Comparing the Accuracy of AlignRT and ExacTrac at Intrafractional Time Points During Cranial Stereotactic Radiosurgery and Stereotactic Radiotherapy Treatments

A Thesis Presented for the Master of Science Degree in Medical Physics at Oregon Health and Science University

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Abstract

Background: Stereotactic radiosurgery (SRS) and stereotactic radiotherapy (SRT) are forms of radiation therapy that are highly conformal with steep dose gradients and a higher dose per fraction than conventional radiation therapy treatments. Frameless SRS/SRT requires image guided radiotherapy (IGRT) systems to ensure that the highly conformal dose is delivered to the correct location. ExacTrac is a kV x-ray IGRT system developed by BrainLab that takes two x-ray images and performs image registration with digitally reconstructed radiographs from the patient's planning CT. AlignRT is an optical surface IGRT system produced by VisionRT that uses projected light and multiple cameras to track a patient's surface against a reference surface.

Many studies have characterized the accuracy of ExacTrac and AlignRT using phantom data, but few have used clinical patient data to compare the accuracy of the systems. Agreement between IGRT systems can change when using patient versus phantom data. Insight into how surface imaging tracks with internal imaging in the patient population cannot be obtained through phantom studies alone. The purpose of this study is to summarize the distribution of readings for each system, and to see how well the systems track with each other. Additionally, patient anatomy and other variables were investigated to see if there was a correlation between them and system agreement.

Methods: 156 treatment checks were analyzed across 43 unique patients. ExacTrac data was pulled from saved documents that contained position information and time stamps of when the images were taken. Time stamps from the ExacTrac images were used to extract the corresponding AlignRT data. The separate readings were recorded as well as the difference (agreement) between the two. The size of the AlignRT surface being tracked for each patient was recorded as well as the patient's cheek thickness. Other variables such as nasal ridge length, nasal protrusion, and treatment time were recorded.

Results: The phantom study showed that AlignRT's position measurements would drift while the system warmed up. The vertical component of position had the largest thermal drift at 0.4mm. The standard deviation of all translational components of position for both systems was below 0.1mm in the phantom study. The systems tracked with each other (they measured the same values for applied shifts) for every component of position in the phantom study.

Agreement between AlignRT and ExacTrac for intrafraction motion detection in the patient population was sub-millimeter on average (average magnitude of disagreement = 0.66mm) with a maximum disagreement of 2.4 millimeters. It was observed that the ExacTrac standard deviations of patient motion in our study were equal to or smaller than those observed in other studies. No correlation was observed between system agreement and any of the patient variables recorded. A correlation between AlignRT vertical position and elapsed time was observed and is likely due to thermal warming. In the patient population, one to one tracking between the two systems was observed only in the lateral component of position.

Conclusions: The phantom study demonstrated that some of the disagreement between the systems was due to thermal warming effects. A revised workflow was proposed to eliminate thermal warming effects from the AlignRT system. Changing the imaging workflow to take one ExacTrac image halfway through treatment is supported by the findings of this study.

In the patient population, one to one relative tracking between AlignRT and ExacTrac was observed only in the lateral component of position. The other components of position demonstrated that a shift of 1mm or 1 degree measured by ExacTrac would on average be measured as smaller by the AlignRT system. Some correlations between AlignRT position measurements and patient anatomy were observed, but in no case was the agreement between the two systems correlated with patient anatomy.

Acknowledgements

I will always feel supported as a professional and a friend by Dr. Stephanie Junell. The completion of this study would not have been possible without her continued guidance. Thank you to the department of radiation medicine at OHSU for allowing me to use their equipment for this study. Thank you to the helpful people at VisionRT for being available for my questions and supporting our technology. Thank you to Jack Schrott for your helpful ideas and enthusiasm early on in this project. The physicists and physics residents at OHSU have happily endured my never-ending questions and I have learned a great deal as a result. And finally to my fiancé, Heather, thank you for always believing in me.

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1. Introduction

1.1 Image Guidance for Frameless SRS/SRT

1.1.1 Overview

Stereotactic Radiosurgery (SRS) and Stereotactic Radiotherapy (SRT) are forms of radiation therapy that are highly conformal with steep dose gradients and a higher dose per fraction than conventional radiation therapy treatments. Because of this, SRS/SRT treatments demand a stricter tolerance on patient localization to avoid geometric misses. Frame based SRS is the utilization of a rigid immobilization device that attaches physically (via metal screws) to the patient’s skull. The American

Association of Physicists in Medicine's (AAPM) task group 42 (TG-42) lists the achievable uncertainties in positioning for frame-based SRS procedures.[1] TG-42 reports that frame-based SRS techniques can limit tissue motion to an uncertainty of 1mm, with an image localization uncertainty of 0.3mm for the fluoroscopy system investigated.

Increased image guidance can be used along with a non-invasive immobilization device to allow for frameless SRS/SRT. The goal with these frameless techniques is to keep positioning uncertainties at or under previous frame-based levels, while improving patient comfort. Examples of image guidance used with frameless SRS/SRT include cone beam computed tomography (CBCT), orthogonal kV image pairs, and optical surface imaging. The Oregon Health and Science University (OHSU) radiation medicine department in Portland, OR, utilizes on-board CBCT, orthogonal kV image pairs, and optical surface imaging for their intracranial open face mask SRS/SRT treatments. The orthogonal kV imaging is with a system called ExacTrac® (produced by BrainLab, Munich, Germany), and the optical surface imaging system is called AlignRT® (produced by VisionRT, London, UK).

1.1.2 ExacTrac

ExacTrac is a kV x-ray imaging system that takes two orthogonal x-ray images and performs image registration with digitally reconstructed radiographs from the patient's planning CT. The x-ray generators are located below the treatment table, and the digital image receptors are located above the treatment table. The image registration calculates the target's current position relative to the planned position. Position measurements are calculated for vertical, longitudinal, lateral, yaw, roll, and pitch movements. At OHSU ExacTrac is integrated with a six degree of freedom treatment table that can apply the suggested shifts remotely. Figure 1 shows the ExacTrac setup at OHSU as well as the orthogonal x-ray images produced. ExacTrac also uses an infrared light source and infrared cameras to track special spheres that reflect infrared light. The spheres are placed on the patient's immobilization device. Two infrared cameras are used to track the three-dimensional location of the spheres. When applying shifts remotely to the table, the reflective spheres are used to determine that the table has moved the correct amount.

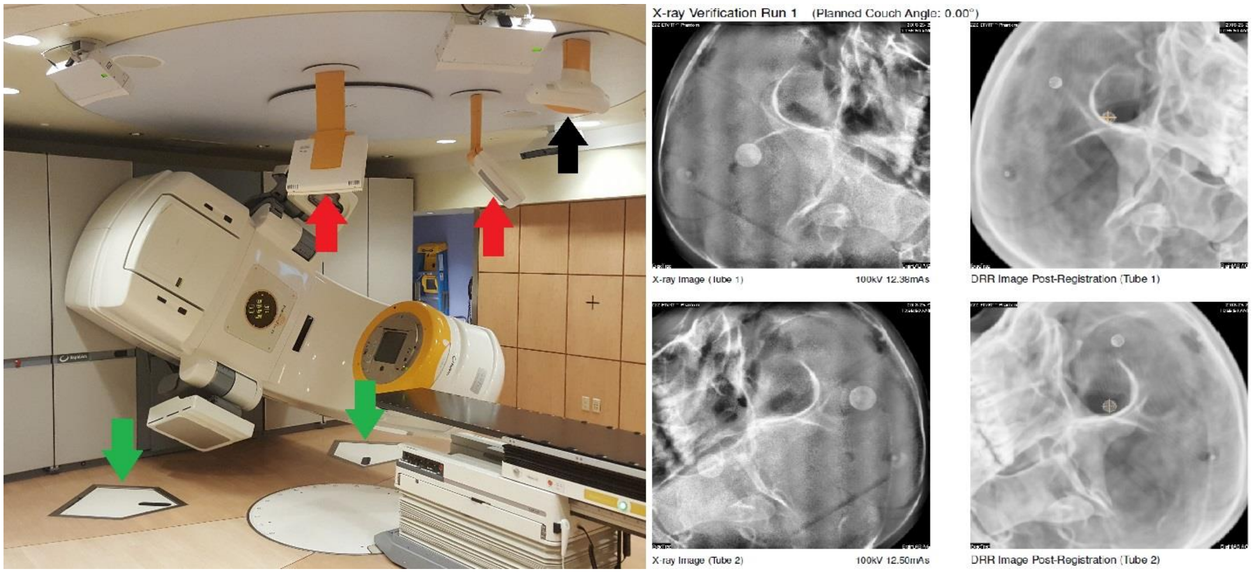

Figure 1. *Left*: The ExacTrac setup at OHSU. The black arrow points to the infrared camera pod. The green and red arrows point to the x-ray generators and detector panels respectively. *Middle Top and Bottom*: The two orthogonal ExacTrac images. *Right Top and Bottom*: Digitally reconstructed radiographs

1.1.3 AlignRT

AlignRT is an optical surface imaging system. AlignRT is comprised of three different camera pods (one central and two lateral). Each pod has two optical cameras and one red light projector. Each projector projects a pseudo-random speckled red light pattern onto the patient to provide texture variations and enhance the surface reconstruction process. A reference image of the patient's surface in the correct location is used to tell the system where the patient should be located in 3D space. This reference image could be taken and recorded manually on the day of treatment, or it could be generated by extracting the patient surface from the planning CT. If the patient moves, then the light pattern on their face will change slightly. The six optical cameras monitor the patient surface for motion. By comparing the expected pattern to the observed pattern, the three-dimensional location of the tracked surface can be calculated along with the rotational orientation.

AlignRT reports vertical, longitudinal, lateral, yaw, roll, and pitch information four times per second. The information is continuously updated on a screen inside the treatment vault, and outside the vault in the control room. Position data is stored in "real time delta" (RTD) files that are saved locally on a computer after treatment. Figure 2 shows the AlignRT setup at OHSU. The central camera pod is slightly offset due to the ExacTrac infrared camera pod already occupying the center location. The standard AlignRT setup would not have the central camera pod offset.

AlignRT uses a region of interest to limit the area of the patient surface that is tracked. The planning CT data set is used to generate a surface structure of the patient. This surface structure is sent to the AlignRT software. A user then manually defines the region of interest to be tracked. During this study, OHSU implemented a manufacturer recommendation to exclude the cheeks from the AlignRT region of interest. The two different region of interest selections used at OHSU during this study are shown in figure 3.

AlignRT uses the patient surface generated from the planning CT for initial setup. For real time monitoring during treatment, OHSU sets a baseline for AlignRT just after internal imaging localization from ExacTrac or CBCT. To set baseline for AlignRT, a new reference image is taken. This is an image that constructs the patient's current facial surface and sets its current position to a value of zero. AlignRT uses the previously defined region of interest from the planning CT surface and propagates the reference surface to the baseline surface. A patient that has the cheeks excluded in the planning CT surface will also have cheeks excluded in the generated reference surface.

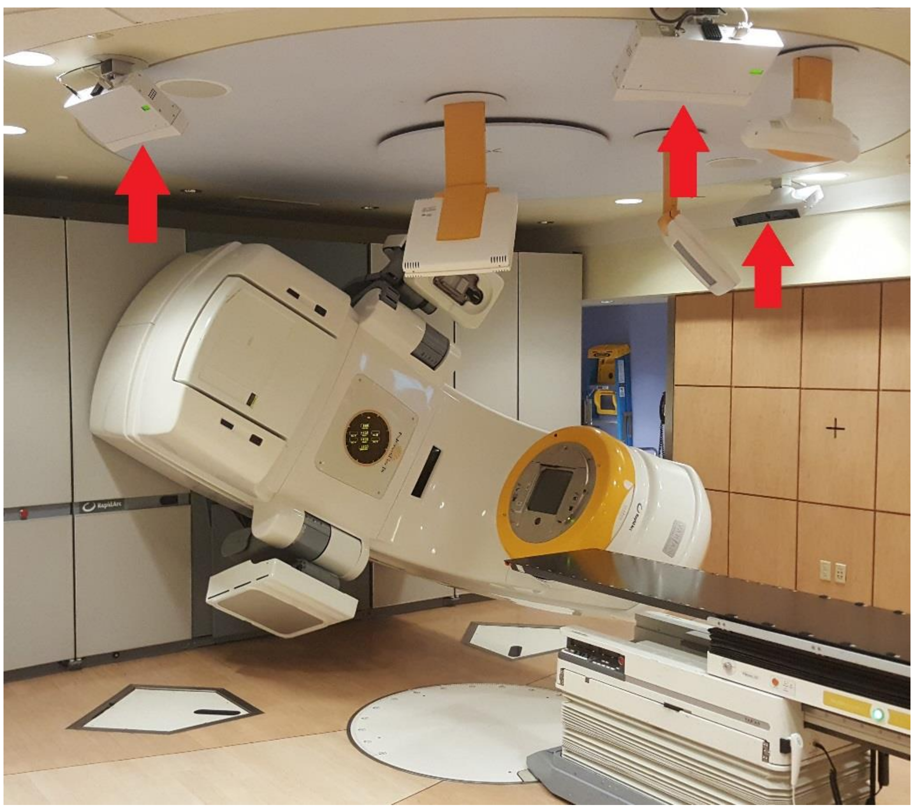

Figure 2. The AlignRT setup at OHSU. The red arrows point to the three AlignRT camera pods. The central camera pod is slightly offset from true center due to the ExacTrac infrared camera pod already being in the center.

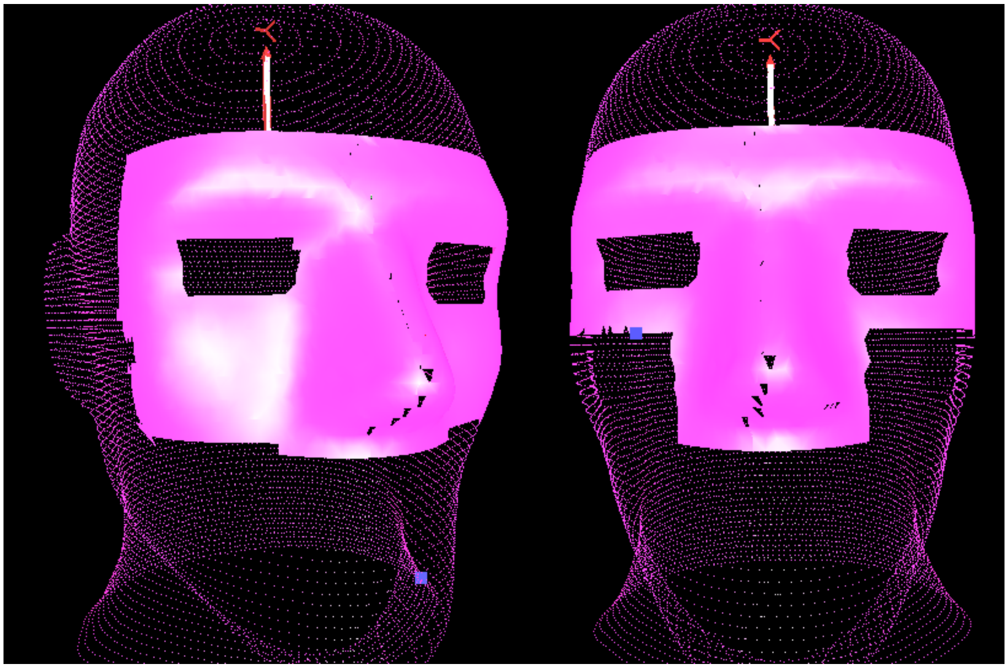

Figure 3. The standard AlignRT region of interest selections used. *Left:* cheeks included. *Right:* cheeks not included

1.2 Purpose

The gold standard for patient positioning in radiation therapy is 3D radiologic imaging.[2] Additionally, the skull has been shown to be a reliable surrogate for tumor positioning.[3-5] For surface imaging, some have called into question whether a fixed spatial relationship between the surface and the internal target exists.[2, 6, 7] For relatively rigid sites such as the cranium, it is argued that the difference between internal anatomy and the patient surface is less important than in other sites.[2] AlignRT has decreased statistical variation in the cranial site as compared to other sites such as the pelvis.[8] This study aims to quantitatively determine the agreement between internal imaging and surface imaging for intracranial SRS/SRT treatments.

Many studies have characterized the accuracy of imaging systems such as ExacTrac and AlignRT using phantom data,[9-13] but few have used clinical patient data to compare the accuracy of the systems. The agreement between systems can change when using a phantom or when imaging patients. Chang et al. showed that the agreement between ExacTrac and CBCT was 0.5mm for their phantom study and increased to 1.5mm for their patient study.[14]

Using a phantom does not answer the question of whether or not surface imaging will track with internal imaging in the patient population. The surface of a phantom will remain rigid to the internal target, whereas the same may not be true for patients. Surface deformation could have an effect on the image registration algorithm as well. The purpose of this study is not only to quantify the distribution of readings for each system, but to see if the systems are tracking with each other. Additionally, patient anatomy and other variables are investigated to see if there is a correlation between them and system accuracy or system agreement.

There will be three main steps that this study will use to investigate the agreement between ExacTrac and AlignRT:

(1) Perform a phantom study to record system variance, agreement, and relative tracking under ideal conditions
(2) Retrospectively gather patient data to determine system variance, agreement, and relative tracking during clinical use
(3) Check for correlation between patient variables (anatomy, treatment time, etc) and system agreement/variance

2. Materials and Methods

2.1 Phantom Study

The STEEV phantom developed by CIRS (Norfolk, Virginia) was used for the phantom study. Figure 4 shows the STEEV phantom with infrared reflective spheres attached. The first part of the phantom study was zeroing each system and taking multiple measurements at the zeroed position to see the variance in the image registration. An ExacTrac image was taken and applied to the phantom. The AlignRT system was zeroed by taking a reference image of the phantom using AlignRT. Real time monitoring was turned on with AlignRT and 20 ExacTrac images were taken.

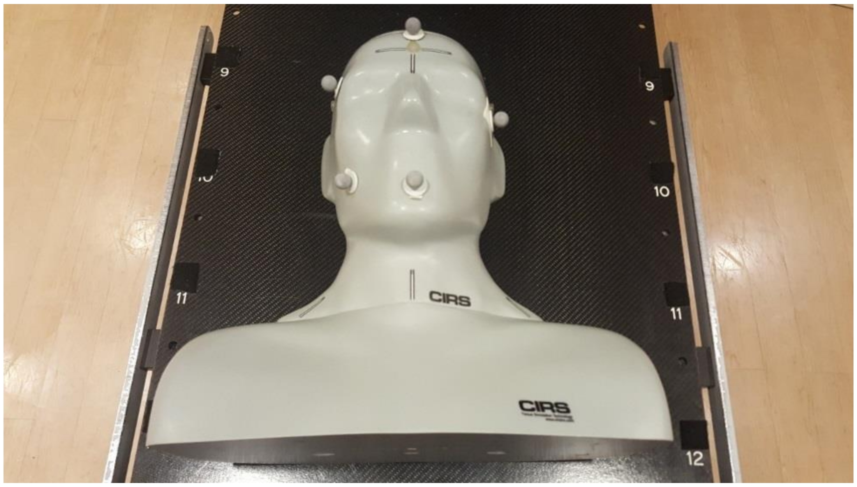

Figure 4. The STEEV phantom with ExacTrac reflective spheres attached

The second part of the phantom study consisted of applying manual shifts in each of the 3 translational and 3 rotational directions. For the translational components, a shift of ±0.5, ±1, and ±2mm was applied. For the rotational components, a shift of ±0.5 and ±1 degree was applied. The shifts were manually applied by looking at the readings coming from the ExacTrac infrared reflective spheres. The shifts did not need to be exact because the purpose of this part of the phantom study was to see how well the systems were tracking relative to each other.

2.2 Clinical Workflow

The imaging frequency and position tolerance differs for SRS and SRT treatments at OHSU. The imaging frequency for SRT is less frequent than for SRS and will be described in the following paragraphs. The position tolerance is 2mm or 1 degree for SRT and is 1mm or 1 degree for SRS. Throughout the paper, SRS and SRT treatments will be pooled together and analyzed in terms of the SRS position tolerance.

Currently at OHSU, ExacTrac images are taken only when the table is at angle 0 and the gantry is at either 0 or 180 degrees. AlignRT is used for course initial setup and for intrafraction motion monitoring. A thorough description of the workflow for intracranial open facemask SRS/SRT treatments is given here. Figure 5 is a flowchart of the described process with the position tolerance being restricted to the SRS tolerance.

Patients are placed on the treatment table and their open face mask is placed on them. The AlignRT system is turned on and the reconstructed skin surface image from their CT simulation is used to roughly align the patient. The knobs on the VisionRT head board are used to adjust rotations as viewed on the AlignRT screen. After AlignRT coarse alignment the radiation therapists leave the room to take an ExacTrac image and apply the suggested shift. Next a CBCT is taken. A physician reviews the CBCT image and suggested shifts and makes a decision to use the CBCT shifts or the ExacTrac shifts. One potential reason for using the CBCT suggested shifts is if the lesion is located in region where there is increased uncertainty in the ExacTrac images. An example would be a lesion located behind the jaw in the digitally reconstructed radiographs (DRRs). The jaw could have changed orientation on the day of treatment compared to the day of simulation rendering the setup DRRs inaccurate.

If the physician chooses to apply the CBCT shifts then an ExacTrac baseline image is taken right after applying the CBCT shifts. If the mid-treatment ExacTrac suggested shifts are greater than 1mm or 1 degree away from the baseline ExacTrac suggested shifts, then they must take another

CBCT and apply its suggested shifts. If the physician decides to disregard the CBCT shifts, then an ExacTrac image is taken and applied if greater than 1mm or 1 degree. If the image is less than 1mm or 1 degree, then that image is taken as the baseline for the ExacTrac system.

At the same time that the ExacTrac baseline image is taken (more realistically, a few seconds after the ExacTrac baseline image is taken) an AlignRT reference image is captured. This AlignRT reference image effectively zeroes out the AlignRT system to the patients position when the image was taken. Then the real time AlignRT monitoring is turned on. The patient is monitored in real time by AlignRT, and the therapists can decide to manually pause treatment if the AlignRT system is reading out of tolerance for an extended period of time.

Every two couch rotations (for SRS treatments), or in the middle of treatment (for SRT treatments), an ExacTrac image is taken to verify that there has not been intrafraction motion. For SRS treatments the tolerance for misalignment is 1mm and 1 degree. If the ExacTrac suggested shifts are within 1mm and 1 degree of the baseline measurement, then the treatment continues as usual. If the suggested shifts are greater than 1mm or degree away from the baseline measurement, then the suggest shifts are applied and a new baseline ExacTrac image is taken. Also, a new reference image is taken with the AlignRT system and monitoring is resumed.

At the end of treatment an additional ExacTrac image is taken to verify positioning. AlignRT positional information in the form of "real time delta" (RTD) files are automatically recorded on a local computer. The ExacTrac measurements are compiled on a document that is then sent to Mosaiq as part of the patient's record.

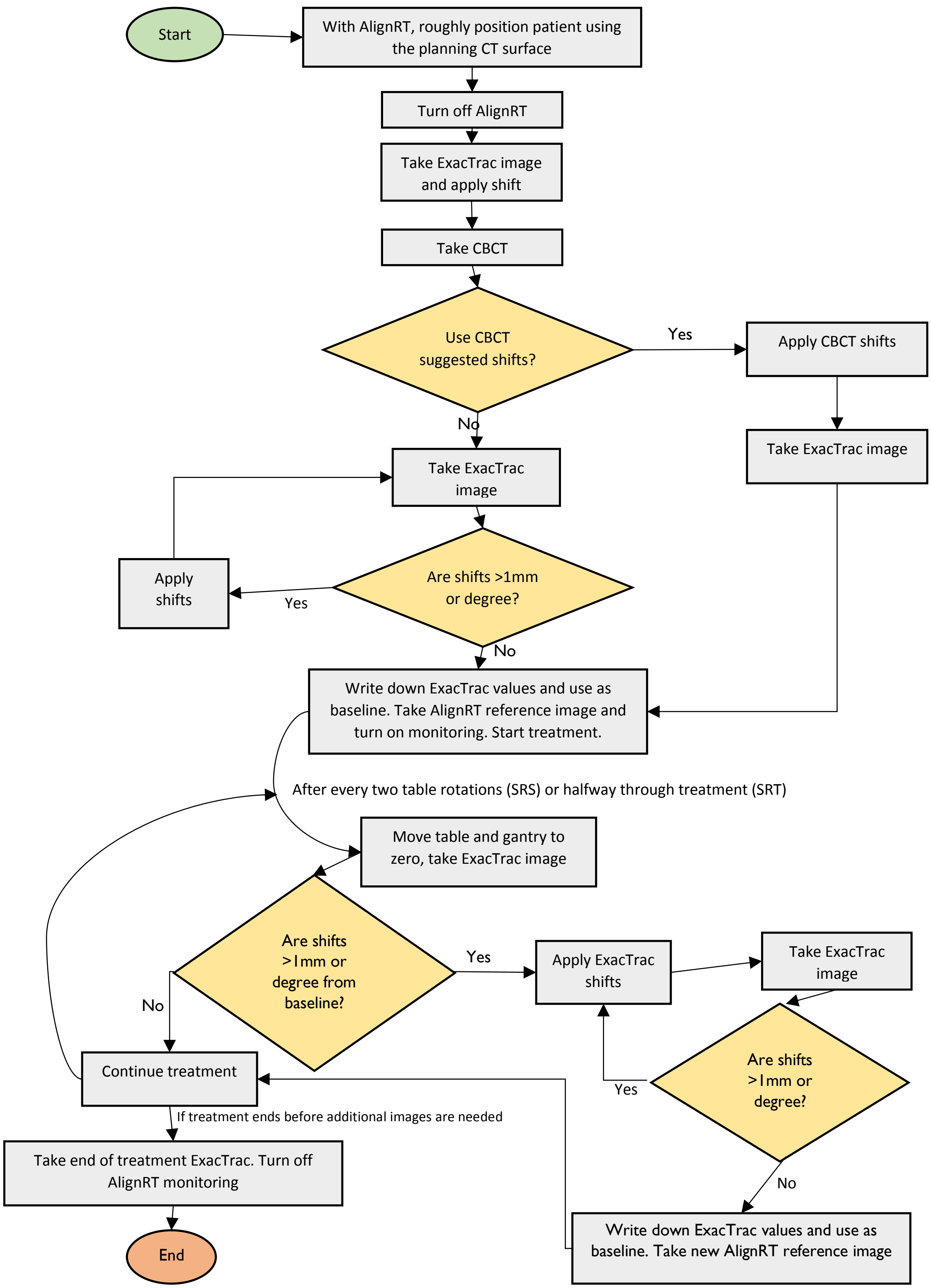

Figure 5. Flowchart for the clinical imaging workflow for open facemask SRS/SRT treatments

2.3 Data Collection

2.3.1 AlignRT

Data for this study was compiled retrospectively. Real time delta (RTD) files for each patient are stored locally on the AlignRT computer. RTD files from April 2017 to November 2017 were used for this study. In total, 109 treatment sessions were analyzed across 43 unique patients. Each treatment session could have a varying number of ExacTrac treatment checks. 156 total treatment checks were obtained from the 109 treatment sessions.

AlignRT saves the RTD files in subfolders that correspond to the reference image used to monitor the patient. It is important that the correct reference image was used to monitor the patient. It is possible for a previous day's reference image to be used to track the patient for intrafraction motion. The folders were cross referenced to ensure that the reference image used was the correct one (taken just before treatment began that day).

2.3.2 ExacTrac

ExacTrac positioning data is stored in Mosiaq under the patient's documents. The compiled list of RTD files was used to determine which patients to look up. ExacTrac baseline, mid-treatment check, and end of treatment check measurements were recorded. The time stamps for each ExacTrac measurement was recorded so that the corresponding AlignRT data could be extracted. To determine the patient movement in the ExacTrac measurements, the baseline measurement was subtracted from the treatment check measurement.

The ExacTrac time stamp was used to extract the corresponding AlignRT measurements from the continuous RTD files. The RTD files list the time when AlignRT monitoring began and the elapsed time since monitoring began for each of the positional data points. The difference between the ExacTrac treatment check time stamp and the AlignRT monitoring start time was calculated. This time difference is the elapsed time since monitoring began that an ExacTrac image was taken. This calculated elapsed time was used to extract the AlignRT positional data that corresponds to the ExacTrac measurements.

The difference between the ExacTrac and AlignRT measurements are recorded by subtracting the AlignRT reading from the baseline corrected ExacTrac measurement. This was done for each component (vertical, longitudinal, lateral, yaw, roll, and pitch) of the readings, and for the difference in translational magnitude of the two systems.

2.3.3 Patient Variables Recorded

In an attempt to see if AlignRT could perform better under certain patient specific conditions, patient anatomy was recorded. There were two hypotheses. One was that AlignRT would be more accurate if there was more surface area on the face available for tracking. Another was that the patients face was more likely to deform over time if they had puffier cheeks. Deformation here refers to changes from the initial reference image taken right before treatment. The effect of nose size was also of interest. To measure these factors, the region of interest used to monitor the patients on AlignRT was examined. The lateral and longitudinal size of the region of interest was measured and multiplied together to give an estimate of the reference image area. The coordinates at the bridge and apex of the nose was recorded and used to determine the nasal ridge length and the nasal protrusion.

The thickness from the inferior and superficial most aspect of the frontal process of the zygomatic bone to the skin surface was recorded. This information was recorded from the simulation CT scans (figure 6). Other variables that were recorded were whether or not the cheeks were included in the AlignRT region of interest, patient age, patient gender, and patient skin tone.

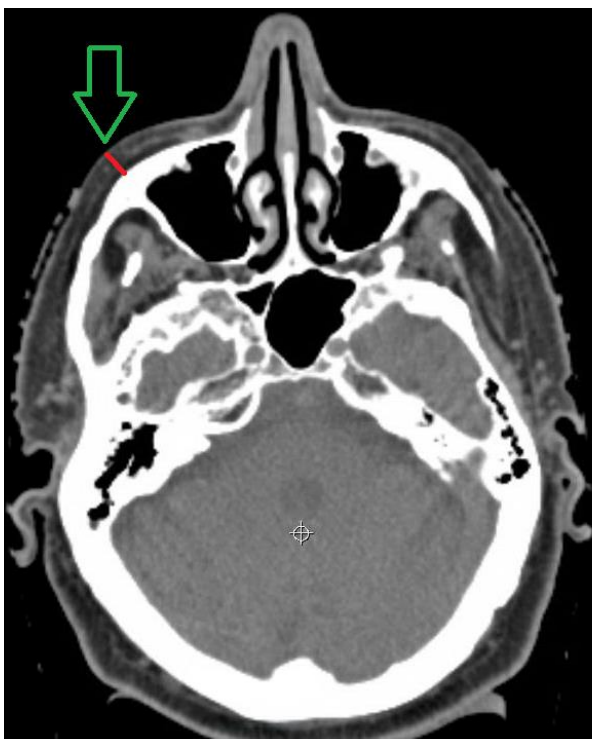

Figure 6. The red line shows the thickness measured. The metric used for cheek thickness was the thickness from the inferior and superficial most aspect of the frontal process of the zygomatic bone to the skin surface.

3. Results

3.1 Phantom Study

3.1.1 AlignRT Thermal Warming Effect

There are small effects on the optics of AlignRT due to thermal warming. This leads to small drifts in the spatial and rotational readouts of AlignRT that stabilize after about 10-15 minutes. This effect has been seen and reported by Li et al.[10] For our system the magnitude of the drift is at most 0.42mm and in the vertical direction. Figure 7 shows the translational and rotational readouts of AlignRT over a 30-minute period. The equilibrium position is shown in red. The thickening of the plots over time (in the vertical component for example) is only a visual effect. A comparison of variance test was performed at multiple time points and concluded that the variance did not change over time.

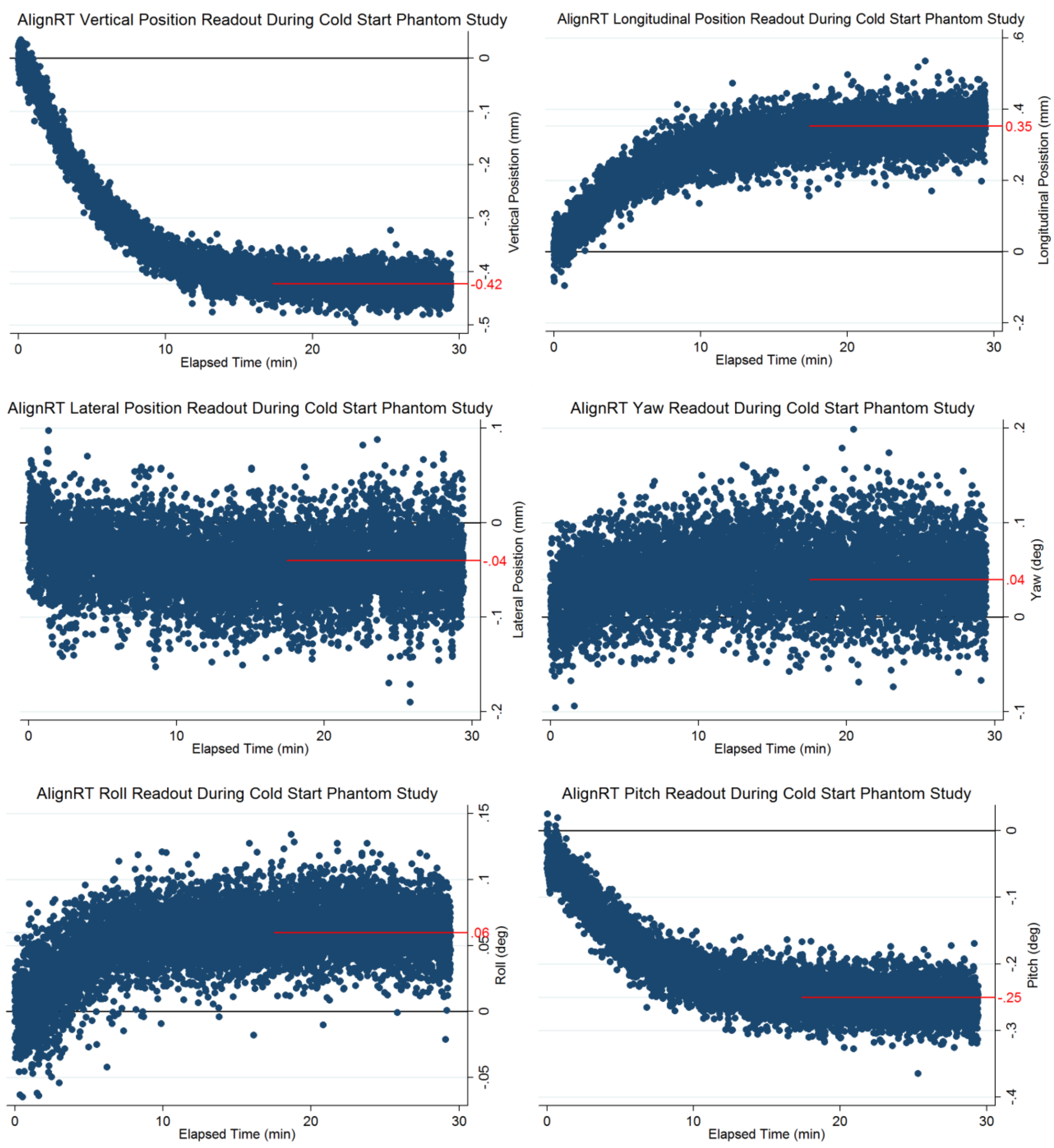

Figure 7. AlignRT thermal warming effect.

3.1.2 Variance of Both Systems

The phantom was left in one position and both systems were zeroed. Multiple measurements were then made with both systems to test the reproducibility of each system. The idea of measuring each systems variance in a phantom study was to see how well the systems could perform under ideal circumstances. Thus, to measure the ideal AlignRT variability, only points from after thermal equilibrium was reached were used.

The main point of interest for this part of the phantom study was to compare the standard deviation of the position measurements for each system. The standard deviations for each of the 6 position components on both systems is listed in table 1. An F-test on the equality of standard deviations between AlignRT and ExacTrac for all 6 position components was performed. The F-test showed that the standard deviations for AlignRT were statistically significantly lower than ExacTrac's for all 6 components ($p<0.002$) except for the longitudinal component ($p>0.05$).

n=20	Vertical	Longitudinal	Lateral	Yaw	Roll	Pitch
ExacTrac Standard Deviation	0.09mm	0.05mm	0.07mm	0.08°	0.09°	0.07°
AlignRT Standard Deviation	0.02mm	0.04mm	0.03mm	0.03°	0.02°	0.02°

Table 1. Standard deviations of position components from the phantom study. Calculated from 20 measurements

3.1.3 Inter-System Tracking

The manual shifts to the phantom allow us to see if a shift of a certain size is detected the same on both systems. Ideally both systems will record the same shift, and a plot of ExacTrac shifts versus AlignRT shifts would form a diagonal line of slope 1. Scatter plots of ExacTrac measurements versus AlignRT measurements for each of the 6 components of positions are given here in figure 8. A diagonal line is overlaid on each of the scatter plots. A linear regression was performed on each of the data sets to determine the slope of the line of best fit. All 6 components had a 95% confidence interval for the slope of the line of best fit that contained the value 1.

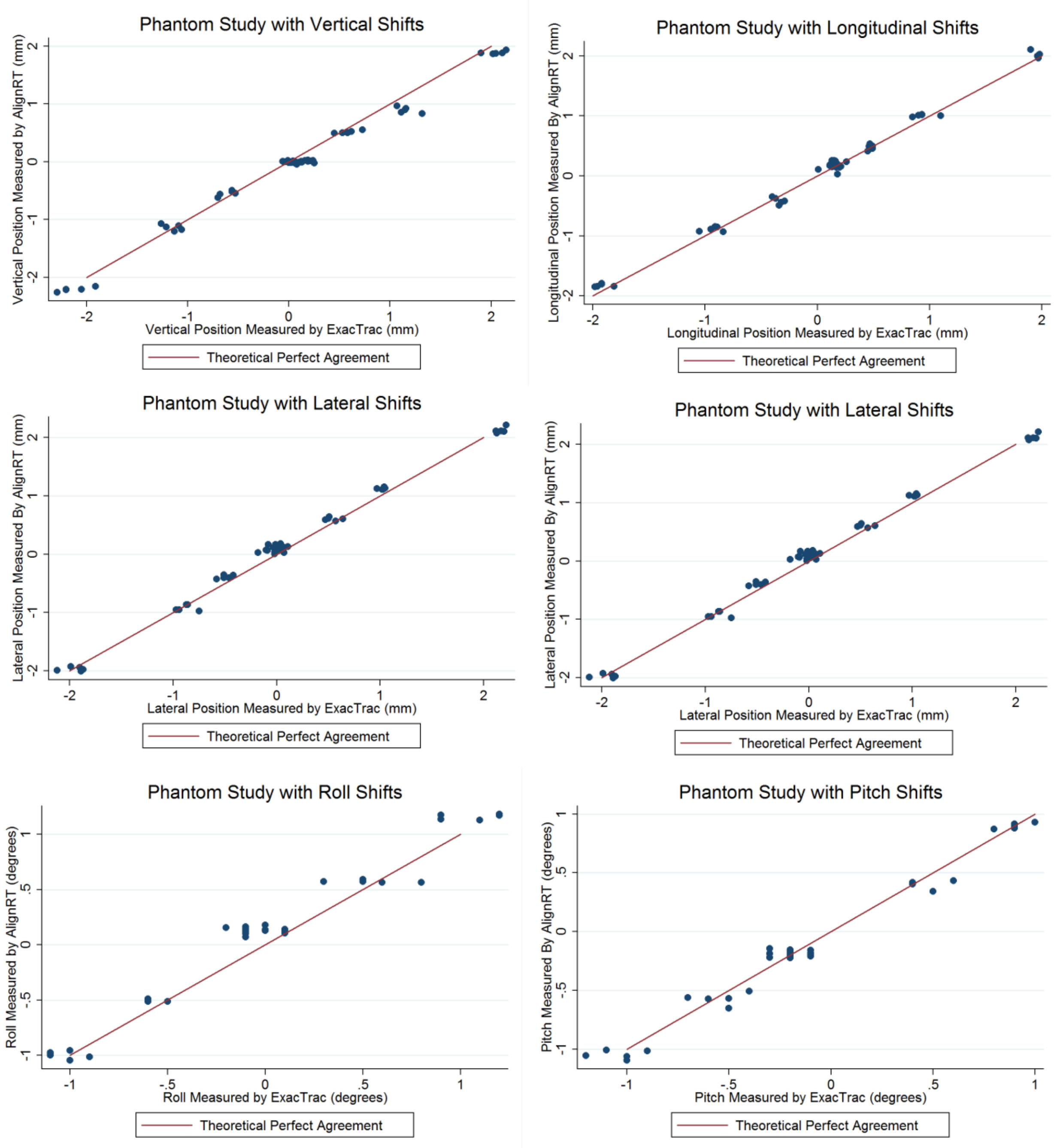

Figure 8. Phantom study relative tracking. Note that ExacTrac reports rotations rounded to the tenth of a degree

3.2 Patient Study

3.2.1 Summary Statistics

In the patient study there were 156 total treatment checks over 43 unique patients. Table 2 summarizes the mean and standard deviation for the treatment check readings from ExacTrac, AlignRT, and the difference (agreement) between the two. The table includes the percentage of treatments where one of the 6 position components was measured to be more distant than ±1mm or ±1 degree. It also includes the percentage where the magnitude of the translational shift would have been measured to be more distant than ±1mm or ±1 degree. Box plots for the same data are also provided here in figures 9-11.

N = 43, n = 156	Vertical	Longitudinal	Lateral	Yaw	Roll	Pitch	Translational Magnitude
ExacTrac Mean Reading	-0.05mm	-0.02mm	-0.05mm	-0.04^{0}	0.03^{0}	-0.04^{0}	0.49mm
ExacTrac Standard Deviation	0.21mm	0.33mm	0.40mm	0.31^{0}	0.24^{0}	0.30^{0}	0.29mm
ExacTrac Percent of Readings ≥ ±1mm or ±1°	0%	1.9%	3.2%	0%	0%	0.6%	7.1%
AlignRT Mean Reading	-0.31mm	0.02mm	-0.16mm	-0.06^{0}	0.00^{0}	-0.05^{0}	0.76mm
AlignRT Standard Deviation	0.28mm	0.53mm	0.50mm	0.32^{0}	0.21^{0}	0.27^{0}	0.40mm
AlignRT Percent of Readings ≥ ±1mm or ±1°	0.6%	5.1%	6.4%	0%	0%	0%	18.6%
Difference Mean Reading	0.27mm	-0.04mm	0.11mm	0.02^{0}	0.03^{0}	0.00^{0}	0.66mm
Difference Standard Deviation	0.29mm	0.51mm	0.35mm	0.29^{0}	0.22^{0}	0.31^{0}	0.34mm
Difference Percent of Readings ≥ ±1mm or ±1°	0%	5.8%	0.6%	0.6%	0%	0.6%	12.8%

Table 2. Various statistics from the patient study with N=43 unique patients and n=156 total treatment checks

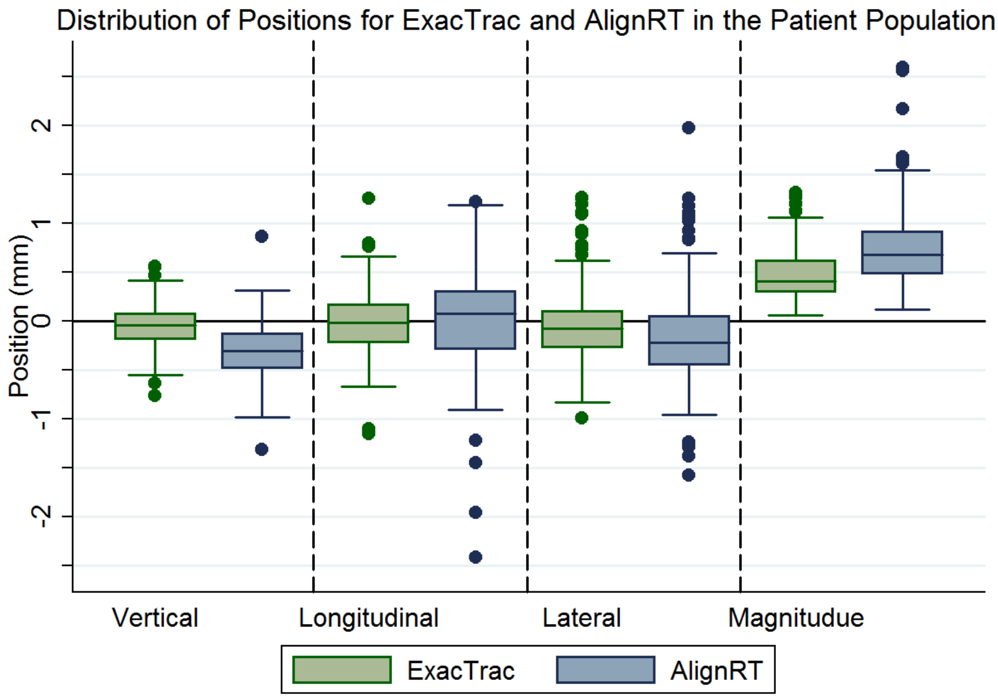

Figure 9. Translational components for both systems measured in the patient population

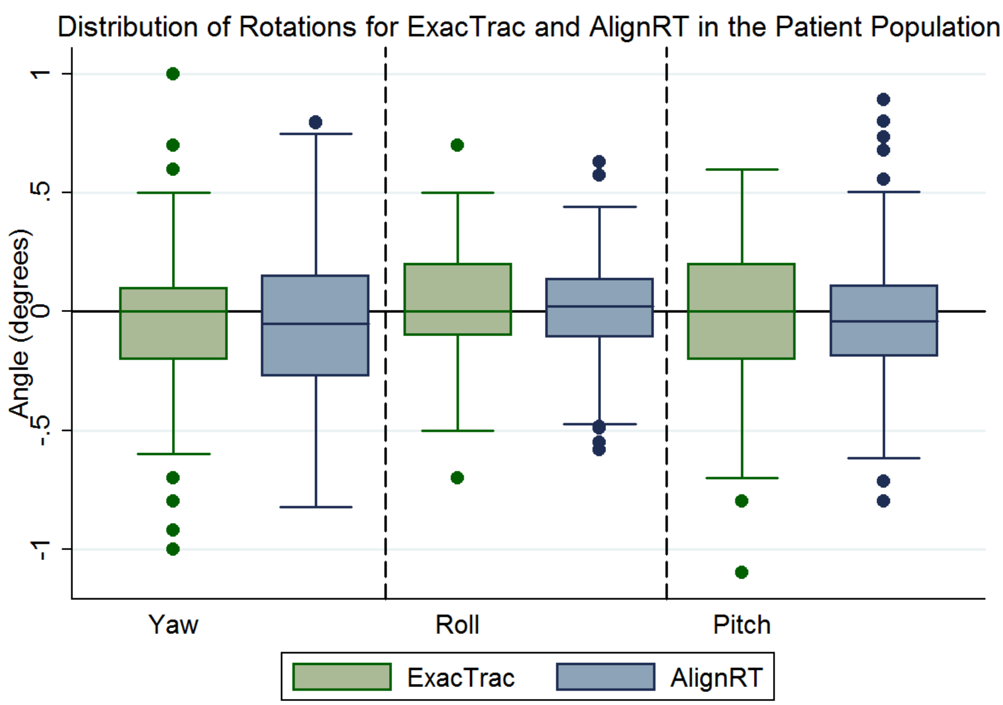

Figure 10. Rotational components for both systems measured in the patient population

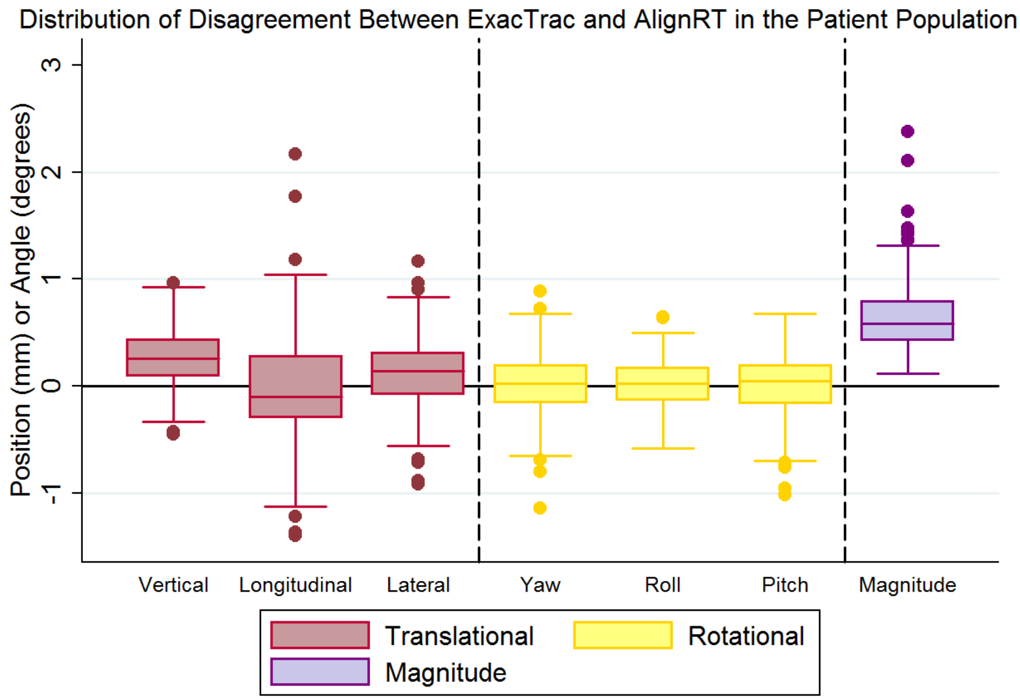

Figure 11. System agreement in the patient population

3.2.2 Relative Tracking in the Patient Population

To get a visual representation of how well the two systems were tracking with each other in the patient population, similar scatter plots to those in section 3.1.3 were generated. Each blue dot in figures 12-17 represents a single treatment check. The diagonal red line of slope 1 represents the place on the plot where the two systems perfectly agree on the measured shift. A linear fit of the treatment checks with a 95% confidence interval is overlaid on the graph. According to a linear regression analysis, the slopes of all of the linear fits were less than 1 ($p<0.05$) except for the lateral component. In the lateral component we can see that the linear fit has a similar slope to the diagonal red line. This is confirmed by calculating a 95% confidence interval for the slope of the linear fit for the lateral data to be 0.75 to 1.03 which contains the slope of 1. Bland-Altman plots were also generated (figure 18) to visualize the agreement between AlignRT and ExacTrac. The slanting structure in the some of the components in figure 18 (roll for example) suggest that disagreement becomes larger as the systems measure larger shifts (in other words, 1 to 1 agreement between the systems does not exist).

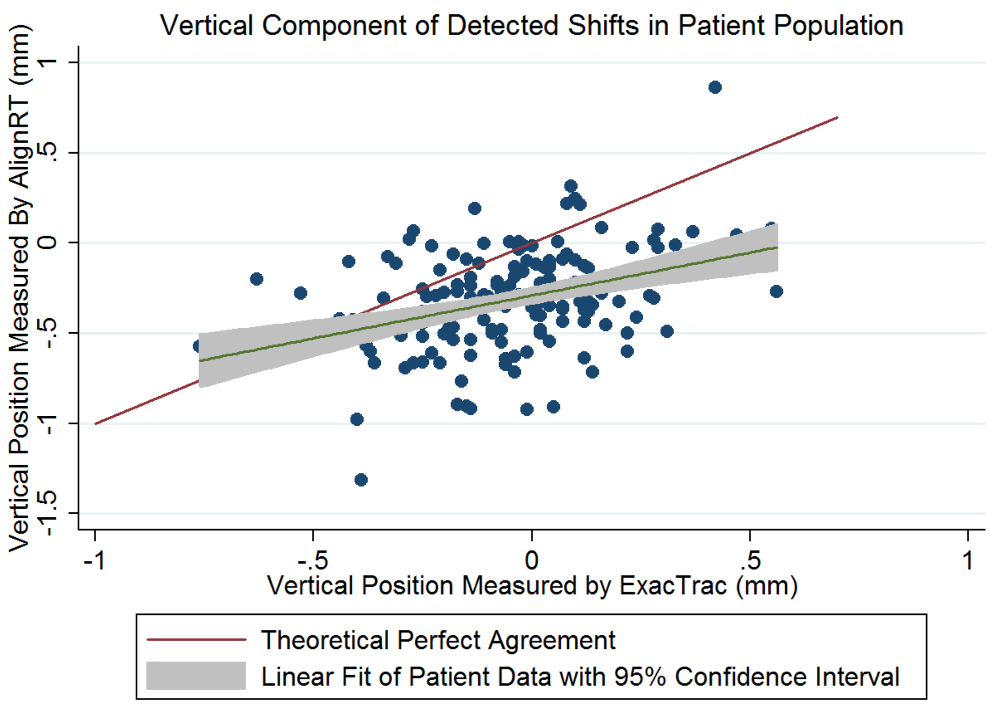

Figure 12. Vertical system agreement. The linear fit of the patient data has a slope of less than 1

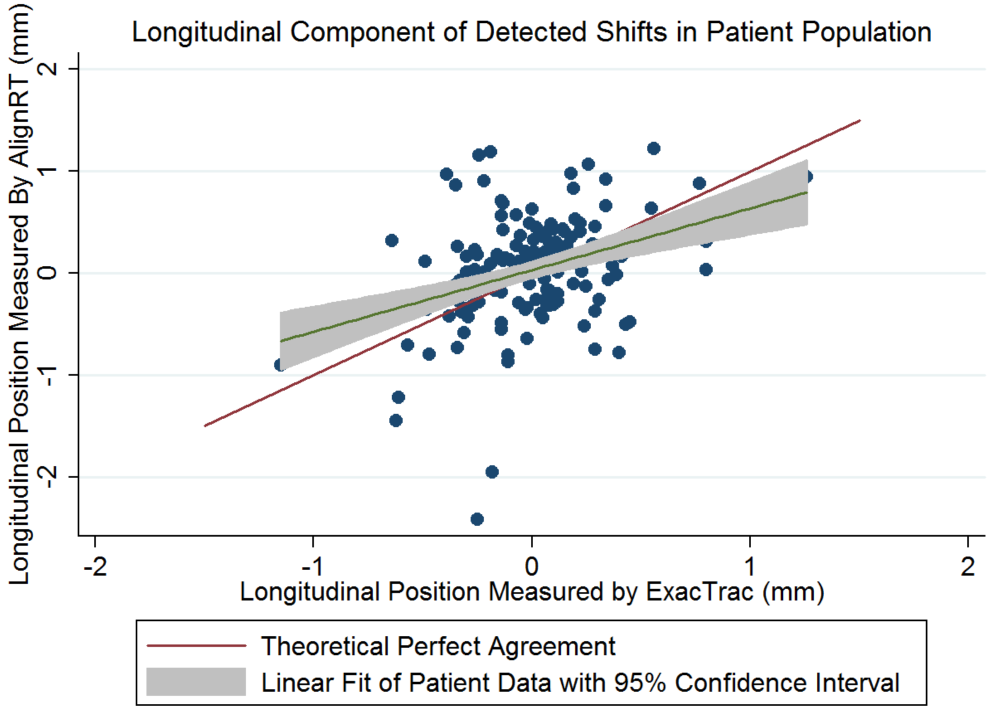

Figure 13. Longitudinal system agreement. The linear fit of the patient data has a slope of less than 1

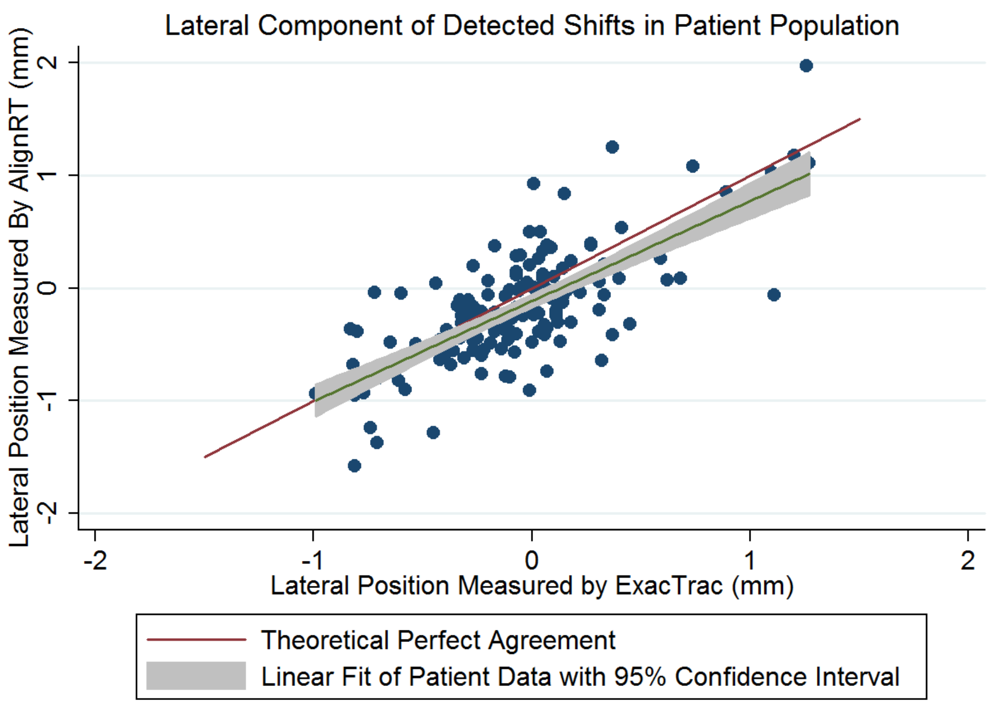

Figure 14. Lateral system agreement. The 95% confidence interval for the slope of the line of best fit is [0.75, 1.03] which contains 1

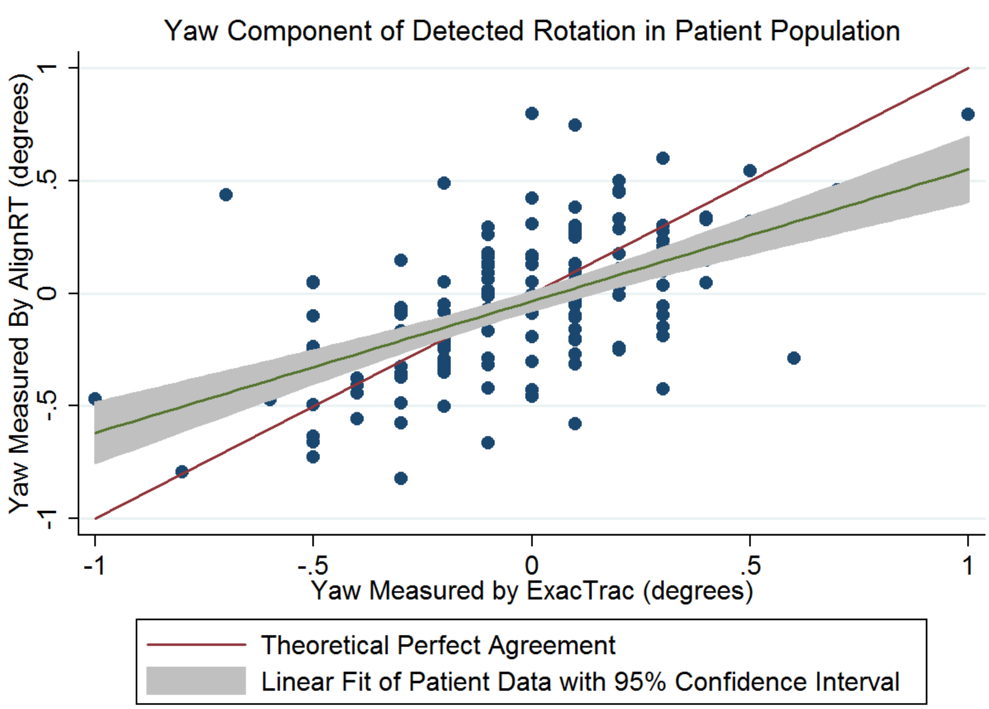

Figure 15. Yaw system agreement. The linear fit of the patient data has a slope of less than 1. Note that ExacTrac reports rotations rounded to the tenth of a degree

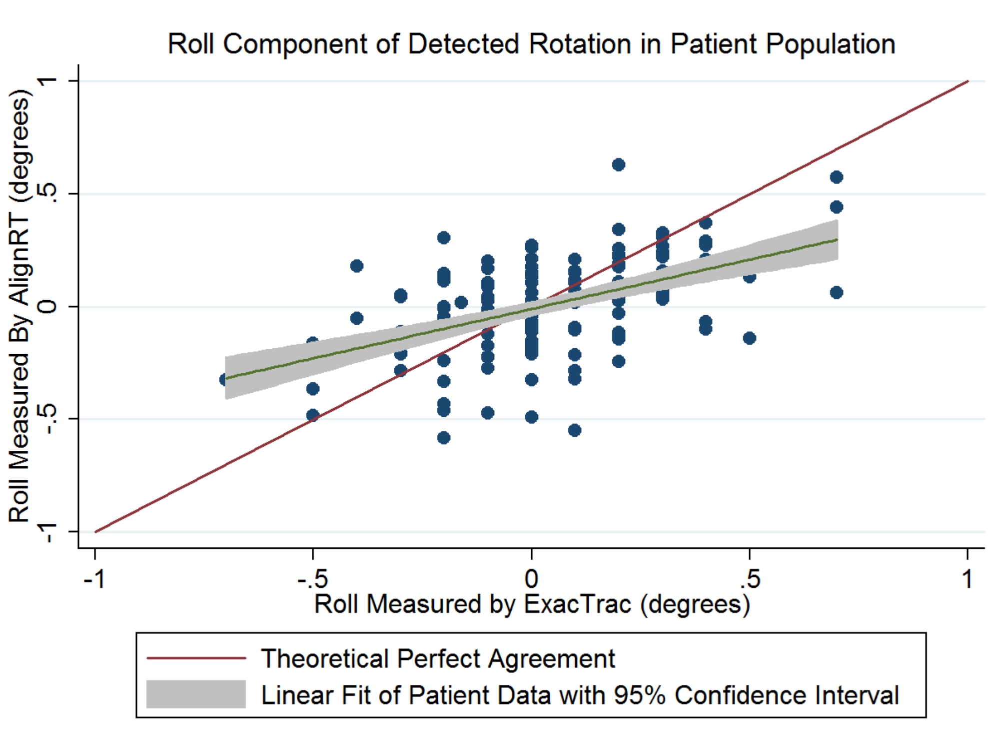

Figure 16. Roll system agreement. The linear fit of the patient data has a slope of less than 1. Note that ExacTrac reports rotations rounded to the tenth of a degree

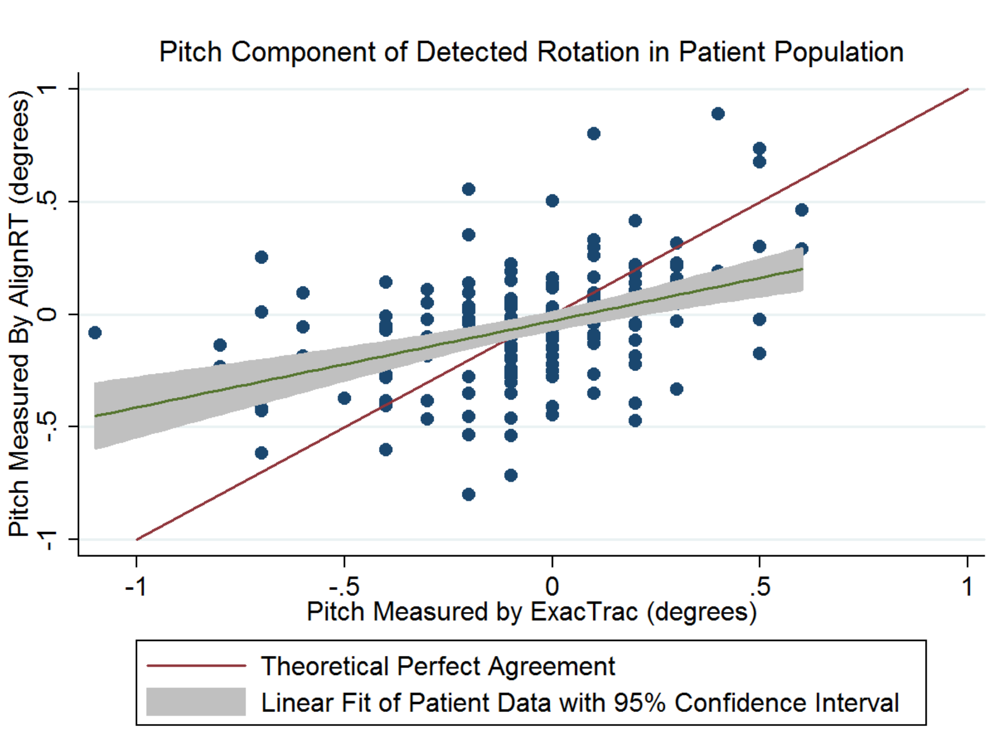

Figure 17. Pitch system agreement. The linear fit of the patient data has a slope of less than 1. Note that ExacTrac reports rotations rounded to the tenth of a degree

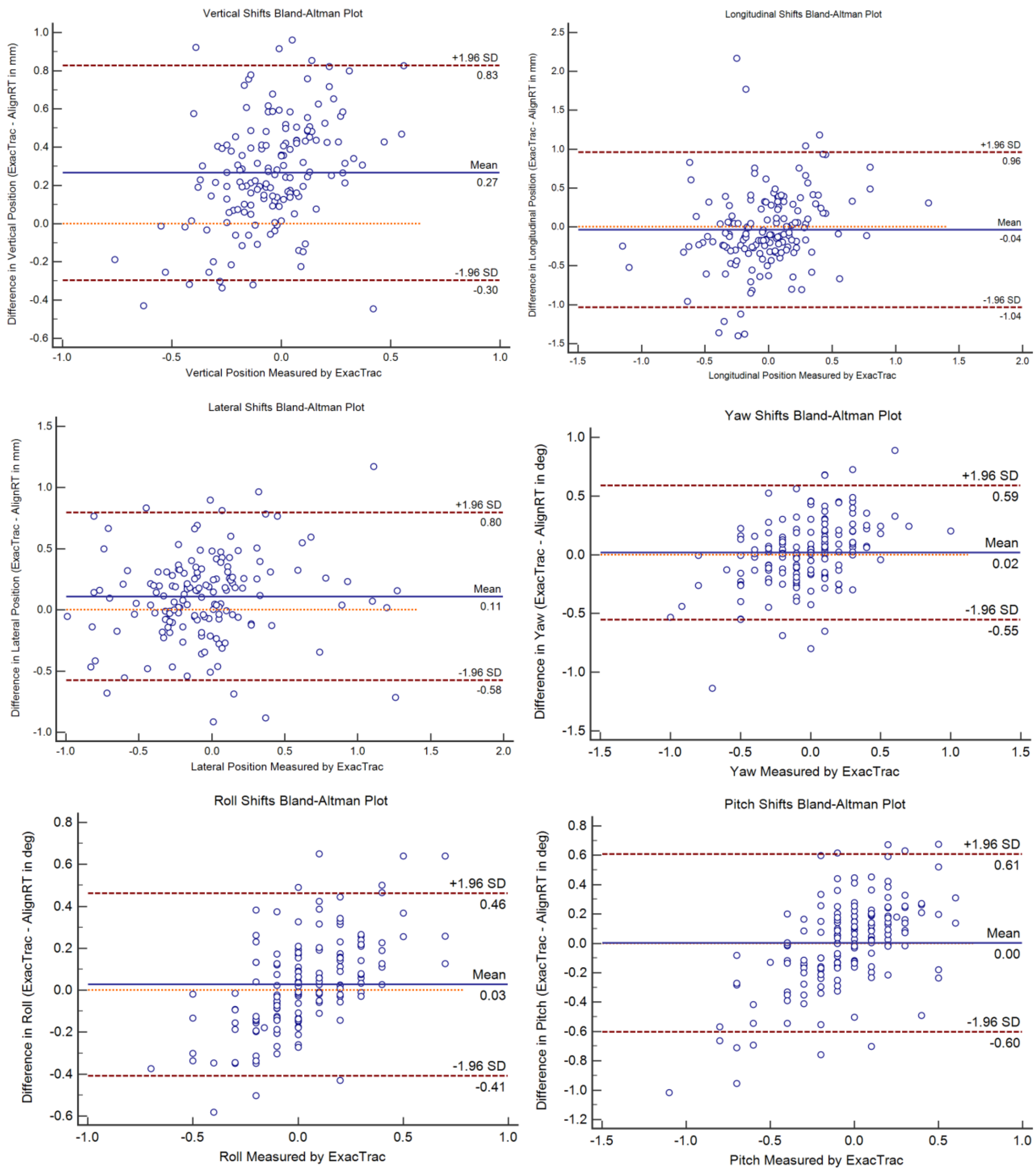

Figure 18. Bland-Altman plots comparing AlignRT and ExacTrac agreement. The difference in readings was plotted against the ExacTrac reading. Perfect agreement would result in all points lying on the horizontal zero line. Space inside the red dashed lines are where 95% of the readings will fall.

3.2.3 Correlation with Time

Some of the measured positional data was found to correlate with the length of time that had passed since treatment had started. The vertical position as measured by AlignRT was seen to have a negative linear correlation with time since treatment had started (p=0.0005) (figure 19). The other 5 components of position measured by AlignRT did not have a linear correlation with time (p>0.05) (figure 20). The absolute value of the vertical and longitudinal components of ExacTrac was seen to have a positive linear correlation with time (p=0.01 and p<0.0001 respectively) (figure 21). The other 4 components of magnitude of position measured by ExacTrac did not have a linear correlation with time (p>0.05) (figure 22).

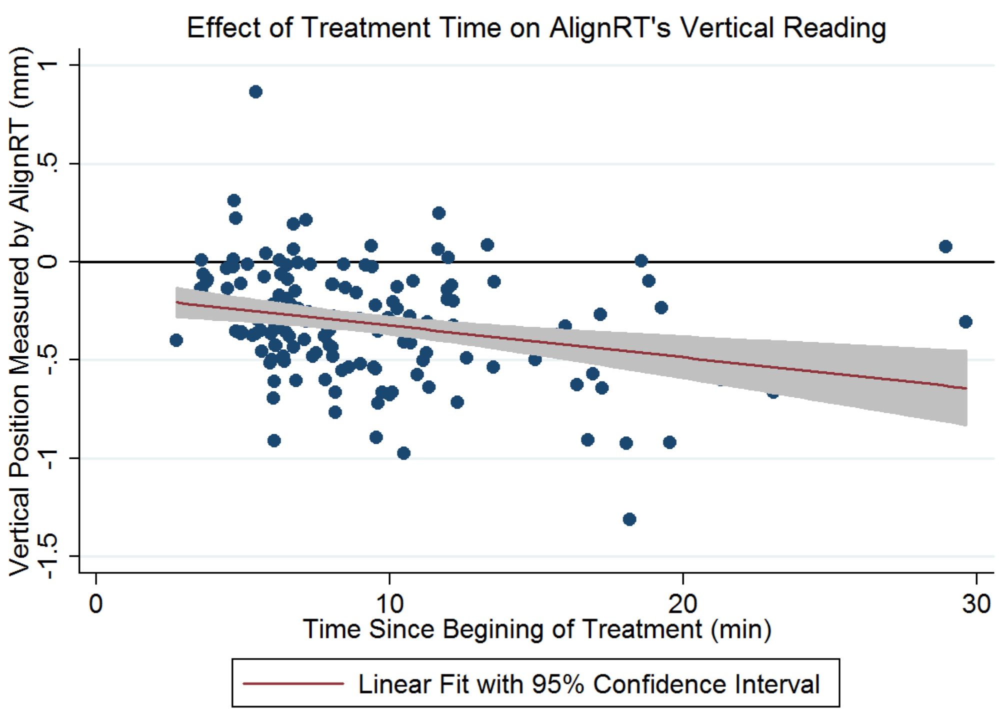

Figure 19. Vertical position tends to decrease over time as measured by AlignRT (p=0.0005).

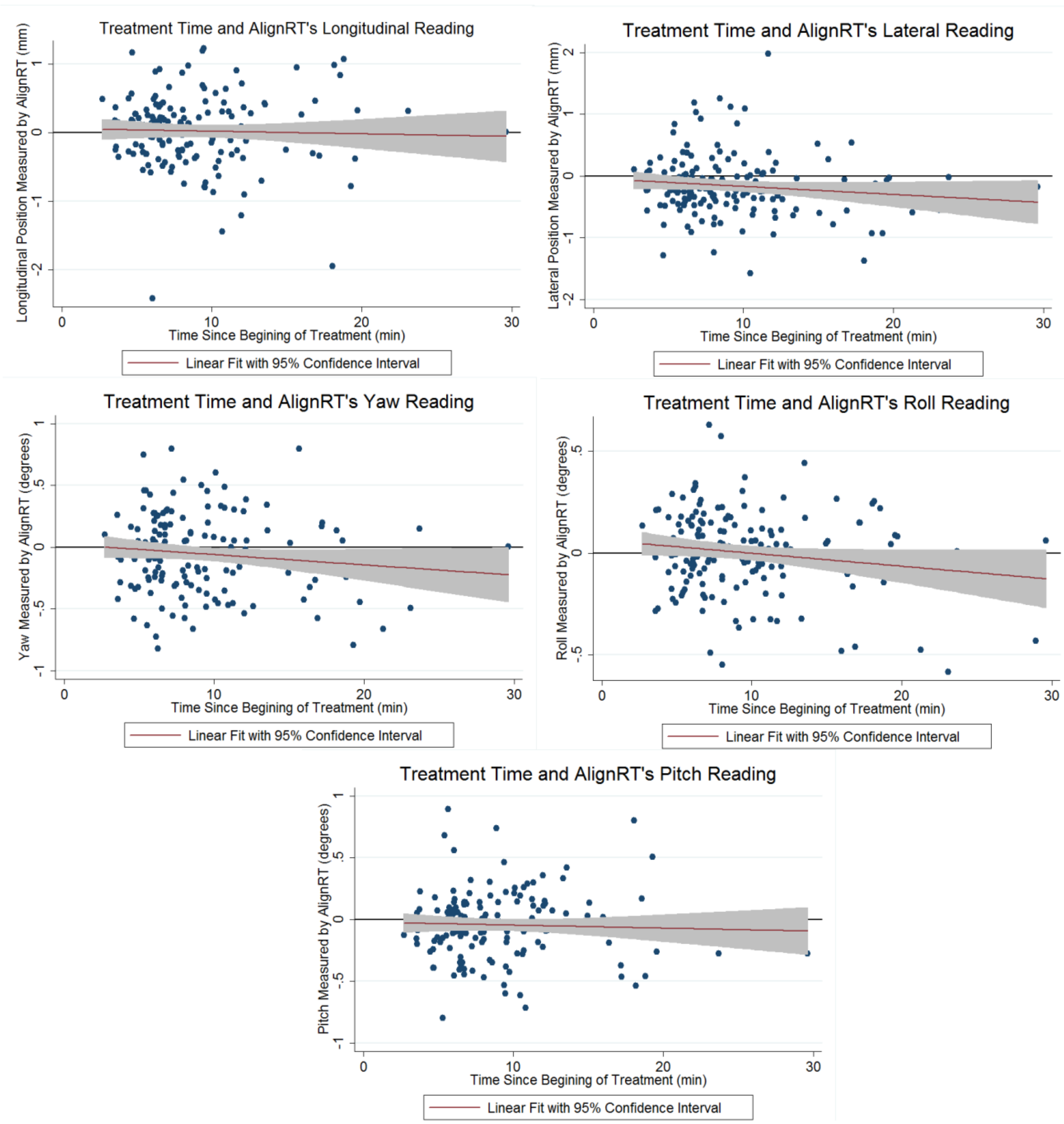

Figure 20. AlignRT did not observe a correlation between treatment time and longitudinal, lateral, yaw, roll, or pitch readings ($p>0.05$)

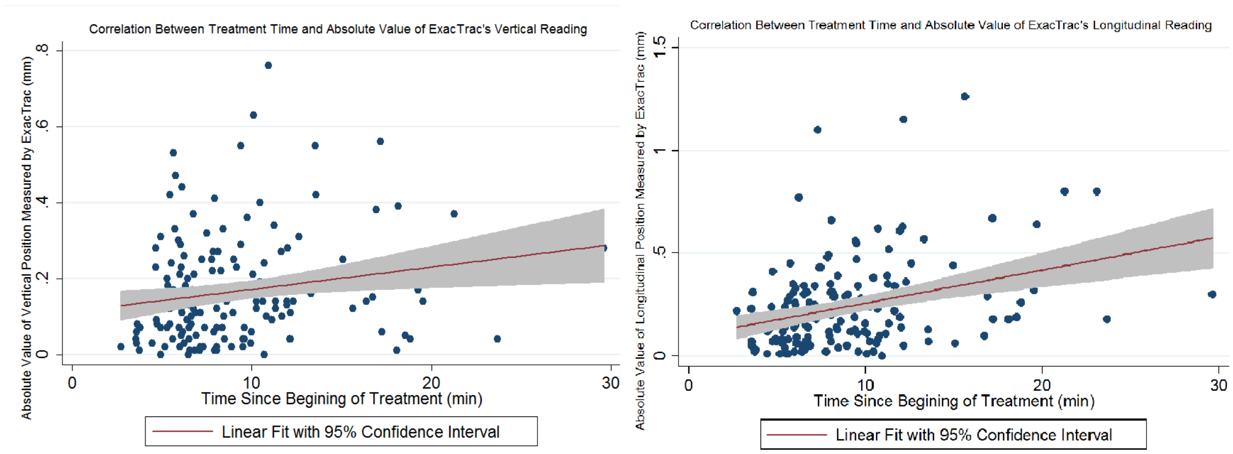

Figure 21. The absolute value of the vertical and longitudinal components of ExacTrac was seen to have a positive linear correlation with time ($p=0.01$ and $p<0.0001$ respectively)

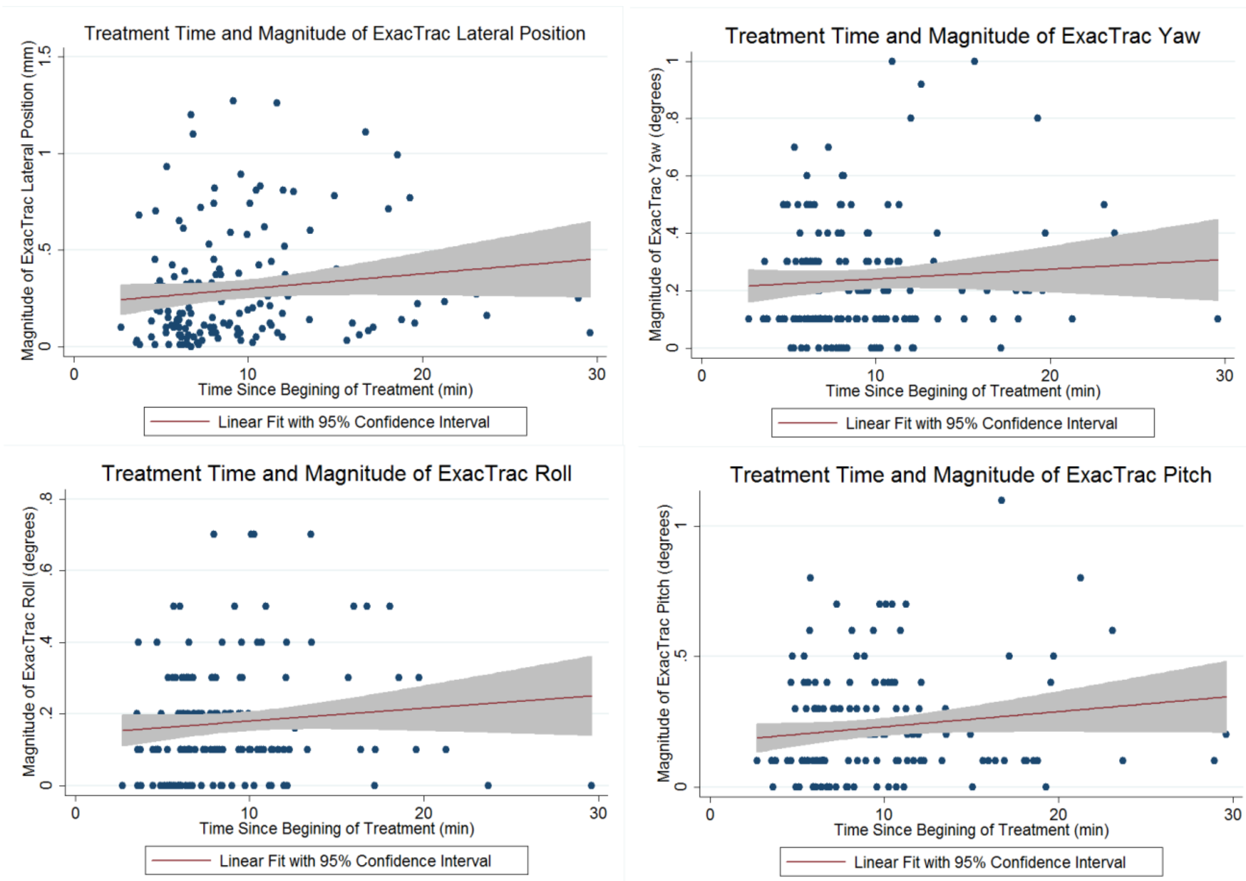

Figure 22. The absolute value of the lateral, yaw, roll, and pitch components of ExacTrac was not seen to have a linear correlation with time ($p>0.05$). Note that ExacTrac reports rotations rounded to the tenth of a degree

There were two main types of treatment checks: mid-treatment checks, and end of treatment checks. The 95% confidence interval for the average translational magnitude as measured by ExacTrac for mid-treatment checks was 0.40 to 0.49mm. The 95% confidence interval for the average translational magnitude as measured by ExacTrac for end of treatment checks was 0.51 to 0.71mm. This shows that the mean translational magnitude as measured by ExacTrac differs between mid and end of treatment checks ($p<0.05$).

3.2.4 Correlation with Anatomy

A summary table of the patient variables is provided here in table 3. Out of the 43 patients, 23 were male and 20 were female.

N=43	Cheek thickness (cm)	AlignRT region of interest area (cm^2)	Nasal ridge length as measured on AlignRT (cm)	Nasal protrusion as measured on AlignRT (cm)	Age
Minimum	0.43	51.9	3.02	0.3	35
Maximum	1.37	111.8	5.04	3.2	95
Average	0.82	83.7	4.01	1.91	65
Standard deviation	0.25	14.5	0.45	0.66	12.6

Table 3. The summary statistics on the patient variables recorded for the N=43 unique patients in the study

For the following analysis, the results of treatment checks for each patient were averaged to give one average data point for each patient. This will ensure that multiple measurements from one patient do not skew the correlation. According to the patient data, the absolute value of the yaw and roll measurements from AlignRT is correlated with the area of the region of interest tracked by AlignRT ($p=0.011$, and $p=0.047$ for yaw and roll respectively). As the region of interest area is increased, the absolute value of the yaw and roll measurements from AlignRT decrease. This relationship is shown with figures 23 and 24.

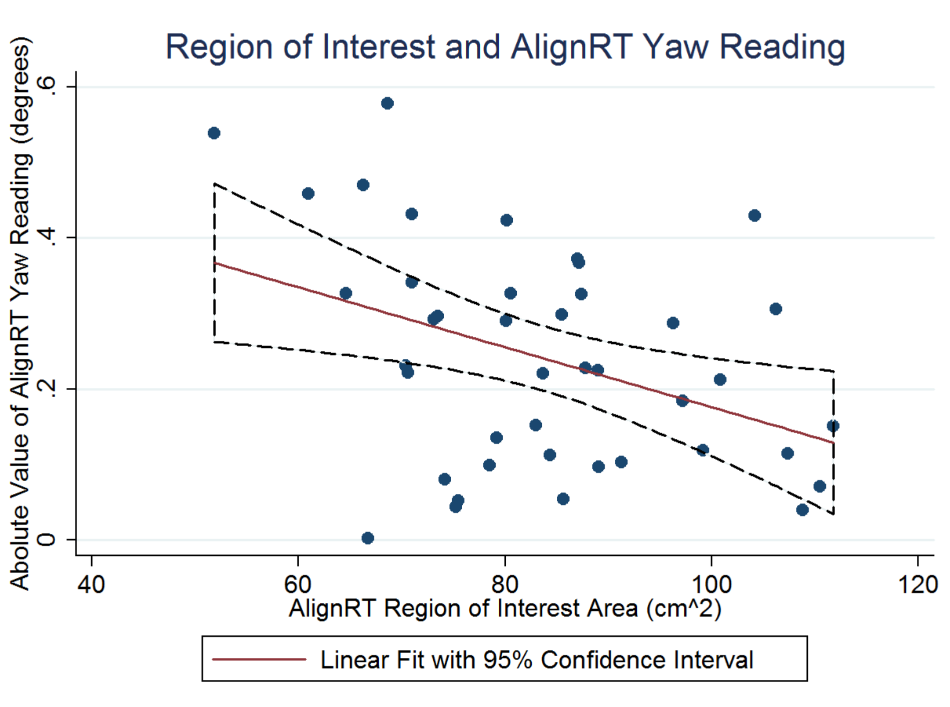

Figure 23. The variance in AlignRT measured yaw tends to decrease as the region of interest increases (p=0.011)

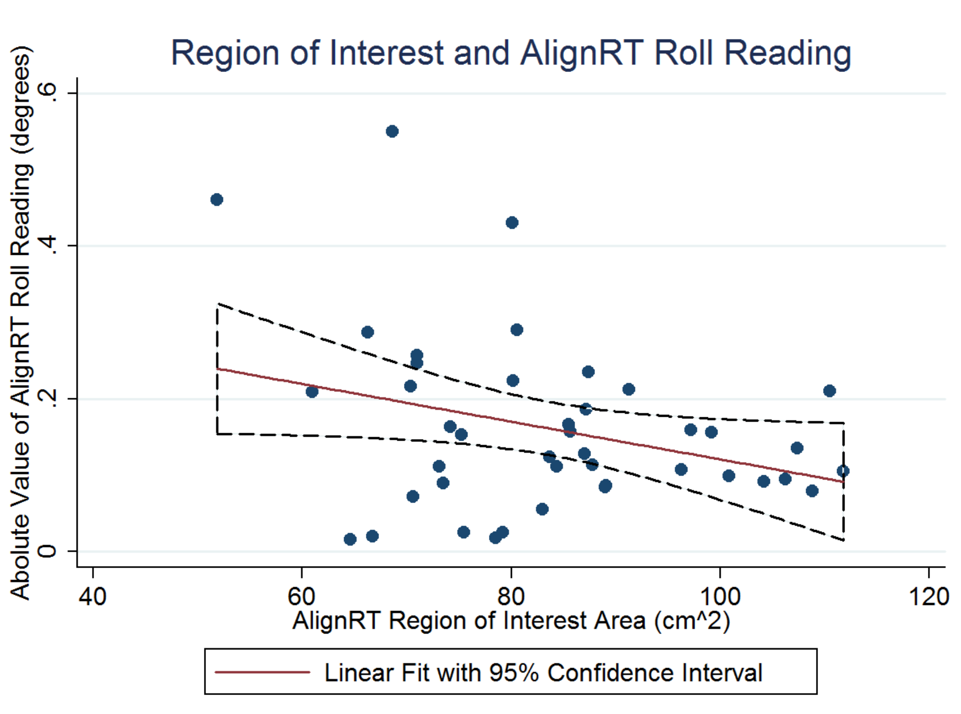

Figure 24. The variance in AlignRT measured pitch tends to decrease as the region of interest increases (p=0.047)

There was no significant correlation between cheek thickness and AlignRT readings or system agreement. Other notable variables that were not seen to correlate with system performance were patient age, gender, nasal ridge length, nasal protrusion, and inclusion or exclusion of cheeks in the AlignRT region of interest.

4. Discussion

4.1 Phantom Study

The main purpose of the phantom study was to characterize the image registration accuracy of each system under ideal conditions, and to see how well the systems tracked relative to each other. The phantom study revealed a small slow drift in some of the position components measured by AlignRT when the projectors were first turned on. This effect would stabilize after 10 to 15 minutes. The effect is due to thermal warming of the system causing small changes in the optics of AlignRT. The effect has been noticed and reported by Li et al.[10] The drift is limited to less than half a millimeter since the largest component of drift is in the vertical direction and has a magnitude of 0.4mm. Li et al. also observed that the maximum drift was less than half a millimeter and the largest component was in the vertical direction.

Ideally a reference image with AlignRT would be taken after the projector has been on for 10 minutes so that no additional drifting would occur after the system has been zeroed. The protocol used at OHSU (figure 5) involved using AlignRT for rough initial positioning, and then turning the projector off until after the ExacTrac shift, CBCT, and ExacTrac baseline images were taken. Once the ExacTrac baseline image was taken the AlignRT system was zeroed and real time monitoring began. With this protocol, the AlignRT system would start cold and warm up during the first 10 minutes of treatment. If the AlignRT projector was left on during the ExacTrac positioning and CBCT, then the system would be in a warm state when the reference image would be taken. A revised protocol where the AlignRT system was left on during the ExacTrac positioning and CBCT would eliminate thermal drift.

The phantom is stationary and its surface is not moving with respect to its internal anatomy. Therefore, the standard deviation values in table 1 are a measure of the image registration variability of each system. In section 4.2.4 these standard deviations in the phantom study will be used in an attempt to decompose the standard deviation of each system in the patient population dataset.

Section 3.1.3 demonstrated that in the phantom study, the two systems tracked with each other in a 1 to 1 fashion. Both systems agreed on the distance that the phantom was shifted in all of the 6 position components. In the patient population, 1 to 1 agreement was not observed across all components of position. The importance of the phantom study is to show that the systems can agree on distance measurements under ideal conditions.

In the phantom study AlignRT had very low standard deviations (when excluding thermal warming). AlignRT had a standard deviation of 0.02mm in the vertical direction which is lower than the standard deviation of 0.09mm in the vertical direction observed by ExacTrac (table 1, section 3.1.2). AlignRT had equal to or lower standard deviations than ExacTrac across the board.

4.2 Patient Study

4.2.1 Correlation with Time

The average value of the vertical AlignRT reading was -0.31mm (table 2). Based on what we know from the phantom study, the cause of this is likely the optical drift in the AlignRT system when warming up. Figure 19 in section 3.2.3 shows the linear correlation with time since treatment began and the vertical AlignRT measurement. Since the optical warming takes 10-15 minutes to take full effect, it makes sense that there would be a linear correlation over time with the vertical AlignRT reading.

The absolute value of the vertical and longitudinal component of ExacTrac was seen to have a positive linear correlation with time (figure 21). It makes sense that patients would be more likely to have moved as the time on the treatment table increases. Based on figure 21, the slope of the line of best fit for the longitudinal component is steeper than for the vertical component. It is possible that the most likely direction of patient movement over long periods of time is the longitudinal direction. Corroborating evidence would be needed from other studies to conclude that patient motion over time in frameless SRS/SRT treatments is most likely in the longitudinal direction.

4.2.2 Frequency of Out of Tolerance Detection

Table 2 lists the percentage of the total checks where according to either of the systems, the patient had moved by more than 1mm or degree. ExacTrac reported that 7.1% of the time, the patient had moved by a magnitude of greater than 1mm. This is smaller than the 18.6% of treatment checks where AlignRT reported that the patient had moved by more than 1mm. The percentage of treatment checks where the two systems disagree with each other by more than 1mm is 12.8%.

In the phantom study, the two systems agreed closely. Of the 170 phantom study measurements, the two systems had a maximum disagreement of less than 0.5mm and 0.4 degrees. One or both of these systems is encountering additional error when measuring patients.

Ackerly et al.[9] gathered clinical data on SRS/SRT treatments using ExacTrac. They reported the percentage of treatment checks where ExacTrac observed a patient shift of more than 0.7mm for the SRS and SRT populations separately. They reported that 43% of the time, their SRS patients were more than 0.7mm out of alignment, and that 37% of the time their SRT patients were more than 0.7mm out of alignment. For our population, ExacTrac measured that patients were more than 0.7mm out of alignment 21% of the time. Also, according to the AlignRT data, patients were more than 0.7mm out of alignment 47% of the time. It is possible that the patients at OHSU move less during treatment, or are better immobilized; however, the ExacTrac measurements in the Ackerly study included measurements at couch angles where couch walkout could increase patient misalignment.

Table 2 also summarizes the standard deviation for the ExacTrac position measurements in the patient population. The vertical, longitudinal, and lateral standard deviations observed by ExacTrac in the OHSU study are 0.2mm, 0.3mm, and 0.4mm respectively. Lewis et al. recorded ExacTrac positioning data for 104 SRS patients and found that the standard deviation for the vertical, longitudinal, and lateral components to be 0.5mm, 0.7mm, and 0.4mm respectively.[15] The standard deviations in the OHSU study are equal to or smaller than those observed by Lewis et al.

4.2.3 Frequency of ExacTrac Imaging

If a correlation between elapsed time and magnitude of position measurements is found, it may motivate the imaging frequency protocol. In the OHSU study, the only correlation between the magnitude of ExacTrac position measurements and elapsed time was observed in the vertical and longitudinal components. Figure 21 demonstrates the correlation between elapsed time and the magnitude of the ExacTrac vertical and longitudinal readings. The slope of the line of fit for the vertical component is shallower than for the longitudinal component. The greatest elapsed time for the first mid-treatment check was 12 minutes. On figure 21, the projected mean value for the magnitude of the longitudinal reading at 12 minutes is approximately 0.3mm. This demonstrates that the current imaging workflow (take an ExacTrac image every two table rotations) is adequate at accounting for increased patient motion in the longitudinal direction over time.

There were eight times where a second mid-treatment check was performed. Out of these eight checks, the patient was observed to be out of alignment by a magnitude of at least 1mm once.

This offers some anecdotal evidence that the additional mid-treatment checks were useful. An argument could be made to eliminate additional mid-treatment checks and to only perform one mid-treatment check at the middle of treatment. Lewis et al. used their clinical data and a lack of correlation with time to argue that only one mid-treatment check is necessary.[15] It has already been shown that the standard deviations of ExacTrac measurements in our patient population were equal to or lower than the standard deviations reported in the Lewis study. The OHSU study has shown that the percentage of total checks where ExacTrac measured a shift greater than 0.7mm in our population was 21%, whereas in the Ackerly study a percentage of 43% was reported.[9] If institutions with reported patient positional deviations larger than OHSU are recommending only taking ExacTrac images midway through treatment, then OHSU would not be an outlier if they adopted the midway only workflow.

4.2.4 Decomposing the Patient Study Variance

The concept that the standard deviation observed in a phantom study is a measure of image registration error has been used in other studies.[12, 16] This fact can be used along with some other assumptions in an attempt to decompose the variance seen in the patient population by both systems. Independent standard deviations can be added and subtracted in quadrature. In ICRU report 62, it is recognized that random errors in positioning are to be added in quadrature.[17] Since the variance is the square of the standard deviation, adding variances using simple addition is the same as adding standard deviations in quadrature.

The assumption is now made that the variance seen in the patient population for the ExacTrac measurements consists only of image registration variance and variance due to patient motion. This assumes that the image registration error in the patient population is the same as in the phantom study. Here is one possible example of how the previous assumption might not be valid: the patient's internal anatomy could change as compared to the simulation CT in such a way that image registration was adversely affected. Holding the assumptions as valid, we can use the following equation:

Equation 1

$$V_{\text{ET, patient}} = V_{\text{ET, image reg}} + V_{\text{patient motion}}$$

Where $V_{\text{ET, patient}}$ is the variance seen by ExacTrac in the patient population, $V_{\text{ET, image reg}}$ is the variance seen by ExacTrac due to image registration (which is assumed to be the same in the phantom and patient study for ExacTrac), and $V_{\text{patient motion}}$ is the variance due to patient motion. The corresponding standard deviation values for the term on the left hand side of equation 1 and the first term on the right hand side of equation 1 are listed in tables 1 and 2. Thus, we can plug in these values and get a value for the vertical variance due to patient motion.

Equation 2

$$V_{\text{patient motion, vert}} = V_{\text{ET, image reg, vert}} - V_{\text{ET, patient, vert}} = (0.21\text{mm})^2 - (0.09\text{mm})^2 = 0.0378\text{mm}^2$$

Letting $S_{\text{patient motion, vert}}$ be the vertical standard deviation due to patient motion, the following can be calculated.

Equation 3

$$S_{\text{patient motion, vert}} = \sqrt{0.0378} = 0.19\text{mm}$$

The same can be done for all 6 components of position for ExacTrac, and they are summarized in table 4.

For the AlignRT system, a rigid surface is assumed as a surrogate for internal target tracking. In the phantom study, the surface being tracked stays rigid, and the surface stays in the same position relative to the internal target. In the patient population, the facial surfaces tracked could deform, and they could move relative to the internal target. The assumption is now made that the variance seen in the patient study for AlignRT can be broken into three components: variance due to AlignRT image registration under ideal circumstances ($V_{\text{ART, image reg}}$), variance due to patient motion, and variance due to other factors such as facial deformation, target/surface decoupling or thermal effects ($V_{\text{ART, other}}$).

Equation 4

$$V_{\text{ART, patient}} = V_{\text{ART, image reg}} + V_{\text{patient motion}} + V_{\text{ART, other}}$$

The previously computed values for $V_{\text{patient motion}}$ can be used to compute each component of $V_{\text{ART, other}}$ and hence $S_{\text{ART, other}}$. The results of this calculation are also tabulated in table 4.

n = 156	Vertical	Longitudinal	Lateral	Yaw	Roll	Pitch
$S_{\text{patient motion}}$	0.19mm	0.33mm	0.39mm	0.30^0	0.22^0	0.29^0
$S_{\text{ART, other}}$	0.20mm	0.42mm	0.31mm	0.11^0	0.08^0	0.11^0

Table 4. Based on 156 treatment checks, this table provides an estimation of the standard deviation of patient motion, and also the standard deviation in AlignRT measurements due to facial deformation, target surface decoupling and thermal effects.

According to the tabulated data, the standard deviation in patient motion in the vertical direction is slightly less than for the longitudinal and lateral directions. The rotational standard deviations due to patient motion are more evenly spread with Roll being the smallest. It is hypothesized that $S_{ART, other}$ is comprised mainly of effects due to facial deformation, target/surface decoupling, and thermal effects. It is known from the phantom study that thermal effects are most prominent in the vertical component, with the longitudinal and pitch components also being affected. The lateral, yaw, and roll components may be a good measure of the standard deviation due to facial deformation and target/surface decoupling alone.

4.2.5 Relative Tracking Interpretation

Figure 14 in section 3.2.2 demonstrates that AlignRT and ExacTrac can track with each other in a 1 to 1 fashion in the patient population in the lateral direction. The other components of position did not exhibit this behavior in the patient population. The other 5 components of position had a slope of less than 1, meaning that AlignRT on average would detect less than a 1mm shift when ExacTrac detected a 1mm shift. The slope of less than 1 could indicate the limitations of using surface imaging for an internal target. It could be that facial anatomy is held slightly in place by the treatment mask. The idea being that while the internal anatomy moves a given amount, the surface anatomy lags behind.

4.2.6 AlignRT Correlation with Anatomy

Figures 23 and 24 in section 3.2.4 demonstrate a correlation between the absolute value of the yaw and roll components of AlignRT and the area of the region of interest used by AlignRT. The correlation between region of interest area and ExacTrac readings for yaw and roll are not statistically significant ($p>0.05$). This suggests that the AlignRT system is more accurate at tracking patient movement when the region of interest area is larger; however, the correlation between system agreement and region of interest area was also not statistically significant ($p>0.05$). The variance in yaw and roll readings from AlignRT may go down with increased region of interest area, but this does not lead to better agreement between the systems. One explanation might be that a larger region of interest might contain some of the stationary mask which would cause the AlignRT readings to have less variance but would not make the system better at detecting true patient motion. Also, it is hard to reason why this correlation between region of interest area and AlignRT variance is limited to only the yaw and roll components. As is always the case, it could be that the observed correlation was due to random chance.

4.2.7 Lack of Correlation with Other Variables

Significant findings from the study have been reported up to this point, meaning that there were many patient variables that were not found to be correlated with individual system performance or system agreement. One specific hypothesis that was held before collecting the data was that puffier cheeks would degrade AlignRT's performance; however, there was no significant correlation between cheek thickness and AlignRT readings or system agreement. It could be that the specific metric used by this study is not adequate at capturing cheek puffiness. Other notable variables that were not seen to correlate with system performance were patient age, gender, nasal ridge length, and nasal protrusion.

4.2.8 AlignRT Sources of Error and Overlooked Benefits

The AlignRT data points recorded from this study were taken from RTD monitoring files. A quick test was performed where an ExacTrac image was taken and the AlignRT system was turned on and off at the exact same time. This verified that the timestamps generated by ExacTrac and the times reported by AlignRT were accurate with each other down to an error of 1 second. Time stamps for ExacTrac images were used to pull the relevant data from the RTD files. It is possible that some of these time stamps were recorded incorrectly, causing the incorrect AlignRT data to be used.

It was noted by an AlignRT field service engineer that the placement of OHSU's central AlignRT camera was offset and is not in the standard central position. Our phantom study demonstrated that the AlignRT system at OHSU had similar or smaller variance than those reported by other phantom studies such as by Peng et al.[12] It is possible that the different camera placement would cause additional unforeseen camera blockage at certain gantry angles; however, this is not relevant to this study since we are only looking at data points when the table and gantry are at position zero.

One of the overlooked benefits of the AlignRT system in terms of this study is its ability to track the patient continuously in real time. Accuracy and variance aside, the ability to track the patient throughout the treatment is a huge benefit that AlignRT has over the ExacTrac system. Real time tracking enables the treatment team to know exactly how long the patient has been out of tolerance. With ExacTrac, the treatment team will be unsure of how long the patient has been out of tolerance. Additionally, the AlignRT system has the advantage of not using ionizing radiation.

5. Future Directions

5.1 New Workflow/Protocol

Leaving the AlignRT system on after initial rough alignment and during the initial ExacTrac and CBCT images would allow the system to be fully warm when the AlignRT reference image is taken. Changing this workflow and observing if the AlignRT variability goes down or if the two systems have better agreement would be a future direction to this study.

The current workflow involves only imaging the patient with ExacTrac at table and gantry position of zero. A new protocol could be implemented where the ExacTrac images would be taken at table angles. This would save time over the current workflow; however, the couch walkout could increase the positional error in this case. A phantom study could be done before implementing this new protocol where the effect of couch walkout with the two imaging systems was thoroughly characterized. If this new protocol was used, the new positional data from both systems could be analyzed to characterize the readings from both systems and compare them to the findings of the current study.

5.2 Mask Tightness

A metric could be developed to measure the mask tightness, and hence see the effect of mask tightness on patient motion. One possible way to measure mask tightness would be to ask the patient to try and move their head in the various translational and rotational directions. AlignRT could be used to track how much the patient is able to move in their facemask. The maximum displacement values could be extracted from the RTD AlignRT files and used as a measure of mask tightness.

5.3 Other Directions

This study has shown that a correlation exists at least in the longitudinal component between elapsed time and increased magnitude of position readings. One could also study the correlation between the number of table rotations and the spatial readings. The current protocol is to take an ExacTrac image every two table rotations. End of treatment checks provide data points where many more than two table rotations have occurred since the start of treatment. Understanding the correlation between the number of table rotations and positional data will help to validate or discredit the current workflow. Mosaiq stores information on the order of treatment fields delivered along with time stamps. This data is sufficient to record the number of table rotations between each ExacTrac image.

If the thermal warming effects in AlignRT are highly reproducible in magnitude and in time, then the drift could be subtracted off of the clinical AlignRT measurements retrospectively. A curve of best fit would be used to predict the drift over time for each position component. After correcting the AlignRT measurements for thermal drift, the agreement between the two systems could be analyzed again and checked for improvement. One potential problem would be if two treatments that involve AlignRT occurred back to back, in which case the system may already be warm.

A shutter system could be added to AlignRT so that the projectors can be on, but the light can be blocked from reaching the patient. This would allow for the revised AlignRT protocol to be followed while sparing the light from getting in the patients eyes during the initial set up phase. Special care and testing would need to be done to ensure that deployment of the shutters does not interfere with system calibration.

6. Conclusion

Agreement between AlignRT and ExacTrac for intrafraction motion detection in the patient population was sub-millimeter on average (average magnitude of disagreement = 0.66mm) with a maximum disagreement of 2.4 millimeters. The phantom study demonstrated that some of the disagreement seen between the systems was due to thermal warming effects. A revised workflow was proposed to eliminate thermal warming effects from the AlignRT system. It was observed that the ExacTrac standard deviations of patient motion in our study was equal to or less than those observed in two other studies.[9, 15] Changing the imaging workflow to take one ExacTrac image halfway through treatment is supported by the findings of this study, even though anecdotal evidence has shown that in at least one instance a secondary mid-treatment check observed patient motion of greater than 1mm.

In the patient population, one to one relative tracking between AlignRT and ExacTrac was observed in the lateral component of position. The other components of position demonstrated that a shift of 1mm or degree measured by ExacTrac would on average be measured as smaller by the AlignRT system. Some correlations between AlignRT position measurements and patient anatomy were observed, but in no case was the agreement between the two systems correlated with patient anatomy.

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