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Abstract

Background: The objective was to investigate the change in segmentation error of Radixact® Synchrony® lung treatment after its kV imaging system was upgraded from Generation 1 to Generation 2 in the ClearRT™ installation.

Materials and methods: Radixact® Lung Synchrony® plans were created for the Model 18023 Xsight® Lung Tracking "XLT" Phantom combined with different lung target inserts with densities of 0.280, 0.500, 0.943 and 1.093 g/cc. After Radixact® Synchrony® treatment delivery using the Generation 1 and Generation 2 kV systems according to each plan, the tracking performance of the two kV systems on each density insert was compared by calculating the root mean square (RMS) error (δ_{RMS}) between the Synchrony-predicted motion in the log file and the known phantom motion and by calculating δ95%, the maximum error within a 95% probability

threshold.

Results: The δ_{RMS} and δ95% of Radixact® Synchrony® treatment for Gen1 kV systems deteriorated as the density of the target insert decreased, from 1.673 ± 0.064 mm and 3.049 ± 0.089 mm, respectively, for the 1.093 g/cc insert to 8.355 ± 5.873 mm and 15.297 ± 10.470 mm, respectively, for the 0.280 g/cc insert. In contrast, no such trend was observed in the δ_{RMS} or δ95% of Synchrony® treatment using the Gen2 kV system. The δ_{RMS} and δ95%, respectively, fluctuated slightly from 1.586 to 1.687 mm and from 2.874 to 2.971 mm when different target inserts were tracked by the Gen2 kV system.

Conclusion: With improved image contrast in kV radiographs, the Gen2 kV imaging system can enhance the ability to track targets accurately in Radixact® Lung Synchrony® treatment and reduce the segmentation error. Our study showed that lung targets with density values as low as 0.280 cc/g could be tracked correctly in Synchrony treatment with the Gen2 kV imaging system.

Key words: Radixact; synchrony lung treatment; ClearRT; log file

Introduction

Radixact® (Accuray, Sunnyvale, CA), a new generation of helical tomotherapy system with improved image acquisition and irradiation time [1], is equipped with intrafraction motion management system called Synchrony® adapted from the CyberKnife system [2–5]. Radixact® Synchrony® can track well-defined targets, such as implanted fiducials or lung tumors, directly and enables the treatment beam to be proactively synchronized to the predicted location of the target during treatment delivery with the combined jaw and multileaf collimator (MLC) tracking [6]. This technique can increase the precision of treatment delivery, which leads to further reductions in the margin size of the target [7–10]. A case report by W. Okada

has demonstrated that Radixact® Synchrony® for lung and liver cancer treatment is clinically feasible and effective in reducing the dose delivered to the lung or liver [11].

To perform proactive beam synchronization with tumor motion, a Synchrony® model must be built before treatment delivery; this model correlates the respiration cycle with the motion of an internal tumor of the respiratory system. A set of light-emitting diodes (LEDs) are placed on the patient's skin and act as an external surrogate for respiratory phase detection by camera. To determine the internal position of the treatment target, a kV imaging system including a kV tube and flat panel detector mounted on the Radixact® gantry rotates around the patient and produces sequential monoscopic images at two to six selected imaging angles during treatment. Target positions from different kV radiographs are detected by the system and correlated to different respiratory phases based on the position of the LEDs throughout the patient's respiratory cycle to create a Synchrony® model. After the model is accepted, Radixact® Synchrony® produces a continuously updated map of where the target is predicted to be based upon the captured motion of a set of LEDs [12]. The MLCs and jaws of Radixact® move accordingly to track the predicted positions of the target throughout treatment delivery.

According to recent studies, 5 different types of error may be produced during Synchrony® treatment:

1 — Segmentation error, results from the position difference of the target between digitally reconstructed radiographs (DRR) and the kV live image;

2 — Deformation error, which is generated from the difference in identifying the target in live image and the planning CT image due to deformation of the target region;

3 — Correlation error, occurs in the difference between the calculated tumor position

from the model and the actual tumor position in live image;

4 — Prediction error, results from the difference of predicted target position generated from prediction algorithm and the corresponding correlation model;

5 — Targeting error, generated from the offset of the machine in moving the treatment beam to the actual target position. Segmentation error is mainly affected by the quality of live image. Deformation error is determined by the influence of internal organ motion on the target position or change in target size or shape during the treatment course. Correlation, prediction and target errors are mainly determined by the system performance [9, 13].

One key to the success of Radixact® Synchrony® treatment is the capability of Radixact® of tracking the position of internal targets precisely in kV radiographs in order to minimize the segmentation error. If the contrast of the tumor in the radiographs is not sufficient for system detection, the segmentation error becomes large and fiducial markers must be implanted around the treatment site to help identify the tumor position precisely.

The generation 1 (Gen1) of Radixact® kV imaging system is designed to produce kV planar imaging, especially for Synchrony® treatment. Recently, Accuray added a new feature, ClearRT™ helical fan-beam kVCT imaging, to the Radixact® Synchrony® system. With the installation of ClearRT™, the Radixact® kV imaging system, including an X-ray tube and detector, is redesigned from generation 1 (Gen1) to generation 2 (Gen2). According to a study by Christian Velten [14], the image quality of kV radiographs is different between Gen1 kV system and Gen2 kV system; the spatial resolution of planar images is better for the Gen1 kV system (average = 1.14 lp/mm) than for Gen2 kV system(average = 0.97 lp/mm) while the contrast and contrast-to-noise ratio (CNR) of the Gen2 kV system are better from an

average of 40–47% and 9.4% respectively, than those of the Gen1 kV system. So the upgrade of kV system should affect the segmentation error of Synchrony® treatment. The main purpose of this study was to investigate which kV system, in the absence of fiducial markers, has better performance in tracking lung targets during Radixact® Synchrony® Lung treatment.

Materials and methods

Model 18023 Xsight ® Lung Tracking "XLT" Phantom Kit (CRIS) was used in the study (Fig. 1). This kit model has been verified and validated by Accuray for use with CyberKnife systems and is designed to work in conjunction with the Synchrony® System; thus, it can be applied in Radixact® Synchrony® treatment as well [15].

The cylindrical lung equivalent insert of the phantom is connected to an actuator with the preprogrammed motion controller, which can induce periodic linear motion of the insert along the IEC-y direction, as shown in Figure 2. The waveform of the motion was modeled by the following equation:

$$y(t) = A * \left(1 - \cos^4\left(\frac{\pi t}{2T}\right)\right) - \frac{A}{2} \quad , \tag{1}$$

where y is the position of the lung insert along the IEC-y direction as a function of time t. A is the peak-to-peak distance of the motion waveform (= 3.0 cm). T is the period of the motion (= 5 seconds). As shown in Figure 3, the waveform produced by Equation (1) mimics the regular breathing of a real patient, in which more time is spent in the exhaling phase than in the inhaling phase [16]. The platform on which

the LEDs are placed, as an external surrogate for respiratory pattern detection, is attached to the actuator so that their motion is synchronized with no phase difference.

A customized rod was used instead of an original lung ball cube rod in the study. It was constructed to carry different cylindrical inserts of different density values, and it can fit into the phantom body with lung lobes and a spine as shown in Figure 4. In our study, the tracking performance was evaluated when inserts with density values of 0.280, 0.500, 0.943 and 1.093 g/cc were placed in the XLT phantom during Radixact® Synchrony® Lung treatment.

Synchrony treatment planning and delivery

This study was started before the ClearRT™ machine upgrade, when the Gen1 kV system was used by Radixact® for Synchrony® imaging. Planning CT of the XLT phantom with different density inserts was performed using a Siemens EDGE CT simulator. In total, 4 sets of CT images were taken with a 1 mm slice thickness for inserts of 4 densities: 0.280, 0.500, 0.943 and 1.093 g/cm^3. The images were exported to Accuray Precision v2.0 (Accuray Incorporated, Sunnyvale, CA) for Radixact® Synchrony® planning. The whole density insert in the XLT Phantom was delineated as the tracking volume (TV) and the planning tumor volume (PTV), as shown in Figure 5. The “Lung with Respiratory” Synchrony® method was chosen. A prescription of 6 Gy to V98% PTV and a pitch of 0.21 were set for plan optimization. A minimum field width of 1 cm was chosen because a tracking range of 1 cm field width was wide enough (± 2.0 cm) to cover the motion of the lung insert (± 1.5 cm). Six projections of kV images in which the tracking target did not overlap with the vertebrae of the phantom were chosen for target localization in

Synchrony® modeling. In total, 4 Radixact® Synchrony® plans with different lung density inserts were generated. The gantry period in each plan was kept below 25 seconds so that the number of kV images taken per respiration was at least 1.2 to avoid aliasing between respiratory frequencies and imaging frequencies.

In Radixact® Synchrony® treatment plan delivery, the phantom was placed motionless in the setup position on the couch for MVCT alignment, as shown in Figure 6. After the alignment was finished, the actuator of the phantom was turned on to set the lung rod in motion. The insert moved along with the lung rod according to the motion trace generated by Equation (1). In the Synchrony® model building stage, the imaging protocol for a medium-sized thorax was chosen. The range of threshold values of potential difference and measured Δ were set at 5-10 mm and 4-6 mm, respectively, depending on the modeling difficulty. If the model could not be built after the upper threshold parameters (potential difference = 10 mm and measured Δ = 6 mm) were applied for 10 minutes, the synchronization treatment was considered a failure, and the treatment delivery was aborted.

In total, 5 fractions of synchronization treatment using the Gen1 kV system were delivered according to each plan. A log file containing the performance of Synchrony® treatment was generated and retrieved after each treatment fraction to track and analyze performance.

After the machine underwent the ClearRT™ upgrade, the Gen1 kV system was replaced with Gen2 for Synchrony® treatments. Radixact® Synchrony® treatments were replanned using Accuray Precision v3.0 (Accuray Incorporated, Sunnyvale, CA) using the same CT, contours and treatment parameters as in previous planning. The Synchrony® treatment delivery was repeated five times according to those plans using a Gen2 kV imaging system. The imaging protocol, threshold values of

potential difference and measured Δ used in the Synchrony model building stage were the same as those used for Gen1 kV delivery. The tracking capabilities of the Gen1 and Gen2 kV systems on Synchrony® treatment plans were compared by analyzing the log files of treatment delivery.

Analysis of Radixact® Synchrony® tracking accuracy

The motion-tracking accuracy of two different kV imaging systems for each density insert was evaluated by comparing a log file of the Synchrony-predicted motion at every point during the treatment to the known motion trace of the insert as modeled by Equation (1). The time interval of the log file was determined by the LED camera acquisition rate, which was approximately 95 Hz. The motion trace of the insert was resampled with Equation (1) to match the LED camera acquisition rate. The root mean square (RMS) error between the Synchrony-predicted motion in the log file and the known phantom motion was calculated by the following equation:

$$\delta_{RMS}=\sqrt{\frac{\sum_{i=1}^{N}\left|y(t)-y_p(t)\right|^2}{N}} \quad (2)$$

where $y_p(t)$ represents the predicted positions of the target by Synchrony® as a function of time, while $y(t)$ represents the motion trace positions modeled by Equation (1) as a function of time. Moreover, tracking accuracy was measured using δ95%, demoting the maximum error within a 95% probability threshold. For example, a δ95% value of 1 mm means that the difference between the actual phantom motion and the tracked motion was 1 mm or less for 95% of the treatment

time. As each plan was delivered 5 times in the study, the values of δ_{RMS} and δ95% are presented as the mean ± standard deviation (SD) with n = 5.

Results

Examples of the predicted and known target positions in IEC-y as a function of time for Radixact® Synchrony® delivery with the Gen1 and Gen2 kV systems are plotted in Figure 7.

Tables 1a and 1b show the mean and SD of the δ_{RMS} and δ95% for Radixact® Synchrony® delivery under the Gen1 and Gen2 kV systems, respectively. It should be noted that in treatment delivery under the Gen1 kV system on the plan with a 0.280 g/cc lung insert, a synchronous model could not be built during the modeling stage in fraction 1 or fraction 3, and the treatment was considered to have failed in these two fractions. Only data from the remaining 3 fractions were available for calculating δ_{RMS} and δ95%.

The δ_{RMS} and δ95% for Gen1 kV systems became greater (less favorable) as the density of the lung insert decreased from 1.673 ± 0.064 mm and 3.049 ± 0.089 mm for a density of 1.093 g/cc to 8.355 ± 5.873 mm and 15.297 ± 10.470 mm, respectively, for a density of 0.280 g/cc. In contrast, no such trend was observed in the δ_{RMS} and δ95% of Synchrony® treatment using the Gen2 kV system. The δ_{RMS} and δ95%, respectively, fluctuated slightly from 1.586 to 1.687 mm and 2.874 to 2.971 mm when different density inserts were tracked under the Gen2 kV system.

Discussion

When the Gen1 kV imaging system was used to track a 0.280 g/cc lung insert, the system failed to build a Synchrony model in fractions 1 and 3. In the remaining three fractions, the δ_{RMS} and δ95% of the Synchrony plan were 8.355 ± 5.873 mm and

15.297 ± 10.470 mm, respectively. This poor performance was due to the inability of the Gen1 kV system to track the position of the low-density insert correctly. When the system used the incorrect target position to build the Synchrony® model, either the model building failed, as seen in fractions 1 and 3, or a large segmentation error was introduced to the model-predicted target position from the system and greatly increased the average δ_{RMS} and δ95%. Synchrony® treatment should be considered a failure for the target with a density of 0.280 g/cc under the Gen1 kV system.

The tracking performance of the Gen1 kV system was better for the 0.500 g/cc insert, with δ_{RMS} and δ95% improved to 4.078 ± 4.995 mm and 7.065 ± 8.834 mm, respectively. However, the system is sometimes still unable to track the density insert precisely, and a large error is introduced. As seen in the performance during fraction 1 delivery, the δ_{RMS} and δ95% reached as high as 12.972 mm and 22.021 mm, respectively, which are not clinically acceptable.

When inserts with high density values of 0.943 and 1.093 g/cc were used in Synchrony® treatment under the Gen1 kV system, the image contrast of the inserts was sufficient for them to be detected by the system; accordingly, the δ_{RMS} and δ95% were greatly improved, ranging from 1.673 to 1.775 mm and from 3.049 to 3.215 mm, respectively.

The performance in target tracking during Synchrony® treatment greatly improved when the Gen2 kV system was used instead of Gen1. As shown in Table 2, the δ_{RMS} and δ95% of the Synchrony® plan with different density inserts using the Gen2 kV imaging system ranged from 1.586 to 1.687 mm and from 2.874 to 2.971 mm, respectively.

Such accuracy was close to the level achieved when a high-density insert (0.943-1.093 g/cc) was used in Synchrony® treatment under the Gen1 kV system. It can be

concluded that with the improved contrast performance of the Gen2 kV system, a target insert with a density as low as 0.280 g/cc can still be tracked correctly in Radixact® Lung Synchrony® treatment.

A study by Ferris showed that when the kV imaging system was upgraded from Gen1 to Gen2, the kV doses per mAs were found to be reduced by ~66% for planar images during motion-synchronized treatments on Radixact® [17]. Hence, with the improved target tracking accuracy and the decrease in the kV imaging dose, the Gen2 kV system is a better option than the Gen1 system for Radixact® Lung Synchrony® treatment.

Although image contrast is a major factor in the performance of target tracking in Radixact® Lung Synchrony® treatment, its impact may be reduced in Radixact® Fiducial Synchrony® treatment, in which implanted fiducial markers are used for target localization. Fiducial markers are made of high-density materials such as gold, which can produce very high contrast in kV radiographs. This makes the segmentation error of Synchrony® less prone to the contrast performance of the kV detector. Other image quality factors such as spatial resolution may become more important in determining the tracking performance of Radixact® Fiducial Synchrony® treatment.

The limitations of our study include an inadequate motion trace and a limited, discrete set of density inserts used in the assessment. Only one motion trace can be generated by the Model 18023 XLT phantom kit in the study. The δ_{RMS} and $\delta 95\%$ under the Gen1 and Gen2 kV systems might be different if a motion trace with different amplitude, frequency and phase shift than the LED markers were used instead. Furthermore, the density inserts used in the study only included discrete density values of 0.280, 0.500, 0.943 and 1.093 g/cc. There is a large discontinuity in

the tracking performance evaluation between 0.500 and 0.943 g/cc. But our study still shows that the Gen2 kV system is more robust than Gen1 in Radixact® Lung Synchrony® treatment, as it can produce better tracking performance with the 0.500 and 0.280 g/cc density inserts. However, since this study is only capable of investigating the change in segmentation error of Synchrony® treatment due to kV system upgrade, other types of error, such as deformation error, cannot be evaluated throughout the study. The improved tracking performance only demonstrates that the segmentation error in Lung Synchrony® treatment can be improved under Gen2 kV system.

Conclusion

With improved image contrast in kV radiographs, the Gen2 kV imaging system can enhance the ability to track targets and reduce the segmentation error in Radixact® Lung Synchrony® treatment . Our study showed that lung targets with density as low as 0.280 cc/g can still be tracked correctly by the Gen2 kV imaging system. With the improved target tracking accuracy the Gen2 kV system is a better option than Gen1 for Radixact® Lung Synchrony® treatment.

Conflict of interest

The authors declare that they have no conflict of interest.

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None declared.

Ethical statement

This article does not contain any studies with human participants performed.

This article does not contain any studies with animals performed.

All patients data were anonymous for the retrospective study with approval obtained

from the research ethic committee of the Hong Kong Sanatorium & Hospital.

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Figure 1. The Model 18023 Xsight ® Lung Tracking “XLT” Phantom Kit

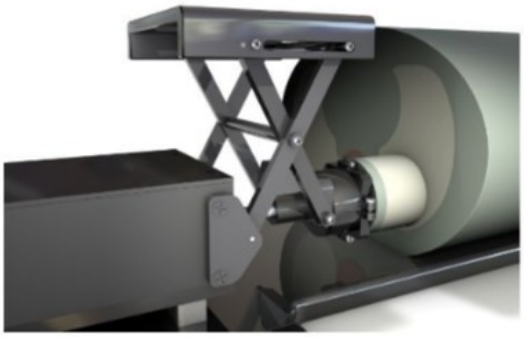

Figure 2. The lung insert is connected to the actuator, which can move along IEC-y

as modeled by Equation (1)

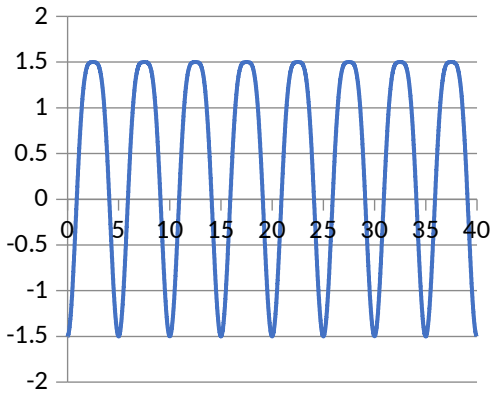

Figure 3. Waveform motion of the lung insert as modeled by Equation 1

Figure 4. A customized rod that could be equipped with cylinders of different densities was connected to the actuator as a lung insert in the study

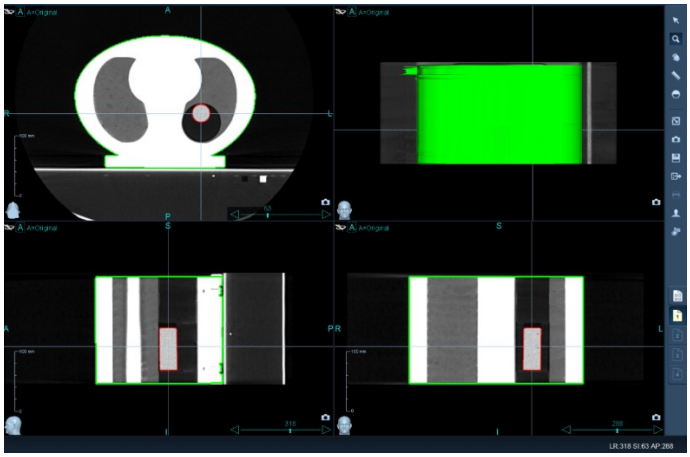

Figure 5. The cylindrical density insert in the moving rod of the phantom was delineated as the TV

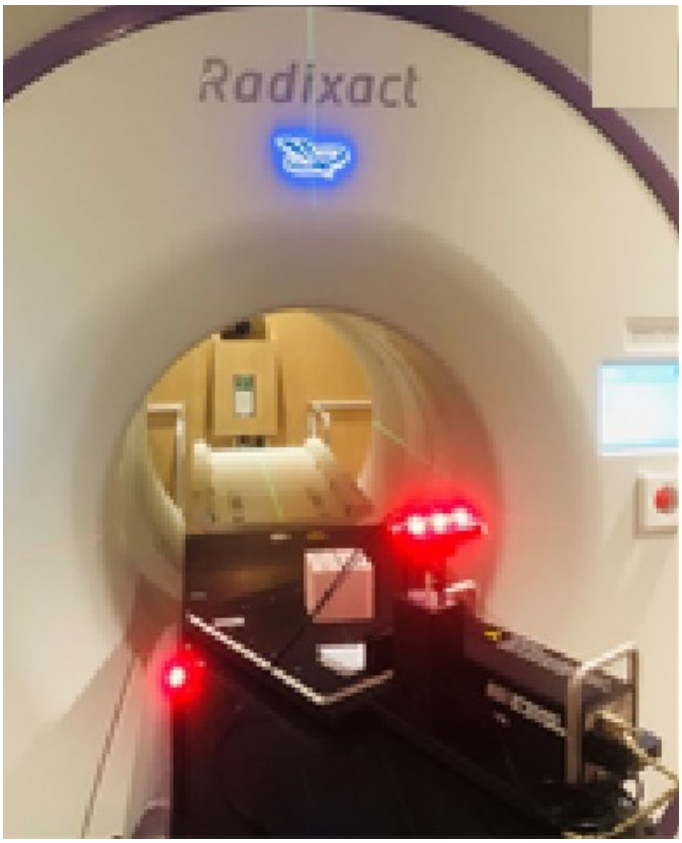

Figure 5. Setup of the XLT phantom in Radixact®

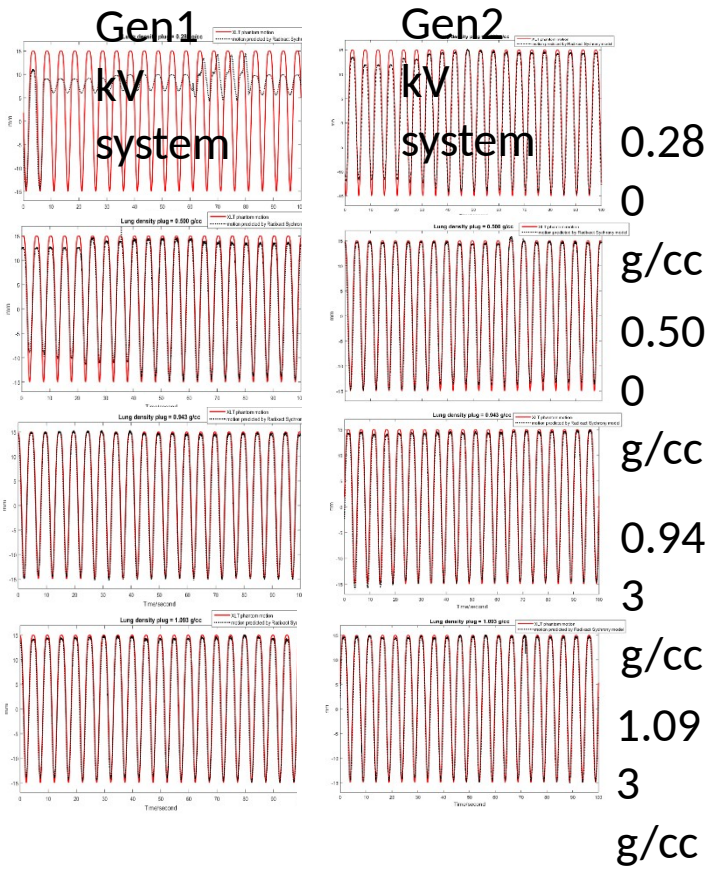

Figure 7. Predicted (black) and known target positions (red) in IEC-y as a function of time for Radixact® Synchrony® plans applied to different target densities by the Gen1 and Gen2 kV systems

Table 1A. Calculated root mean square (RMS) error and δ95% for each fraction of Radixact® Synchrony® treatment under the Gen1 kV system

Density of lung insert [g/cc]		**Fx1**	**Fx2**	**Fx3**	**Fx4**	**Fx5**	**Mean**	**SD**
0.280	δ_{RMS} [mm]	Failed	12.839	Failed	1.706	10.518	8.355	5.873
	δ95% [mm]	Failed	21.815	Failed	3.220	20.855	15.297	10.470
0.500	δ_{RMS} [mm]	12.972	1.532	1.451	1.763	2.675	4.078	4.995
	δ95% [mm]	22.021	2.923	2.807	3.195	4.377	7.065	8.384
0.943	δ_{RMS} [mm]	1.705	1.849	1.818	1.844	1.658	1.775	0.087
	δ95% [mm]	3.103	3.296	3.247	3.299	3.132	3.215	0.092
1.093	δ_{RMS} [mm]	1.629	1.705	1.773	1.629	1.631	1.673	0.064
	δ95% [mm]	3.008	3.075	3.192	3.002	2.969	3.049	0.089

SD — standard deviation

Table 1b. Calculated root mean square (RMS) error and δ95% for each fraction of Radixact® Synchrony® treatment under the Gen2 kV system

Density of lung insert [g/cc]		**Fx1**	**Fx2**	**Fx3**	**Fx4**	**Fx5**	**Mean**	**SD**
0.28	δ_{RMS}	1.703	1.554	1.557	1.821	1.561	1.639	0.120

	[mm]							
	δ95% [mm]	2.971	2.856	2.885	3.101	3.040	2.971	0.103
0.5	δ_{RMS} [mm]	1.466	1.753	1.565	1.765	1.609	1.631	0.127
	δ95% [mm]	2.629	3.194	2.934	3.020	2.906	2.937	0.205
0.943	δ_{RMS} [mm]	1.631	1.784	1.764	1.408	1.846	1.687	0.174
	δ95% [mm]	2.868	3.075	3.042	2.573	3.143	2.940	0.229
1.093	δ_{RMS} [mm]	1.585	1.618	1.613	1.509	1.607	1.586	0.045
	δ95% [mm]	2.832	2.903	2.964	2.817	2.851	2.874	0.060

SD — standard deviation