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Evaluation of the new respiratory gating system

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Abstract

Objective—The newly released Respiratory Gating for Scanners (RGSC; Varian Medical Systems, Palo Alto, CA, USA) system has limited existing quality assurance (QA) protocols and pertinent publications. Herein, we report our experiences of the RGSC system acceptance and QA.

Methods—The RGSC system integration was tested with peripheral equipment, spatial reproducibility, and dynamic localization accuracy for regular and irregular breathing patterns, respectively. A QUASAR Respiratory Motion Phantom and a mathematical fitting method were used for data acquisition and analysis.

Results—The results showed that the RGSC system could accurately measure regular motion periods of 3–10 s. For irregular breathing patterns, differences from the existing Real-time Position Management (RPM; Varian Medical Systems, Palo Alto, CA) system were observed. For dynamic localization measurements, the RGSC system showed 76% agreement with the programmed test data within ±5% tolerance in terms of fitting period. As s comparison, the RPM system showed 66% agreement within ±5% tolerance, and 65% for the RGSC versus RPM measurements.

Conclusions—New functions and positioning accuracy improve the RGSC system's ability to achieve higher dynamic treatment precision. A 4D phantom is helpful for the QA tests. Further investigation is required for the whole RGSC system performance QA.

Keywords

breathing curves; computed tomography; dynamic phantom; quality assurance; RGSC

1 | INTRODUCTION

Accuracy and precision of radiation therapy are essential to a successful radiation treatment, which requires localizing the target and positioning the patient to their treatment location. Therefore, the quality assurance (QA) of localization and positioning systems is critical for

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CONFLICT OF INTEREST

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accurately emplacing the patient to their treatment location. This is further complicated in the management of respiratory motion in radiation oncology.[1] A new respiratory gating system called Respiratory Gating for Scanners (RGSC; Varian Medical Systems, Palo Alto, CA, USA) has been implemented in clinics.[2] Because the system is relatively new to the field, few publications exist about acceptance testing and QA guidelines.[1,3–5] The American Association of Physicists in Medicine has published QA guidelines in referencing respiratory motion, which can be found in task group (TG) reports 76,[1] 142[3], and 147.[4] The TG-76 report explains the importance of frequent testing for not only the function of respiratory motion management device alone, but also for the accuracy of the device while interfacing with peripheral equipment, such as a computed tomography (CT) scanner. In TG-142, Klein *et al.* suggested that phase, amplitude, and gating interlocks should be tested for functionality, and the temporal accuracy of phase/amplitude gate on should be within 100 ms of their expected values. The temporal accuracy tolerance is recommended for respiratory gating devices on linear accelerator, but not given for those on CT simulator. In TG-147, more detailed information was provided by Willoughby *et al.* for the test of the integration of the respiratory gating device with peripheral equipment, spatial reproducibility and drift, static localization accuracy, dynamic localization accuracy, and vendor-recommended assessment. However, detailed procedures are still unavailable for the gating systems, especially for the RGSC system. Furthermore, the RGSC system has several features that differ from the Real-time Position Management (RPM) system (Varian Medical Systems), including new design of the reflector block for the CT simulator, and camera hardware and software.[6] These new features require investigation for new QA methodologies. Recently, a RGSC system was installed on the Philips Brilliance Big Bore 4D CT scanner (Philips Medical Systems, Andover, MA, USA) in our clinic. Following acceptance testing and a subsequent investigation of this system, we report our findings, and provide some detailed QA methods for the RGSC system.

To the best of our best knowledge, this was the first RGSC system installation in the USA, and there are few publications available for detailed QA guidelines and procedures of gating systems. Therefore, the present study can provide future users of the RGSC system with a point of reference.

2 | METHODS

2.1 | Equipment and tools

A recently installed RGSC system (SN 1825; Varian Medical Systems, Palo Alto, CA, USA) was used for the test that was interfaced with a recently installed Philips Brilliance Big Bore 16 CT scanner (SN 50566500972; Philips Healthcare,Andover, MA, USA). A CARINAiso 3 green laser system (LAP Laser, Boynton, FL, USA) was used as the alignment reference. A dynamic 4D phantom, QUASAR (Modus Medical Devices, London, ON, Canada) was also used in the QA of the RGSC system. A set of 30 × 30 × 30-cm^3 solid water (Gammex RMI; Sun Nuclear, Melbourne, FL, USA) slabs were used in certain tests as buildup material, and a regular ruler with millimeter resolution was also used. MATLAB (R2016a; The MathWorks, Natick, MA, USA) code was programmed to read in and compare the breathing curves recorded by the RGSC and RPM (version 1.6; Varian Medical Systems) systems. The breathing curves recorded from an RPM system were used for patient-specific breathing pattern tests and comparison. Up to now, the RGSC system was only benchmarked with a Philips CT scanner in the USA (personal communication with Varian Medical Systems representative); therefore, we only focused on its acceptance and commissioning for the Philips Brilliance Big Bore CT scanner in the present study. However, the procedures used should be easily adapted to other types of CT scanners.

2.2 | Acceptance test

The acceptance tests used were based on the vendor recommendation. Table 1 lists the tasks and corresponding expected results. First of all, the software version for the gating system needs to be of version 1.7 or higher, which can be verified through the software information button. The correct scanner setting and camera type need to be verified inside the software configuration tab. The gating system needs to be connected to the current ARIA (version 13 or above) record and verify (R&V) system. Hardware and software connection with the CT scanner needs to be tested as well. The camera motion position accuracy must be better than 2 mm, which can be tested by moving the reflector block by a millimeter distance. With a local or shared hard drive, the recorded breathing curve and patient Digital Imaging and Communications in Medicine file can be exported to the configured destination. Finally, the acceptance document needs to be signed by a local physicist and a representative from Varian for future reference.

2.3 | QA of integration with peripheral equipment

The RGSC system integration with the peripheral equipment should be checked, including integration with the R&V system and CT scanner. A dry run test of the RGSC system integration was carried out by scaning a QUASAR phantom, and sending the images through the Digital Imaging and Communications in Medicine protocol to the R&V system. There are four different scanning modes available in the RGSC system: “4D Scan,” “Phase Gating,” “Amplitude Gating,” and “Breath-hold Gating.” The “4D Scan” mode was tested by programming a QUASAR phantom with a sinusoidal breathing cycle of a 5-s period, and the phantom was CT scanned. The trigger signal from the RGSC system was synchronized with the CT scanner, and the 4D scan was then carried out. The CT images with correct breathing phases could be reconstructed by the CT scanner using the RGSC system recorded breathing curve file. For “Phase Gating” and “Amplitude Gating,” similar to the “4D Scan,” the QUASAR phantom was used, and the trigger signal was synchronized with the CT scanner during scanning. The CT software further generates the correct image set using the trigger signal file. To test the “Breath-hold Gating”, a pre-recorded breathing curve was loaded into the QUASAR software through a patient-specific curve import function. Then, CT images were acquired with the motion of QUASAR phantom reproducing the pre-recorded breath-hold breathing curve. All these CT scans should be successfully completed by working with RGSC system and with intended image sets reconstructed. Figure 1 shows the connection between the RGSC and a Philips CT scanner.

2.4 | QA of spatial reproducibility

One improvement over the RPM system is that the RGSC system can distinguish the markers’ positions in 3D. With the help of wall lasers and CT couch position digital indicator, the reflector block was moved left/right to the observer, in/out, and up/down 0.2 cm, 0.5 cm, 1 cm, 5 cm, 7 cm, and 10 cm in each direction to verify spatial reproducibility and accuracy. Before the shift detection test, the RGSC system was calibrated to the original position by detecting the reflector block aligned with the wall lasers' center (isocenter). For an up/down shift, the corresponding thickness of solid water was added/removed for the height. For an in/out shift, the couch was moved in/out of the gantry, and the reflector box was replaced back to the isocenter. For a left/right shift, the reflector block was physically aligned to the sagittal laser. Each test was repeated twice to reduce the random uncertainty. Figure 2 shows the test setups for the 5-cm shift.

2.5 | QA of dynamic localization accuracy, regular breathing pattern

To test the dynamic localization accuracy, the QUASAR phantom was programmed to move in a sinusoidal pattern with different periods ranging from 1 to 10 s. Then, the RGSC software-measured values for the inspiration and expiration were recorded for comparison. Figure 3 shows the QUASAR phantom setup and one of the screenshots for the measured values.

2.6 | QA of dynamic localization accuracy, patient-specific breathing pattern

To test the system limitation and ability, 50 previously recorded breathing curves using the RPM system for different patients were randomly selected and imported into the QUASAR phantom software as programmed input signals. The QUASAR phantom then generated motion as programmed to simulate the input breathing curves. All the programmed curves were previously recorded under patient free breathing simulation. The RGSC phase gated curves were recorded and compared with the RPM phase gated curves to observe the phase period matching. For comparison, the same curves were also programmed into the QUASAR phantom and recorded, respectively, using another RPM system.

For some patients, the RGSC system could not gate due to a system limitation on the time period (should be >3 s) or amplitude (should be >4 mm), but the curves could still be recorded. In extreme cases (such as period = 1 or 2 s, or amplitude = 2 or 3 mm), the curves could not be recorded at all. In total, 15 patients could not be gated due to either the shortness of the breathing cycle (≤3 s) or the small amplitude (≤4 mm). Among these 15 patients, two of them could not record. When the same set of breathing curves were tested on another RPM system using the QUASAR phantom, all the curves were able to be recorded.

To compare the phase period differences of the breathing curves recorded by the RPM and RGSC systems, the MATLAB program was written to read the "*.vxp" files generated by both systems. The curve fitting toolbox in MATLAB was used to fit the curves in the frequency domain by using the following function:

$$y = a0 + a1 \times \cos(\omega x) + b1 \times \sin(\omega x) + a2 \times \cos(2\omega x) + b2 \times \sin(2\omega x) \quad (1)$$

where y is the amplitude of the breathing curve, x is the time in seconds, a0, a1, a2, b1, and b2 are parameters for fitting, and $\omega \in [0, 2\pi]$ is the angular velocity in the unit of s^{-1}. The purpose of this fitting is not to fit the whole curve points precisely, but to derive the best fitted ω value for the breathing curves generated by both systems, because the curves were acquired under phase gating. Then the fitted period can be further derived by using period = $2\pi/\omega$. Therefore, we can observe how the system performed to capture the phase period in the patient-specific scenario.

2.7 | Camera thermal drifting test

Although the camera is shielded in a box and the room temperature is stable in the CT simulation room, it is still necessary to verify the camera thermal drifting in the beginning to establish a baseline. The "Breath-hold Gating" mode was selected for the test. For the first 30 min once the camera was plugged in, the breathing curves were recorded. The MATLAB program was used to analyze the recorded "*.vxp" data. By using the "Breath-hold Gating" mode, the recorded breathing curve was flat overall. With the thermal drifting, the breathing curve shows fluctuations and systemically goes down with time. To compare the thermal drifting, the average amplitude value in the first 15 min was compared with the averaged amplitude value in the second 15 min.

3 | RESULTS

3.1 | Acceptance test

All the tasks' results listed in Table 1 have met the specifications of the manufacturer. Because our system used a couch-mounted camera, the tasks for a wall-/ceiling-mounted camera did not apply. Because the video coaching device (VCD) was not purchased, the tasks for VCD were unavailable.[7] During the acceptance, one challenge could be obtaining department local IT and ARIA system administrator support. The RGSC system is integrated with the ARIA R&V system, which requires setting up the network connection with the organization to share files and connect to the ARIA system.

3.2 | QA of integration with peripheral equipment

The RGSC system integration with the Philips CT scan has been verified. The "4D Scan," "Phase Gating," "Amplitude Gating," and "Breath-hold Gating" functionalities were tested, and the results satisfied the manufacturer's specifications. The RGSC system can generate correct gating signals, and control the Philips CT scanner correctly.

3.3 | QA of spatial reproducibility

Table 2 shows the results for the spatial reproducibility and accuracy tests. The Philips CT coordinate system was used. When a patient lies on the couch in a head-first supine position, the positive Z direction points to the patient's anterior direction, the positive X direction to the patient's left side, and the positive Y direction to the patient's feet. The RGSC system has recommended <2 mm uncertainty for positioning. We found the spatial accuracy to be within 1 mm in the X and Z directions over a broad range of shifts. The spatial accuracy in the Y direction was the worst among all, but was still no more than 2 mm for shifts up to 5 cm. The results showed that the Y direction has lower accuracy than the X and Z directions – this might be because the camera is less sensitive to depth. However, the results were under the manufacturer's specification.

3.4 | QA of dynamic localization accuracy, regular breathing

Figure 4 shows a period comparison of the programmed sinusoidal breathing curves versus the recorded breathing curves. The RGSC manual suggests optimal working user breathing frequency of 6–20 respiratory cycles/min, or a breathing cycle corresponding to a 3–10-s period.[5] When the period is <3 s, the RGSC system might fail to record the curve and generate a gating signal. When the period is <1 s, the system predicted period would be incorrect compared with that of the programmed period. Figure 4 shows the period limitation of the RGSC system.

3.5 | QA of dynamic localization accuracy, patient-specific breathing pattern

Figure 5 compares the fitted periods of the programmed, RGSC recorded, and RPM recorded breathing curves, respectively. For the 48 recorded breathing curves, due to the irregularity of the breathing patterns, the RGSC system recorded differently from the RPM system. The programmed breathing curves could be considered as "ground truth." If within ±5% fitted period difference from the "ground truth" is considered as tolerance, for the RGSC system, 76% will be within tolerance. As a comparison, the RPM system will have 66% within tolerance. For the RGSC versus the RPM, 65% of the data will be within ±5% agreement. Therefore, the RGSC and RPM systems will measure the fitted period differently in the real situation. The differences could be due to an irregular patient breathing pattern, reflector block differences between the RPM and the RGSC systems, and/or the differences in system design and software algorithms.

3.6 | Camera thermal drifting result

Figure 6 shows the recorded data for the first 30 min once the camera was power on. The mean difference of drifting for the first 15 min and second 15 min was 0.086 mm. The maximum difference for the entire 30 min was 0.297 mm.

In summary, the newly designed RGSC system shows differences from the RPM system in both spatial accuracy and dynamic performance. Being more complex than the RPM system, the RGSC system requests extensive QA for system integration, as well as spatial and dynamic accuracy.

Considering clinical application and system limitation, we have proposed QA tasks for the RGSC system. Table 3 shows the recommended daily, monthly, and annual QA tasks for the new RGSC system.

4 | DISCUSSION

The RPM system has been implemented both in CT simulators and treatment machines for over a decade, and the QA on the system has been widely reported.[8–11] Cardenas *et al.* evaluated duty cycle, amplitude of fiducial motion, fraction of amplitude of motion during gated delivery, and respiratory cycle time; and suggested that a hardcopy of the gating traces can be used to document gated treatment delivery.[8] When the RPM system is used in our institution, we are in a total agreement of generating a document (*.pdf format) of the breathing traces for both gating patients and deep-inspiration breath hold patients. In addition, we suggest that such documents should be uploaded into the ARIA system for easy access and billing compliance. The whole process is not only time-consuming, but it might also bring error into the system, such as importing an incorrect patient document. The RGSC system is fully integrated with the ARIA R&V system, which will reduce those human errors and efforts. The new features of the software design will also assist the therapist/ physicist in better patient setup and system QA.

The RGSC system has several new features that are superior to the RPM system. (i) The infrared reflector block is designed in 3D instead of in a 2D plane, as in the RPM system used in the CT scanner. The four reflectors in 3D can provide the system better space information than in a single plane. (ii) The current camera system has a shielded design, as shown in Figure 1. The shielded box will screen out background lights and will also immobilize the camera, which improves the accuracy. (iii) The software design is totally different from the RPM system, which is not only integrated with the ARIA R&V system, but also designed under. Net framework, providing better software compatibility to the Microsoft Windows operating system. (iv) The overall system has dynamic accuracy compared with the RPM system, as shown in Figure 5a. (v) The current RGSC system has the time-period limit of 3 s and the amplitude limit of 4 mm, which is acceptable in clinical work, as most of the patients will breathe more than the 3-s period and higher than the 4-mm amplitude. It is only the QA limit for irregular breathing patterns. For real patients with breathing period < 3 sor amplitude < 4 mm, other clinical choices (such as using a breath control device) should be considered.

The RGSC system recently passed the US Food and Drug Administration clearance for clinical use.[12] The main reason that the RGSC system is superior to the RPM system might be due to improved camera resolution and better predictive functionality from the software design. Our preliminary findings showed the differences between the two systems, as highlighted in Figure 5, especially for irregular breathing patterns. For regular breathing patterns, the RGSC system performs as well as the RPM system. The results are listed in Table 2 and Figure 4. Therefore, to make the RGSC system work even better, audiovisual biofeedback information might help.[13] Because a VCD system was not installed, a test on the VCD was not carried out with our settings. The recommended QA tasks in Table 3 are based on the TG-142 and TG-147 reports, and our initial experience with the new RGSC system. Clinical physicists can implement these QA tasks according to the needs of their clinic. The tolerances provided should be reasonably achieved in the clinic, and satisfy the requirements of the TG-142 and TG-147 recommendations.

The present study serves as a reference guideline for the acceptance test, commissioning, and routine QA of the RGSC system installed in a radiotherapy clinic. However, clinical physicists are urged to establish their own clinical QA standards optimized for the needs of their clinic and available tools.

In this work, we have presented our experience of the new RGSC system acceptance and QA tests. The RGSC system performs differently from the RPM system in most cases. New functions and position accuracy might improve the RGSC system's ability for dynamic treatment precision. A 4D phantom, such as QUASAR, is helpful for QA tests. Further investigation is required for the whole RGSC system performance, including the delivery at the linear accelerators.

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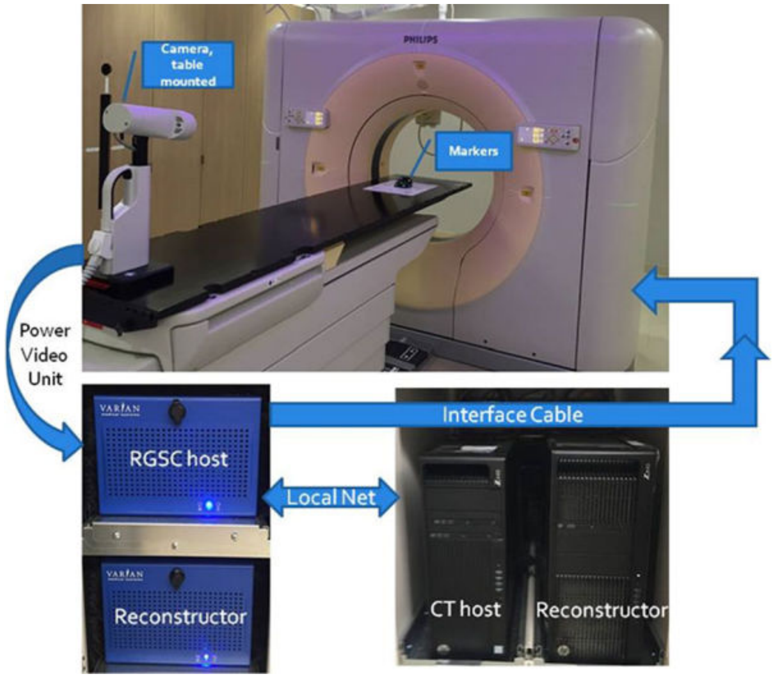

FIGURE 1.

Scheme of Respiratory Gating for Scanners (RGSC) and computed tomography (CT) scanner connections

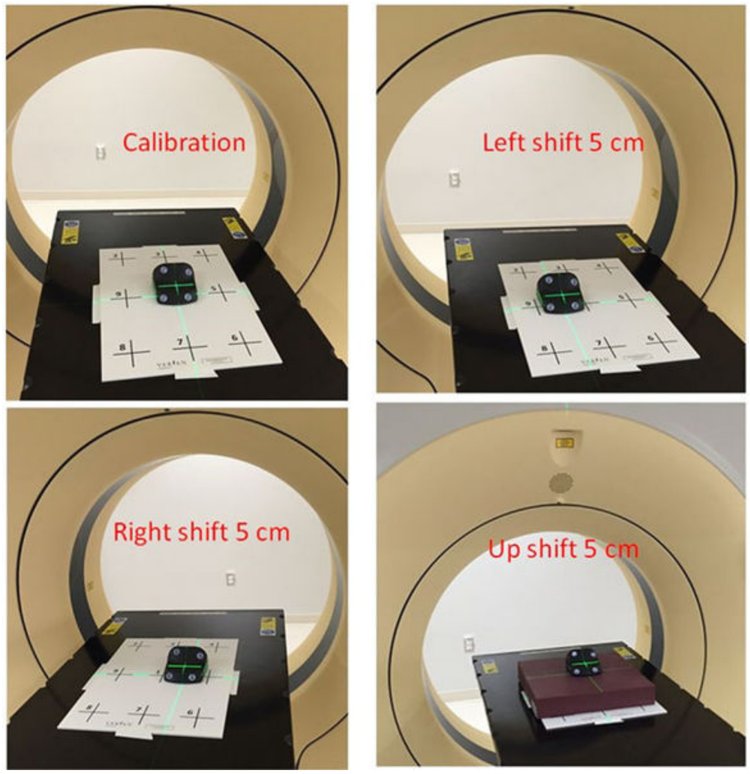

FIGURE 2.

Diagram of spatial location accuracy tests. The white plate provides background reflection and reference locations to place the reflector block. The newly designed reflector block with four markers was aligned with the wall lasers and at a location with a number on the white plate

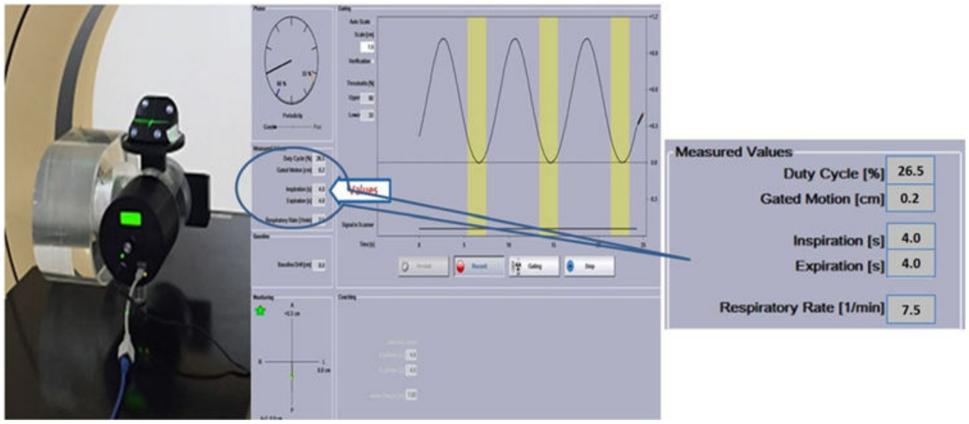

FIGURE 3.
QUASAR phantom setup for dynamic localization accuracy and screenshot of Respiratory Gating for Scanners software (here 8 s per breathing cycle)

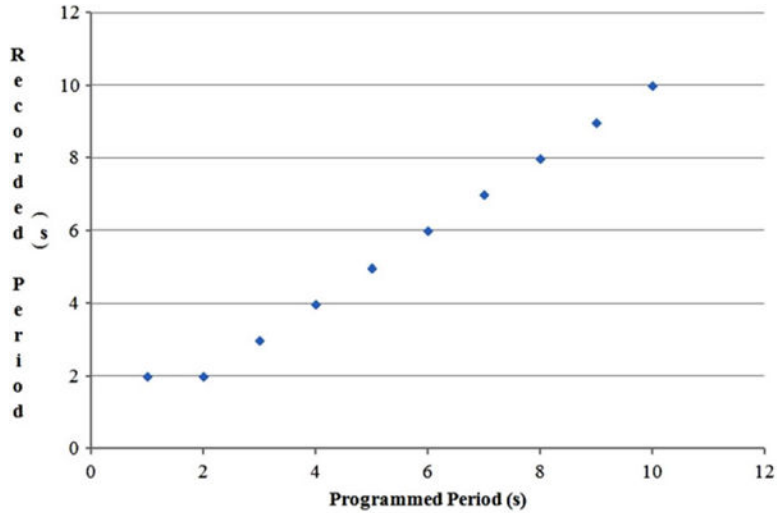

FIGURE 4.

Comparison between programmed period and recorded period

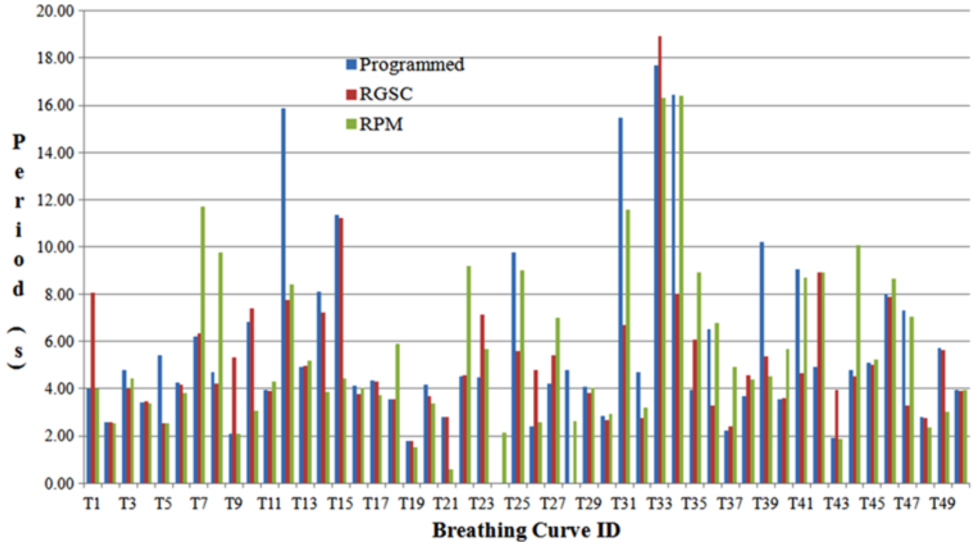

FIGURE 5.

Comparison of the calculated period for patient-specific breathing curves recorded by Real-time Position Management (RPM) and Respiratory Gating for Scanners (RGSC) systems

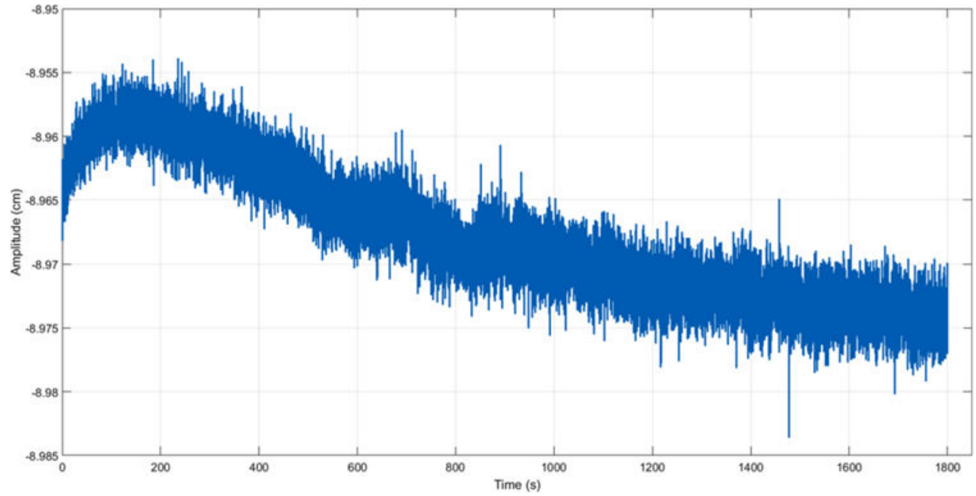

FIGURE 6.

Trace plot for the first 30 min since the camera was plugged in. The *y*-axis shows the distance away from the calibration point. The *x*-axis shown time elapsed since the camera was plugged in

TABLE 1

Acceptance tasks of a new Respiratory Gating for Scanners system[7]

Task	Purpose	Expected result
1	Software version	Software version ≥1.7
2	Scanner vendor and camera type	Scanner manufacturer should be verified and camera type is correct
3	Integration with ARIA system	ARIA is higher than version 13
4	Calibration of camera	Pass
5	Integration with scanner	Hardware connection and software control
6	Camera motion position accuracy in 3D	≤2 mm
7	Export breathing curve	File can be exported to destination
8	Export patient into database	File can be exported into the database
9	Export breathing pattern as DICOM	DICOM file can be exported
10	Documents	User related documents are available from vendor

DICOM, Digital Imaging and Communications in Medicine.

TABLE 2

Static physics coordinate accuracy results

Direction	Shift amount						
	0.2 cm	**0.5 cm**	**1 cm**	**3 cm**	**5 cm**	**7 cm**	**10 cm**
X-Left of the observer	0.2	0.5	1.0	3.0	5.0	7.0	10.0
X-Right of the observer	0.2	0.5	1.0	3.0	5.0	7.0	10.0
Y-In to the gantry	0.2	0.5	1.0	3.0	4.8	6.8	9.8
Y-Out of the gantry	0.2	0.5	1.0	2.9	4.8	6.8	9.8
Z-Up shift	0.2	0.5	1.0	3.0	5.0	7.0	9.9
Z-Down shift	0.2	0.5	1.0	3.0	5.0	7.0	10.0

TABLE 3

Recommended quality assurance tasks for daily, monthly, and annual quality assurance

Period	Tasks	Tolerance
Daily	Calibration of camera	Pass/fail
Monthly	Calibration of camera	Pass/fail
	Spatial localization accuracy	≤2 mm[7]
	Dynamic localization accuracy – regular	≤0.1 s[3] for the period of range of 3–10 s
Annual	Calibration of camera	Pass/fail
	Integration of peripheral equipment	End-to-end pass/fail
	Spatial localization accuracy	≤2 mm
	Dynamic localization accuracy-regular	≤ 0.1 s[3] for the period of range of 3–10 s
	Dynamic localization accuracy-irregular	≤ 0.2 s[+] for the period of range compared with acceptance recorded curve

[+]Based on the authors' experience.