Placement Criteria for Improved Fiducial Tracking in Stereotactic Ablative Radiotherapy for Treatment of Lung Tumors.

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INTRODUCTION

Among lung cancer patients in whom for surgery is contraindicated, stereotactic ablative radiotherapy (SABR) is considered the standard of care. Due to the nature of radiation therapy, accurately targeting treatment to the tumor is important to both ensure appropriate delivery of treatment to the tumor and to avoid irradiating healthy surrounding tissue. Accurately targeting lung tumors, which exhibit continuous motion due to the breathing cycle, presents a challenge. Fiducials can be placed around the tumor for treatment targeting via the robotic SABR system. However, errors commonly cause some fiducials to remain untracked which may reduce treatment accuracy. Common errors are listed below.

Error Categories	
Rigid Body (RBE)	Deviance of fiducial geometry from rigid composition during the breathing cycle. May occur in fiducials placed far apart due to extra expanding and contracting lung tissue in between the fiducials.
Spacing	Due to either excessive fiducial proximity or separation. Although spacing errors indicate either excessive fiducial proximity or separation, it was found that the average maximum fiducial separation in the spacing error-absent group was greater than that of the spacing error-present group. Therefore all spacing errors were treated as proximity errors in this study due to the lack of specification of error type.
Shadowing	Occurs when two fiducials are in the same diagonal plane in relation to the detector. Shadowing can also occur due to foreign objects such as pacemakers.
Uncertainty	Indicates uncertainty in the system recognition of fiducial location.
High Collinearity	Occurs when three fiducials are aligned in the same plane such that rotations are not trackable.

MATERIALS & METHODS

Treatments Involved

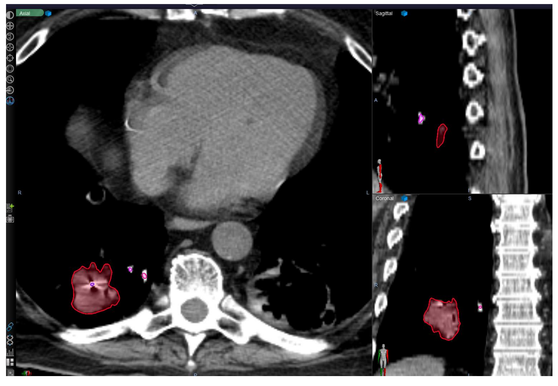
- 83 SABR treatments were studied to determine error frequencies, while fiducial centroid data were obtained for 28 of those patients.

Data Collection

- Centroid location data was obtained by threshold contouring 4DCT images using the Velocity imaging informatics software. Analysis was performed on data for either phase 0, 90, or scans indicating average inspiratory pressure based on availability in that order. Thresholds of 1100 and -250 Hounsfield units were used for fiducials and tumors respectively. CERR was used in Matlab to perform the centroid calculations.

Analysis

- Maximum inter-fiducial distances were compared between RBE+ and RBE-treatments to determine ideal placement distances. A similar procedure to RBE analysis using minimum instead of maximum fiducial distances was performed to analyze spacing proximity errors.
- A Mann-Whitney U test was then performed on these results to determine significance. A chi square analysis was also performed on the percentages of treated lobes producing each type of error.



RESULTS

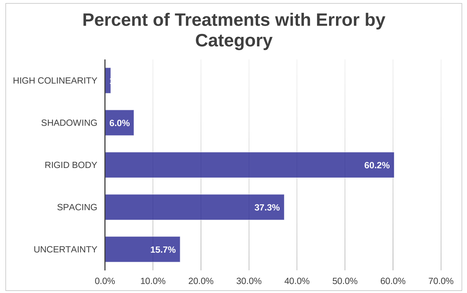


Figure 1. The percent of total treatments containing specific errors are shown. Rigid body and spacing errors appeared most frequently, and were therefore studied most extensively in this study.

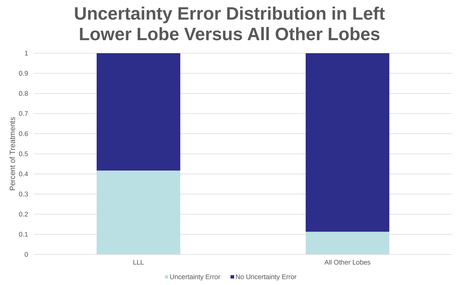


Figure 2. The percent chance of a subset of lung lobes displaying an uncertainty error is shown based on the number of uncertainty errors detected per lobe corrected for the number of treatments per lobe. 41.7% of LLL treatments expressed uncertainty errors compared to 11.3% in all other lobes. This deviation was found to be significant with a chi-square of 7.81 and a p value of .007.

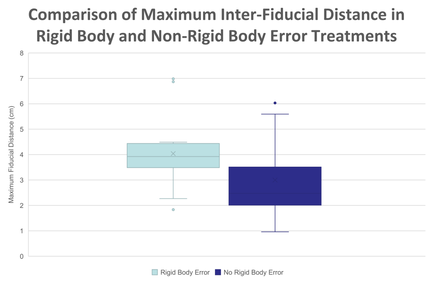


Figure 3. The maximum inter-fiducial distance per treatment are displayed, separated by those expressing RBEs and those without. The mean for RBE+ and RBE- treatments are 4.04 cm and 3.00 cm respectively. The median values are 3.92 cm and 2.48 cm respectively. A Mann-Whitney U value of 142 and a p value of .022 were found indicating significant deviance in the two data sets.

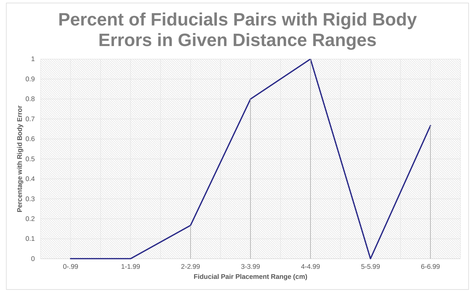


Figure 4. The percentages of treatments within 1 cm intervals displaying RBEs are shown. It can be seen that RBE probabilities rise dramatically with greater than 3 cm of separation. The deviance in the “5-5.99” and “6-6.99” data points from the general data trend is likely due to the low N value at the larger distances, and additional data would likely smooth out the curve.

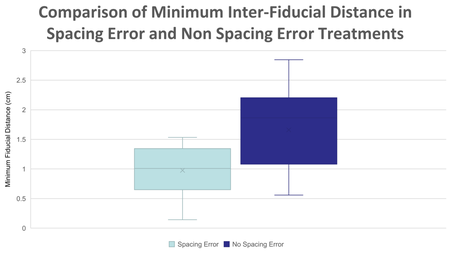


Figure 5. The minimum inter-fiducial distance per treatment are displayed, separated by those expressing spacing errors and those without. The mean for spacing error + and spacing error - treatments are 0.976 cm and 1.66 cm respectively. The median values are 1.01 cm and 1.86 cm respectively. A Mann-Whitney U value of 45 and a p value of 0.017 were found indicating significant deviance in the two data sets. . Spacing errors were not observed for any fiducials farther than 1.533cm apart, although some fiducials placed closer than this value did not express these errors.

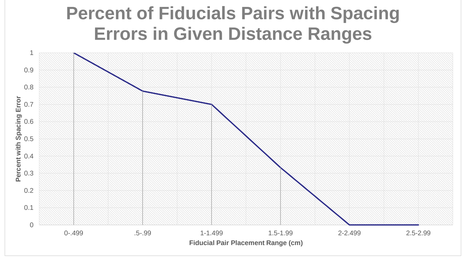


Figure 6. The of treatments within 0.5 cm intervals displaying spacing errors are shown. It can be seen that spacing error probabilities rise drop to 0% with greater than 2cm of separation.

ANALYSIS AND DISCUSSION

Placement Criteria

- Spacing errors did not occur in any treatments with inter-fiducial distances of at least 2cm, while rigid body errors were 57% more likely in treatments with fiducials greater than 3cm apart. Current guidelines already recommend a minimum distance between fiducials of 2cm, and thus it is suggested to place fiducials between 2cm and 3cm apart to limit both errors.

Uncertainty Error Analysis

- Uncertainty errors were found to be significantly overrepresented in LLL treatments (chi square = 7.181, p=0.007), and may be due to proximity to the heart. Further research is required to confirm this relationship.

Conclusion

- Analysis of relative fiducial location can provide insight regarding why particular errors occur as well as how to best avoid those errors. The continued development of these criteria for ideal fiducial placement will allow for improved tracking of lung tumors and may contribute improved outcomes in SBRT treatments.

FUTURE DIRECTIONS

Continued collection of error data from SABR treatments will allow for both the confirmation of the trends expressed for RBE and spacing errors as well as the determination of criteria for uncertainty, shadowing, and collinearity errors.

Regarding shadowing, determination of the minimum angle necessary between fiducials relative to the detector to avoid shadowing errors can be determined once more data is collected. Further research can also be performed to determine the cause of increased uncertainty errors in the left lower lobe. Determination of fiducial proximity to the heart of LLL treatments with uncertainty errors versus those without will demonstrate whether the motion of the heart is responsible.

Fiducial geometries involving all implanted fiducials can also be studied to determine whether particular geometries are more prone to cause errors. Clinical data can be combined with tracking data in order to create a complete criteria for ideal fiducial placement for the SABR system.

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