards

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Ethical approval This article does not contain any studies with human participants or animals performed by any of the authors.

Abstract

Inter-fraction and intra-fraction motion management methods are increasingly applied clinically and require the development of advanced motion platforms to facilitate testing and quality assurance program development. The aim of this study was to assess the performance of a 5 degrees-of-freedom (DoF) programmable motion platform HexaMotion (ScandiDos, Uppsala, Sweden) towards clinically observed tumor motion range, velocity, acceleration and the accuracy requirements of SABR prescribed in AAPM Task Group 142. Performance specifications for the motion platform were derived from literature regarding the motion characteristics of prostate and lung tumor targets required for real time motion management. The performance of the programmable motion platform was evaluated against (1) maximum range, velocity and acceleration (5 DoF), (2) static position accuracy (5 DoF) and (3) dynamic position accuracy using patient-derived prostate and lung tumor motion traces (3 DoF). Translational motion accuracy was compared against electromagnetic transponder measurements. Rotation was benchmarked with a digital inclinometer. The static accuracy and reproducibility for translation and rotation was <0.1 mm or <0.1°, respectively. The accuracy of reproducing dynamic patient motion was <0.3 mm. The motion platform's range met the need to reproduce clinically relevant translation and rotation ranges and its accuracy met the TG 142 requirements for SABR. The range, velocity and acceleration of the motion platform are sufficient to reproduce lung and prostate tumor motion for motion management. Programmable motion platforms are valuable tools in the investigation, quality assurance and commissioning of motion management systems in radiation oncology.

Introduction

Tumors are not static during radiotherapy treatment but move dynamically, especially for thoracic, abdominal and pelvic cancers. Prostate tumors were observed to translate up to 25 mm during radiotherapy [1] and lung tumors to rotate up to 45° [2]. In the modern image-guided radiation therapy (IGRT) era, a number of imaging techniques such as cone-beam computed tomography (CBCT) have reduced the impact of interfractional tumor motion [3]. Intrafractional tumor motion management is currently the more critical issue to manage and various strategies to detect and correct or encompass motion are in use or under investigation. For example, continuous kV imaging [4] and Calypso electromagnetic transponders (Varian, CA, USA) [1] have been used for tumor motion detection. Couch tracking [5], gating [6, 7], dynamic multileaf collimator (DMLC) tracking [8], robotic tracking with CyberKnife [9] and VERO [10] techniques have all been used for treatment adaptation.

With the recent clinical implementation of tumor motion monitoring and MLC tracking on standard linear accelerators [11, 12, 13], adaptive radiotherapy is set to become increasingly accessible. Clinical tools are required to evaluate the accuracy of the tumor motion management systems. Several 3D [14], 4D [15], static 6 degrees-of-freedom (DoF) [16] and dynamic 6 DoF [17] phantoms and motion platforms were built for the purposes of system commissioning, validation and quality assurance (QA) at academic clinics but commercial products are now becoming available.

This paper addressed the gap in knowledge of the performance of a commercial multidimensional programmable motion platform, HexaMotion (Scandidos, Uppsala, Sweden) for quality assurance of motion management in radiotherapy. We developed comprehensive performance criteria from literature and published clinical data for the Hexamotion. We also extended Cetnar's approach [18] to include the range, velocity and acceleration of the HexaMotion. These limitations are of importance when using the motion platform for linac machine QA.

Materials and methods

Determination of performance specification

We reviewed the radiotherapy equipment QA literature to develop performance specification for HexaMotion. Task Group 40 (TG40) recommended the threshold for QA medical accelerator to be 2 mm and 1° [19]. Task Group 142 (TG142)'s requirements for SABR is more demanding, with the spatial accuracy <1 mm/0.5° [20]. The tolerance of the on-board imager of the Novalis Tx linear accelerator was 2 mm/1° [21]. For modern motion adaptation systems, 1 mm was set for tolerance and the reported achievable geometric precision/accuracy was 0.7 mm [22], and 0.8 mm [23] for CyberKnife and VERO respectively.

To develop a comprehensive performance criteria, we further studied published clinical data [4] and calculate prostate and lung tumor mean and 95th percentile of motion range, velocity and acceleration for each of the 6 DoF. Up to 50 fractions of three lung cancer patients' and 276 fractions of ten prostate patients' data was analyzed.

Configuration of the motion platform and the assessment of the maximum range, velocity and acceleration

The Hexamotion consisted of two parts: the control system—software, Ethernet cable, remote control and the motion platform—a base stage with stepper motors and a cabled tower on wheels (Fig. 1). The HexaMotion was originally set up with the Delta4 dosimeter [18] (ScandiDos, Uppsala, Sweden, Fig. 1, bottom left) to verify dose in moving targets. It was also mounted on an in-house platform to carry user phantoms, such as anthropomorphic pelvis or dosimetry phantom (Fig. 1, bottom right).

The motion platform moves in 5 DoF—left–right (LR), superior–inferior (SI) and anterior–posterior (AP) pitch and roll in the IEC 1217:1996 coordinate system (Fig. 1, bottom right). We used in-house software to generate various input trajectory files to determine range, velocity and acceleration. An input trajectory file has five columns of data representing the 5 DoF motion with the unit of mm/° and in the frequency of 50 Hz.

The motion platform's range was determined by creating a long continuous motion trajectory with range slightly below the manufacturer's advice. This trajectory file was executed and revised up until it could not be carried out; then the range was determined. Maximum velocity and acceleration for each axis were determined individually in the same manner.

Assessment of the static position accuracy

The translation accuracy assessment was performed against the Calypso electromagnetic transponders tracking system, which has been shown to detect transponders with high system stability and precision [24, 25]. The in-house platform carried a cubic phantom with embedded Calypso transponders and moved to various designated positions (Fig. 2, left). Four positions were measured for LR, SI and AP axis respectively and each position was repeated five times. The transponder reported positions were compared with the input position.

The rotational accuracy of static angles was measured by a Digi-Pas™ DWL-280 inclinometer (Fig. 2, right) which has a manufacturer quoted resolution and accuracy of 0.05°. The inclinometer was calibrated before each set of measurements and then mounted on the Delta4, perpendicular to either roll or pitch rotation axes. The Delta4 rotated with HexaMotion and carried the inclinometer to rotate in pitch and roll independently. Six positions were chosen for pitch and five positions were chosen for roll. Each position was repeated five times. Rotation angle displayed on the inclinometer were recorded and compared with the requested rotation.

Hysteresis in the LR, SI and AP axis was tested by sending the HexaMotion to various positions, bringing it back and then measuring the returned position. Eight measurements were done for each axis.

Evaluation of the dynamic accuracy to reproduce patient measured trajectories

Two clinically recorded tumor motion trajectories were selected to assess the accuracy of reproducing dynamic motion: erratic prostate motion [26] and lung tumor motion [4]. The prostate erratic motion trajectory contains 14,734 data points and lasts 300 s which is long enough to represent a SABR treatment course. The lung tumor trajectory contains 7577 data points and spans 150 s, with amplitude of 1–3 mm and ~2 s per cycle. The lung tumor motion is faster so it represents a more challenging case for the motion platform. Only translational motion (3 DoF) was evaluated as there was no means available to independently measure rotation in real-time.

The motion platform was setup to carry a cubic phantom embedded with three Calypso transponders. Motion trajectories were executed and the transponders' real-time positions were recorded and used to compare with the ground truth—the requested trajectory. Alignment of the requested and measured trajectory was done by minimizing the root mean square differences between the two. We assumed there was no delay between the direction motion and the actual motion.

Results

Performance specification

We derived from published data and calculated the magnitude of lung and prostate tumor mean and 95th percentile of motion, velocity and acceleration for each of the 6 DoF—translation along and rotation about the LR, SI, AP directions (Table 1).

Maximum range, velocity and acceleration

The range, velocity and acceleration of the motion platform were measured and listed in Table 2. The HexaMotion pre-experiment setup involves self-calibration, aligning the system to room lasers and accepting the new origin. This updates the motion platform's position and range. Therefore for each setup, the range can be slightly different depending on the flatness of the bench/couch.

The translational range of the motion platform is much larger than clinical observed prostate and lung tumor motion specifications (Table 1). The acceleration was also high to encompass both sites' motion acceleration. The pitch range and velocity achieve the mean magnitude of motion but fail to encompass the 95th percentile of the prostate and lung tumor motion. The motion platform also lacks the yaw rotation capability.

Static position accuracy

The accuracy of discrete static positions was measured for the motion platform. It achieved accuracy <0.1 mm and <0.1° for each of the 5 DoF (Fig. 3). The reproducibility of the static position was less than 0.1 mm/° that error bars were too small to show. Hysteresis is minimal for HexaMotion. In 24 measurements in the LR, SI and AP directions, all data points were 0.0 mm besides one LR and one SI measurement were 0.1 mm.

Dynamic position accuracy

The 300 s prostate and the 150 s lung trajectories were executed and measured by the Calypso system. The requested trajectory (black lines) and the measured trajectory (colored lines) were compared and plotted against each other in Fig. 4. For lung trajectory, only a section was selected to show breathing cycles. Quantitatively, the motion platform demonstrated dynamic position accuracy better than 0.3 mm in individual cardinal axes (Table 3). It achieved the TG142 accuracy requirements of 1 mm/0.5°for SABR.

Discussion

Tumor motion creates one of the central challenges of radiotherapy. Many novel techniques, including tumor motion monitoring, adaptation and dosimetric evaluation have been recently developed or are being developed to reduce the negative impact of tumor motion. To effectively test and QA these novel techniques, a programmable motion platform is necessary. The HexaMotion is such a motion platform that can be programmed to move in 5 degrees-of-freedom (LR, SI, AP, pitch and roll) to reproduce clinically measured tumor motion trajectories. The HexaMotion cannot rotate in yaw. Clinical data showed that yaw is less prominent; with pitch the dominant rotation for prostate tumors and roll the dominant rotation for respiratory induced motion like lung [4]. This degree of freedom is accomplished through the rotation of the couch.

Our results agree favorably with Cetnar et al. who described the commissioning the HexaMotion phantom [18]. In this manuscript we extended Cetnar’s approach to include the range, velocity and acceleration of the HexaMotion. The performance was evaluated relative to patient-derived tumor motion compared to external respiratory motion. We used a different device—Calypso electromagnetic transponders to track the motion platform’s performance. We also measured the accuracy and precision of the HexaMotion with an in-house platform configuration which is widely applicable for various experiments compared to the result from the HexaMotion plus Delta4 configuration for dosimetry.

This paper also developed a comprehensive performance tolerance to QA motion management techniques. It is applicable to motion management studies in general. We compared the HexaMotion’s performance characteristics against these criteria and showed that the translational and rotational range, velocity and acceleration achieved the mean and the 95th percentile of the prostate and lung tumor motion range, velocity and acceleration, besides the 95th percentile of pitch range and velocity. Its static and dynamic positional accuracy achieved the TG142 accuracy requirements of 1 mm/0.5° for SABR. A limitation of the rotation measurements was that our in-house platform’s dimensions don’t match manufacturer’s Delta4 device length and the cubic phantom cannot be placed at the rotation pivot of the motion platform, therefore the requested and the Calypso reported rotation is not directly comparable.

The HexaMotion has been used as a tool to perform end-to-end test to verify the dosimetric accuracy of gated liver SABR treatment [27]. It has also been used in our center to facilitate the development of QA for novel motion management technologies such as kilovoltage intrafraction monitoring (KIM) [28, 29] and electromagnetic transponder-guided MLC tracking [11].

Conclusion

We characterized the performance and QA a programmable 5 degrees-of-freedom motion platform HexaMotion. The HexaMotion can achieve clinically relevant translation and rotation ranges besides yaw motion and the range and velocity for pitch. It reproduced individual patient-specific tumor trajectories, meets the TG142 accuracy requirements for SABR. The HexaMotion can serve as a tool to design, commission, validate and QA tumor motion management systems including imaging, real-time tumor position localization and motion adaptive radiotherapy treatment.

References

1. Kupelian P, Willoughby T, Mahadevan A, Djemil T, Weinstein G, Jani S, Enke C, Solberg T, Flores N, Liu D, Beyer D, Levine L (2007) Multi-institutional clinical experience with the calypso system in localization and continuous, real-time monitoring of the prostate gland during external radiotherapy. Int J Radiat Oncol Biol Phys 67:1088–1098

2. Plathow C, Schoebinger M, Fink C, Hof H, Debus J, Meinzer H-P, Kauczor H-U (2006) Quantification of lung tumor volume and rotation at 3D dynamic parallel MR imaging with view sharing: preliminary results. Radiology 240:537–545

3. Sonke J-J, Lebesque J, Van Herk M (2008) Variability of fourdimensional computed tomography patient models. Int J Radiat Oncol Biol Phys 70:590–598

4. Huang C-Y, Tehrani JN, Ng JA, Booth J, Keall P (2015) Six degrees-of-freedom prostate and lung tumor motion measurements using kilovoltage intrafraction monitoring. Int J Radiat Oncol Biol Phys 91:368–375

5. Qiu P, D D’Souza W, McAvoy TJ, Liu KR (2007) Inferential modeling and predictive feedback control in real-time motion compensation using the treatment couch during radiotherapy. Phys Med Biol 52:5831–5854

6. Keall P, Kini V, Vedam S, Mohan R (2002) Potential radiotherapy improvements with respiratory gating. Australas Phys Eng Sci Med 25:1–6

7. Keall PJ, Chang M, Benedict S, Thames H, Vedam SS, Lin PS (2008) Investigating the temporal effects of respiratory-gated and intensity-modulated radiotherapy treatment delivery on in vitro survival: an experimental and theoretical study. Int J Radiat Oncol Biol Phys 71:1547–1552

8. Colvill E, Booth JT, O’Brien R, Eade TN, Kneebone AB, Poulsen PR, Keall PJ (2015) Multileaf collimator tracking improves dose delivery for prostate cancer radiation therapy: results of the first clinical trial. Int J Radiat Oncol Biol Phys 92:1141–1147

9. Hoogeman M, Prévost J-B, Nuyttens J, Pöll J, Levendag P, Heijmen B (2009) Clinical accuracy of the respiratory tumor tracking system of the cyberknife: assessment by analysis of log files. Int J Radiat Oncol Biol Phys 74:297–303

10. Mukumoto N, Nakamura M, Sawada A, Takahashi K, Miyabe Y, Takayama K, Mizowaki T, Kokubo M, Hiraoka M (2012) Positional accuracy of novel X-ray-image-based dynamic tumortracking irradiation using a gimbaled MV X-ray head of a Vero4drt (MHI-TM2000). Med Phys 39:6287–6296

11. Keall PJ, Colvill E, O'Brien R, Ng JA, Poulsen PR, Eade T, Kneebone A, Booth JT (2014) The first clinical implementation of electromagnetic transponder-guided MLC tracking. Med Phys 41:020702

12. Booth JT, Caillet V, Hardcastle N, O'Brien R, Szymura K, Crasta C, Harris B, Haddad C, Eade T, Keall PJ (2016) The first patient treatment of electromagnetic-guided real time adaptive radiotherapy using MLC tracking for lung SABR. Radiother Oncol 121:19–25

13. Keall PJ, Ng JA, Juneja P, O'Brien RT, Huang C-Y, Colvill E, Caillet V, Simpson E, Poulsen PR, Kneebone A (2016) Realtime 3D image guidance using a standard LINAC: measured motion, accuracy, and precision of the first prospective clinical trial of kilovoltage intrafraction monitoring–guided gating for prostate cancer radiation therapy. Int J Radiat Oncol Biol Phys 94:1015–1021

14. Nakayama H, Mizowaki T, Narita Y, Kawada N, Takahashi K, Mihara K, Hiraoka M (2008) Development of a three-dimensionally movable phantom system for dosimetric verifications. Med Phys 35:1643–1650

15. Malinowski K, Noel C, Lu W, Lechleiter K, Hubenschmidt J, Low D, Parikh P (2007) Development of the 4D Phantom for patient-specific, end-to-end radiation therapy QA. Medical imaging. In: International society for optics and photonics, pp 65100E–65109E

16. Ngar DYK, Cheung ML-M, Kam MK-M, Poon W-S, Chan AT-C (2014) A novel compound 6D-offset simulating phantom and quality assurance program for stereotactic image-guided radiation therapy system. J Appl Clin Med Phys 14:100–116

17. Belcher AH, Liu X, Grelewicz Z, Pearson E, Wiersma RD (2014) Development of a 6DoF robotic motion phantom for radiation therapy. Med Phys 41:121704

18. Cetnar AJ, James J, Wang B (2016) Commissioning of a motion system to investigate dosimetric consequences due to variability of respiratory waveforms. J Appl Clin Med Phys 17:283–292

19. Kutcher GJ, Coia L, Gillin M, Hanson WF, Leibel S, Morton RJ, Palta JR, Purdy JA, Reinstein LE, Svensson GK (1994) Comprehensive QA for radiation oncology: report of AAPM radiation therapy committee task group 40. Med Phys 21:581–581

20. Klein EE, Hanley J, Bayouth J, Yin F-F, Simon W, Dresser S, Serago C, Aguirre F, Ma L, Arjomandy B (2009) Task group 142 report: quality assurance of medical accelerators. Med Phys 36:4197–4212

21. Kim J, Wen N, Jin J-Y, Walls N, Kim S, Li H, Ren L, Huang Y, Doemer A, Faber K (2012) Clinical commissioning and use of the Novalis Tx linear accelerator for SRS and SBRT. Appl Clin Med Phys 13:124–151

22. Antypas C, Pantelis E (2008) Performance evaluation of a CyberKnife® G4 image-guided robotic stereotactic radiosurgery system. Phys Med Biol 53:4697–4718

23. Solberg TD, Medin PM, Ramirez E, Ding C, Foster RD, Yordy J (2014) Commissioning and initial stereotactic ablative radiotherapy experience with Vero. Appl Clin Med Phys 15:205–225

24. Balter JM, Wright JN, Newell LJ, Friemel B, Dimmer S, Cheng Y, Wong J, Vertatschitsch E, Mate TP (2005) Accuracy of a wireless localization system for radiotherapy. Int J Radiat Oncol Biol Phys 61:933–937

25. Franz AM, Schmitt D, Seitel A, Chatrasingh M, Echner G, Oelfke U, Nill S, Birkfellner W, Maier-Hein L (2014) Standardized accuracy assessment of the calypso wireless transponder tracking system. Phys Med Biol 59:6797–6810

26. Langen KM, Willoughby TR, Meeks SL, Santhanam A, Cunningham A, Levine L, Kupelian PA (2008) Observations on realtime prostate gland motion using electromagnetic tracking. Int J Radiat Oncol Biol Phys 71:1084–1090

27. James J, Cetnar A, Dunlap NE, Huffaker C, Nguyen VN, Potts M, Wang B (2016) Validation and implementation of a wireless transponder tracking system for gated stereotactic ablative radiotherapy of the liver. Med Phys 43:2794–2801

28. Ng JA, Booth JT, O'Brien RT, Colvill E, Huang C-Y, Poulsen PR, Keall PJ (2014) Quality assurance for the clinical implementation of kilovoltage intrafraction monitoring for prostate cancer VMAT. Med Phys 41:111712

29. Keall PJ, Aun Ng J, O'Brien R, Colvill E, Huang C-Y, Rugaard Poulsen P, Fledelius W, Juneja P, Simpson E, Bell L, Alfieri F, Eade T, Kneebone A, Booth JT (2015) The first clinical treatment with kilovoltage intrafraction monitoring (KIM): a realtime image guidance method. Med Phy 42:354–358

Table 1
The magnitude of lung and prostate tumor mean and the 95th percentile of motion, velocity and acceleration of each of the 6 DoF

	Motion (mm, °)		**Velocity (mm/s, °/s)**		**Acceleration (mm/s^2, °/s^2)**	
	Mean	**95th percentile**	**Mean**	**95th percentile**	**Mean**	**95th percentile**
Lung						
LR	0.8	2.1	1.2	3.4	5.8	17.0
SI	1.8	5.3	2.8	7.4	13.9	36.8
AP	0.8	2.2	1.0	2.8	4.9	13.8
Pitch	1.8	5.7	3.2	10.9	15.8	54.3
Roll	2.2	6.4	4.0	13.0	19.9	64.8
Yaw	1.2	4.1	2.0	5.8	9.8	28.8
Prostate						
LR	0.3	0.9	0.1	0.2	0.5	2.0
SI	0.6	1.7	0.2	0.7	2.3	7.0
AP	0.6	1.8	0.2	0.6	1.8	6.0
Pitch	1.3	4.0	2.0	7.3	19.0	72.0
Roll	0.7	2.0	0.9	3.1	8.5	30.0
Yaw	0.6	1.7	1.0	3.5	9.4	34.0

Table 2

The HexaMotion maximum range, velocity and acceleration in each of the 5 degrees-of-freedom motion direction

	Range by software (mm, °)	Range by remote control (mm, °)	Velocity (mm/s, °/s)	Acceleration (mm/s^2, °/s^2)
LR	−43, 43	−52, 44	−30, 30	up to ±100
SI	−43, 43	−44, 49	−30, 30	up to ±100
AP	−40, 41	−44, 51	−37.5, 20	up to ±100
Pitch	−3.5[a,b], 8	−3.5[a,b], 8	−6[a,b], 7.5[a]	up to ±100
Roll	−11, 11	−16.1, 15.1	−10, 10	up to ±100

[a] Less than 95th percentile of lung tumor motion

[b] Less than 95th percentile of prostate tumor motion

Table 3

HexaMotion dynamic accuracy to reproduce patient measured trajectories

	Mean difference (mm)			**Root-mean-square error (mm)**		
	LR	**SI**	**AP**	**LR**	**SI**	**AP**
Prostate tumor trajectory	−0.3	0.1	0.1	0.2	0.1	0.1
Lung tumor trajectory	0.0	−0.1	0.0	0.3	0.2	0.1

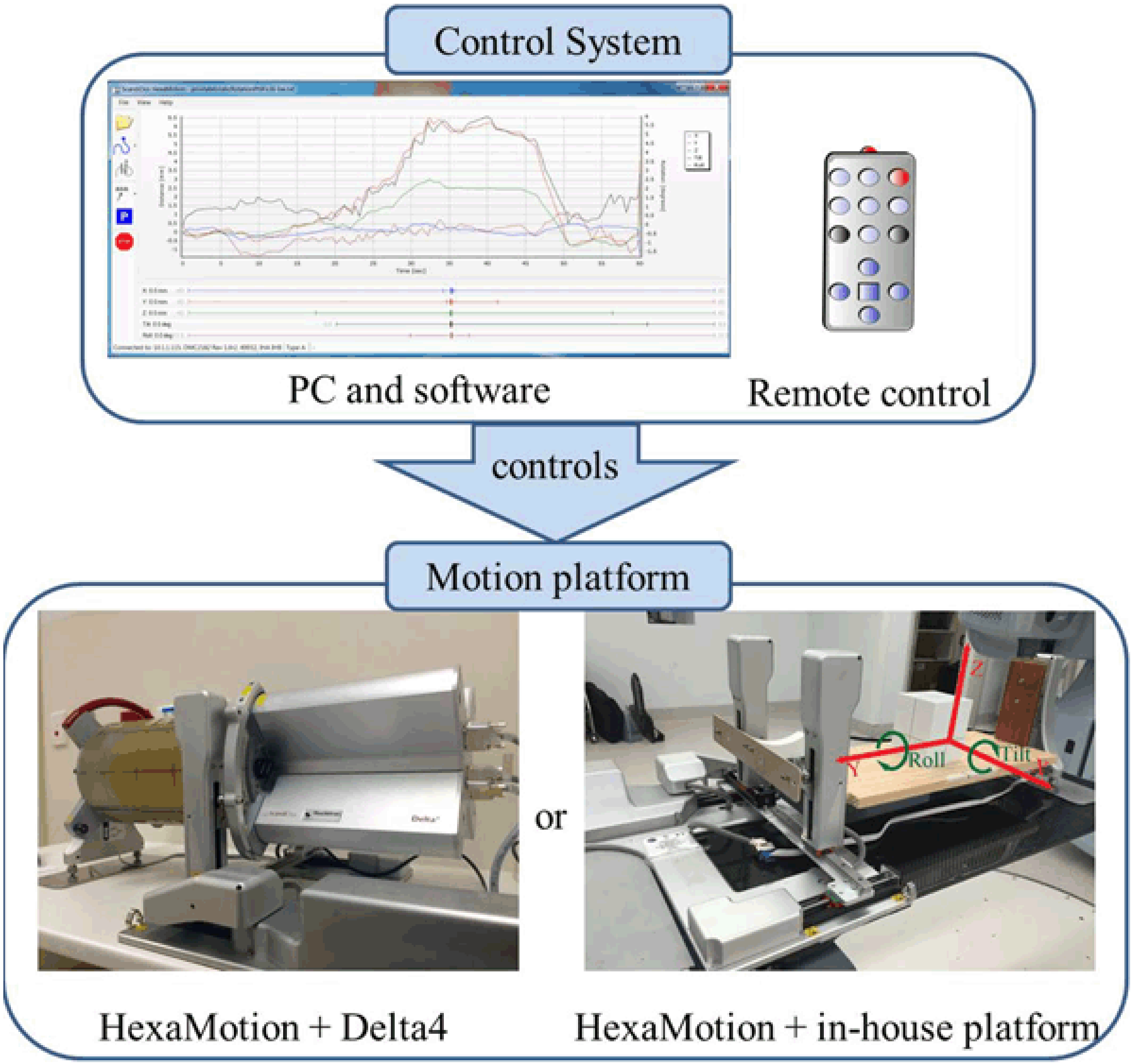

Fig. 1

Configuration of the HexaMotion. The motion platform can be configured with the Delta4 to measure dose or an in-house developed platform to carry other phantoms

Fig. 2

Calypso was used to measure the motion platform’s static translational motion accuracy (left), and the inclinometer was used to measure rotational motion accuracy (right)

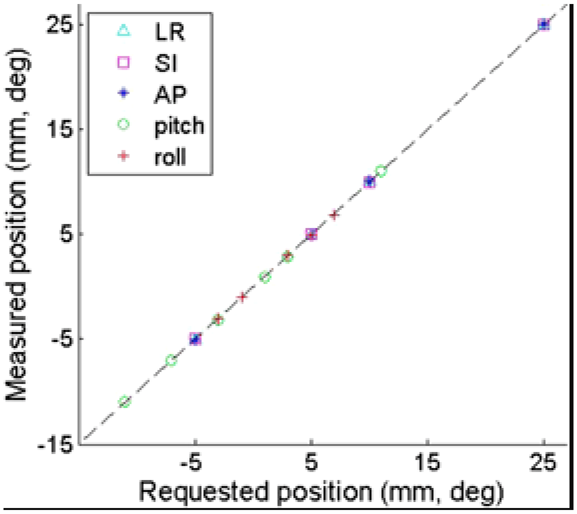

Fig. 3

HexaMotion static position accuracy

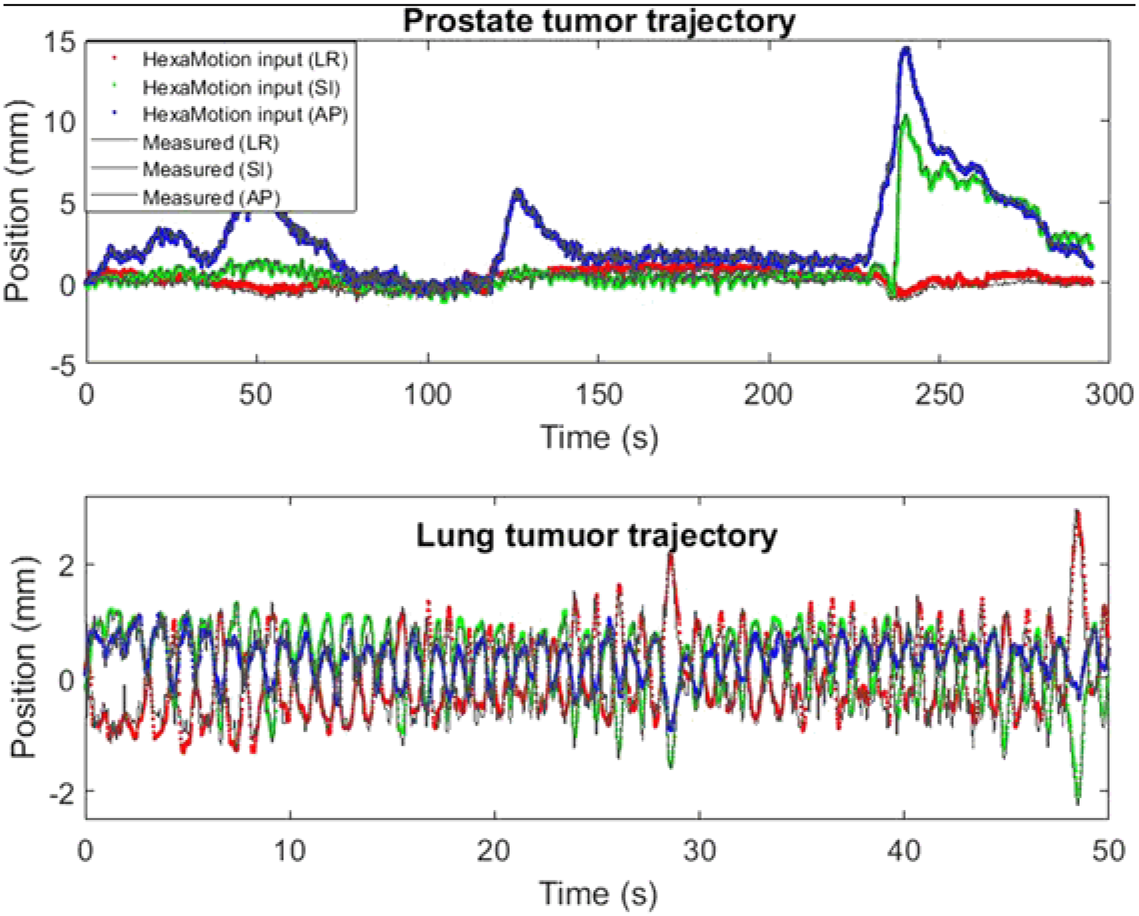

Fig. 4

The requested (black lines) and measured (colored lines) prostate and lung tumor trajectories