International Journal of
Radiation Oncology
biology • physics

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Physics Contribution

Evaluation of the Accuracy of a 3D Surface Imaging System for Patient Setup in Head and Neck Cancer Radiotherapy

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Received May 3, 2011

Summary

This study demonstrates that the rigid setup errors detected by AlignRT are in good agreement with bony computed tomography registration in Pinnacle[3] (<3 mm and 2° at 90% confidence level). This suggests that the AlignRT system may be used for verifying and correcting daily rigid setup of the head positions in fractionated radiotherapy. Further investigations are necessary to improve the accuracy for the nonrigid realignment.

Purpose: To evaluate the accuracy of three-dimensional (3D) surface imaging system (AlignRT) registration algorithms for head-and-neck cancer patient setup during radiotherapy.

Methods and Materials: Eleven patients, each undergoing six repeated weekly helical computed tomography (CT) scans during treatment course (total 77 CTs including planning CT), were included in the study. Patient surface images used in AlignRT registration were not captured by the 3D cameras; instead, they were derived from skin contours from these CTs, thereby eliminating issues with immobilization masks. The results from surface registrations in AlignRT based on CT skin contours were compared to those based on bony anatomy registrations in Pinnacle[3], which was considered the gold standard. Both rigid and nonrigid types of setup errors were analyzed, and the effect of tumor shrinkage was investigated.

Results: The maximum registration errors in AlignRT were 0.2° for rotations and 0.7 mm for translations in all directions. The rigid alignment accuracy in the head region when applied to actual patient data was 1.1°, 0.8°, and 2.2° in rotation and 4.5, 2.7, and 2.4 mm in translation along the vertical, longitudinal, and lateral axes at 90% confidence level. The accuracy was affected by the patient's weight loss during treatment course, which was patient specific. Selectively choosing surface regions improved registration accuracy. The discrepancy for nonrigid registration was much larger at 1.9°, 2.4°, and 4.5° and 10.1, 11.9, and 6.9 mm at 90% confidence level.

Conclusions: The 3D surface imaging system is capable of detecting rigid setup errors with good accuracy for head-and-neck cancer. Further investigations are needed to improve the accuracy in detecting nonrigid setup errors. © 2012 Elsevier Inc.

Keywords: Align RT, Head-and-neck cancer, Image registration, Nonrigid, Rigid, Setup error

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Conflict of interest: none.

Supplementary material for this article can be found at www.redjournal.org.

Acknowledgment—We thank Tony Ruto and Norman Smith from Vision RT for technical assistance with the registration tools.

Int J Radiation Oncol Biol Phys, Vol. 84, No. 2, pp. 547−552, 2012
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doi:10.1016/j.ijrobp.2011.12.004

Introduction

One requirement for the success of head-and-neck (HN) cancer radiation therapy (RT) is the accurate and reproducible patient setup during fractionated treatment (1, 2). To ensure target coverage, a safety margin is usually added to the clinical target volume to form the planning target volume in treatment planning to compensate for residual and uncorrected setup errors and other uncertainties during the treatment course. Because the HN region contains many organs at risk (OAR) with various, and most of the time, very low tolerance to doses, a large safety margin is often associated with an increased dose to these OARs and surrounding healthy tissues, which can lead to increased risks of treatment-related complications and poorer quality of life after treatment. Minimizing the positioning uncertainties is therefore essential for the safe reduction of the margins, adequate tumor dose, lower OAR doses, and eventual improved outcomes.

The current standard method of verifying HN cancer patient setup accuracy is cone beam computed tomography (CBCT) (3, 4); other types of two-dimensional (2D) projection imaging are also used. CBCT is available on many modern linear accelerators and offers imaging quality that is adequate for differentiating bone, soft tissue, and air cavity. It has the advantage over traditional megavoltage (MV) portal imaging and even kV projection imaging in that it is 3D in nature and provides accurate setup information during treatment. One apparent drawback is the additional radiation dose to the patient, although the dose is very small per fraction, it can add up considerably if performed at each fraction (>30 fractions for a typical HN treatment course; hypofractionation is not commonly used for HN-RT). In addition, CBCT acquisition, reconstruction, and registration may take 2−5 min, which prolongs treatment time at each fraction, where a 15- to 20-min time slot is typically used. In addition, CBCT is not suitable for monitoring intrafraction motion.

In this study, we investigated an alternative method of verifying and correcting patient setup, using a commercial 3D surface imaging system, AlignRT (VisionRT Ltd., London, UK) for HN-RT patient setup. There have been a few published reports of its accuracy for patient setup, for example, in breast (5, 6), thorax (7), and prostate (8) cancers. These studies showed that this technology allowed a high degree of precision for patient setup.

Unlike other tumor treatments, HN cancer radiotherapy has its unique challenges. Tumors in the HN regions are "attached" to the bony structures abundant in the regions; therefore, the bony anatomy is used as surrogates for the tumors (*i.e.*, a good match in bones between treatment and reference usually means good tumor localization). Hence, the bone registration in CT is considered the gold standard for HN image guidance. Some bones in the HN regions, such as spine vertebrae, may move relative to each other and are considered "flexible" as a whole. Therefore, patient setup has both rigid and nonrigid components (3, 4). This complicates the correlation analysis between the surface match using a camera system and bone match using CTs.

Most HN treatments in the form of intensity-modulated RT (IMRT) and 3D conformal RT require that the patient is immobilized. In our practice, a thermoplastic mask is normally used, which can obscure the patient's skin surface from being seen directly by the camera system. This makes it impossible to directly compare the registration between the CT images with the mask and the surface images without the mask. To overcome this problem, one group designed a customized bite block system to allow tracking head position under an immobilization mask (9). Alternatively, one can treat the patient without the mask and use the camera system to continuously monitor patient position during the treatment. However, this feature needs to be thoroughly investigated before being used clinically.

Furthermore, most HN cancer patients lose weight during the treatment course (10, 11). The bony structures change little; therefore, the simulation CT is still suitable for CT-based patient setup verification through the entire treatment course. However, the shrinkage of tumor and normal tissues with time can be pronounced, appearing as apparent skin surface changes. This makes it more difficult for the surface image from simulation to be used as the reference throughout the treatment course, and such effect needs to be investigated.

In this study, we compared surface registrations with bone matching using CTs in the HN region to assess whether a 3D camera system can replace CT for patient setup verification for HN cancer patients. To avoid the mask issue, we took a different approach. The surface images were not acquired directly by the camera system but were derived from the skin contours in the CT images. Therefore, the data source was the same, only two registration algorithms focusing on different aspects were compared: internal 3D image pixel values for CT registration and surface spatial information for AlignRT registration. Both rigid and nonrigid registrations were investigated, and the effect of tumor and normal tissue shrinkage was also included in the analysis.

Methods and Materials

Patient data and work flow

In this study, we used helical CT images from 11 patients who previously underwent HN-IMRT treatment. Each patient underwent one planning CT scan as a reference and six weekly CT scans during the treatment course (11). Patients were set up the same way as in the treatment position with the mask. These helical CTs were chosen over CBCTs mainly because we wanted to include the entire region from head to shoulder in the study, and the current CBCT system has limited field of view, with truncations in either head or shoulder in a single scan. CT scans were imported into Pinnacle^3 treatment planning system (version 8.0; Philips Radiation Oncology System, Madison, WI), where patient bony anatomy registrations were performed. The cross-correlation registration algorithm implemented in Pinnacle^3 was chosen because this is effective for intramodal CT-CT registration (12, 13). The skin contours were carefully delineated in Pinnacle^3 to avoid the artifact from the mask, and they were transferred through the DICOM interface as RT-structures to the AlignRT system, where they were converted to surface mesh before the registration was performed (14). The two registrations have the same goals and data sets but different approaches: the CT image pixel values representing internal anatomy were registered as volume in Pinnacle^3, and the surface mesh patterns representing patient outline were registered as surface in AlignRT. Both registrations were performed automatically by the system, with operator visual inspection afterward. Results of the registrations were stored as transformation matrices in text files, although in different formats. A tool was developed inhouse to convert between these formats, taking into account the differences in axis notation, rotation sequence, units, and other factors. The transformation matrix was further decomposed into a set of six variables through the tool, namely the translation and rotations in three axes: left−right (LR, or lateral), anterior−posterior (AP, or vertical), and superior−inferior (SI, or longitudinal). The translation component was chosen as the isocenter shift. The registration results can be applied as the couch shifts to correct the patient positions.

Accuracy of the surface registration algorithm

To evaluate the accuracy of the AlignRT surface registration algorithm and validate the conversion tool, we used a single helical CT of an HN cancer patient to create a reference skin contour in Pinnacle[3], referred to as Skin-0. A set of predefined transformations, $U(P3)_i$, for each one and combinations of the six degree freedom, were applied to the CT in Pinnacle[3], and the transformed CT was used to create a second skin contour, Skin-*i*, where the Skin-*i* was not transformed from Skin-0 but generated independently from the transformed CT. Here, P3 denotes Pinnacle[3].The transformation, $U(P3)_i$, consisted of predefined translations and rotations:

$$U(\mathrm{P3})_i = (r\_vrt,\ r\_lng,\ r\_lat,\ d\_vrt,\ d\_lng,\ d\_lat)_i \qquad \text{(Eq.1)}$$

Here, *r_vrt* and *d_vrt* are the rotations and translations, respectively, in the vertical axis, and so on and so forth. The two contours of the skin (Skin-0 and Skin-*i*) were transferred to AlignRT, where they were registered, as shown in Fig. 1. The registration reported by AlignRT contains, similarly, translational and rotational motions, defined as

$$U(\mathrm{AR})_i = (r\_vrt,\ r\_lng,\ r\_lat,\ d\_vrt,\ d\_lng,\ d\_lat)_i \qquad \text{(Eq.2)}$$

Here, AR denotes AlignRT. The difference between $U(AR)_i$ and $U^{-1}(P3)_i$, ΔU_i, was used to evaluate the accuracy of the AlignRT registration algorithm

$$\begin{aligned}\Delta U_i &= U^{-1}(\mathrm{P3})_i - U(\mathrm{AR})_i\\ &= (\delta r\_vrt,\ \delta r\_lng,\ \delta r\_lat,\ \delta d\_vrt,\ \delta d\_lng,\ \delta d\_lat)_i \qquad \text{(Eq.3)}\end{aligned}$$

Rigid setup accuracy

To evaluate the accuracy of AlignRT for rigid patient setup, only the head region was used for registration between the weekly CTs and the planning CTs. In Pinnacle[3], the head region was defined in the CT image as all slices above the second cervical vertebra, or C2. This definition was inclusive, rather general, and not specific to each type of tumor.

Data for all 11 patientswere included in this part of study. Each patient had six repeated weekly helical CTs, all of which were registered to the reference planning CT image. HN tumors respond well to radiation, shown typically as tumor and normal tissue shrinkage during the treatment course. The purpose here was to investigate the sensitivity of the surface registration accuracy to the shrinkage. Statistical analyses were performed whenever necessary to test the significance.

For each patient, the weekly CT (CT_j, where $j = 1, 6$) was rigidly registered to the planning CT (CT_0) based on bony anatomy inside the head region in Pinnacle[3], and the corresponding transformation, $U\_head(P3)_j$, was recorded. The Head-0 (skin contour of the head in CT_0) and Head-*j* (skin contour of the head in CT_j) were transferred to the AlignRT system, and the corresponding registration, $U\_head(AR)_j$, was recorded. The difference, ΔU_head_j, was used to quantify the accuracy of AlignRT for rigid registration by using

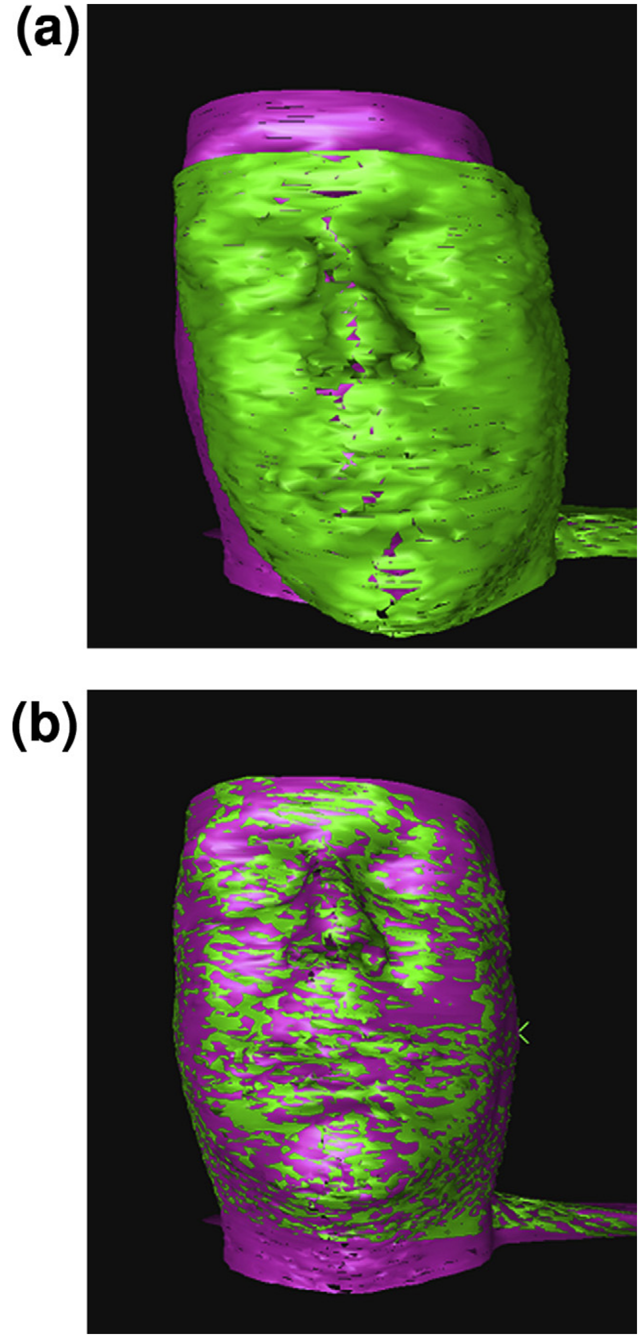

Fig. 1. The reference (purple) and secondary surface (green) images in AlignRT: (a) before registration and (b) after registration.

$$\Delta U\_head_j = U\_head(\mathrm{P3})_j - U\_head(\mathrm{AR})_j \qquad \text{(Eq.4)}$$

Ideally, the ΔU_head_j value should be zero, *i.e.*, the registration of the skin in AlignRT should agree with the registration of the bone in Pinnacle[3] for the same patient and same CTs.

Table 1 Accuracy of the surface registration algorithm

Registration (n = 22)	Rotations (°)			Translations (mm)		
	r_vrt	r_lng	r_lat	d_vrt	d_lng	d_lat
Mean	0.03	0.07	0.03	0.04	0.14	0.05
SD	0.02	0.05	0.02	0.03	0.14	0.06
Max. (abs.)	0.07	0.16	0.10	0.11	0.63	0.27
Min. (abs.)	0.00	0.01	0.00	0.01	0.02	0.00

Abbreviations: Max. (abs.) = Maximum (Absolute); Min. (abs.) = Minimum (Absolute); SD = standard deviation.
Table data show differences between the registration in AlignRT and Pinnacle, using a single head CT but a set of predefined combinations of rotations and translations.

Nonrigid setup accuracy

Because of the flexible bony structures in the neck regions, largely the vertebrae, different regions may have translations and rotations that are different from the reference positions. This is commonly referred to as nonrigid patient setup. To evaluate the accuracy of AlignRT for nonrigid realignment of HN patients, we used two regions in this part of the study: the head and the shoulder. In Pinnacle[3], the shoulder was defined on the CT image for all slices below the sixth cervical vertebra, or C6. The neck region was not used because loose skin in this region is not reproducible. The differences between the registration results for these two regions represent the nonrigid setup errors. If the whole HN region moves together, then the difference is zero. Different types of subregions can be used to define nonrigid setup errors (4), but only two were used here to illustrate the point.

$$\Delta U(\text{non}-\text{rigid})_k = \left(U\_head(\text{P3})_k - U\_shoulder(\text{P3})_k\right) - \left(U\_head(\text{AR})_k - U\_shoulder(\text{AR})_k\right) \quad (\text{Eq.5})$$

Results

Accuracy of the surface registration algorithm

The accuracy of the AlignRT registration algorithm is summarized below and in Table 1. The ranges evaluated were −15° and 15° for rotations and −60 mm and 60 mm for translations; values much larger than those that are clinically possible. They included the changes along each single axis and the combinations of multiple axes. The translation errors were typically less than 0.1 mm, and rotations were less than 0.1°, except for that of *d_lng*, translation along the longitudinal direction. This might have been caused by the finite resolution of CT, whose slice thickness is 2 mm. The maximum discrepancies for the translations and rotations were less than 0.2° and 0.7 mm. For each degree of freedom, a correlation analysis was performed between $U^{-1}(\text{P3})_i$ and corresponding $U(\text{AR})_i$, and the linear fits were obtained with coefficients from 0.9999 to 1.0. At 90% confidence level, the accuracy is 0.03°, 0.15°, and 0.07° in rotations and 0.09, 0.38, and 0.15 mm in translations along vertical, longitudinal, and lateral axes, respectively. Therefore, the AlignRT registration algorithm was considered excellent.

Rigid setup accuracy

Results for rigid setup accuracy are summarized in Table 2. The mean errors were, in general, <1° for rotations and ∼1 mm for translations. The cumulative histograms are shown in Fig. 2. The rotational errors by AlignRT along the vertical, longitudinal, and lateral axes exceeded 1° in 12%, 3%, and 36% of the measurements, respectively. The translational errors by AlignRT exceeded 3 mm in 26%, 8%, and 8% of the measurements. The most frequent deviations occurred on the *r_lat* axis and *d_vrt* axis.

The time dependency of registration errors was evaluated with one-way repeated measure analysis of variance (ANOVA) (15) as shown in Figure 3. This is similar to the paired Student *t*-test but with more samples (weekly measurements). The *p* values for within-subject analysis are described in the legend of Fig. 3. Clearly, the *r_lat* and *d_vrt* values show significant trends with time. We consider this the result of weight loss. The gradual shrinkage of tumor and normal tissue was demonstrated by increased registration discrepancy between bone and skin along these two axes due to the effect of gravity when the patient is placed in a supine position.

The accuracy versus patient is shown in Fig. 4. One-way ANOVA analyses showed that the errors were patient-specific in at least three axes: *r_lat*, *d_vrt*, and *d_lng*. Specifically, patients 3, 4, and 8 exhibited larger mean errors, with *r_lat* of >1.5° and *d_vrt* >3 mm. This was due to the larger changes in these patients' surfaces. To minimize the effect, we selected part of the patient

Table 2 Rigid and nonrigid registration accuracy

Registration types	Index (n = 66)	Rotations (°)			Translations (mm)		
		r_vrt	r_lng	r_lat	d_vrt	d_lng	d_lat
Rigid (head)	Mean	−0.02	−0.40	0.68	−1.14	0.42	0.26
	SD	0.66	0.31	1.17	2.50	1.51	1.44
	Max (abs.)	1.89	1.17	4.53	8.88	4.12	4.85
	Min (abs.)	0.00	0.00	0.00	0.04	0.05	0.04
Rigid (head) after ROI selection	Mean	0.05	−0.32	0.34	−0.48	0.56	0.39
	SD	0.59	0.36	0.78	1.73	1.52	1.27
	Max (abs.)	1.89	1.17	2.53	4.47	5.77	4.85
	Min (abs.)	0.00	0.00	0.00	0.02	0.05	0.04
Nonrigid (head and shoulder)	Mean	0.04	0.15	−1.20	1.28	3.97	0.42
	SD	1.17	1.37	2.71	6.32	5.34	4.18
	Max (abs.)	3.37	3.21	11.89	20.63	15.65	13.54
	Min (abs.)	0.03	0.05	0.12	0.05	0.10	0.01

Abbreviations: Max (abs.) = Maximum (Absolute); Min (abs.) = Minimum (Absolute); ROI = region of interest; SD = standard deviation.

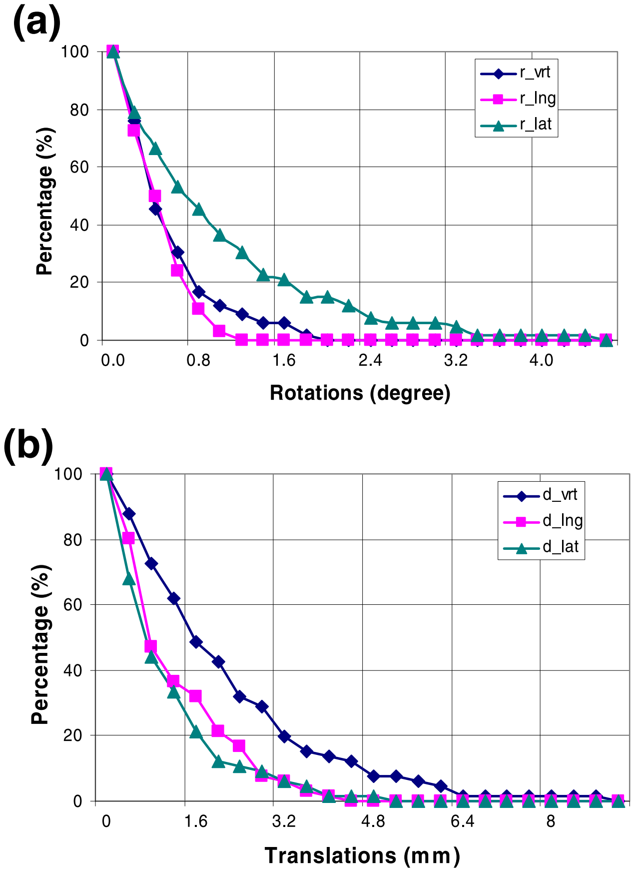

Fig. 2. Rigid realignment accuracy is shown as cumulative histograms for (a) rotational errors and (b) translational in three axes.

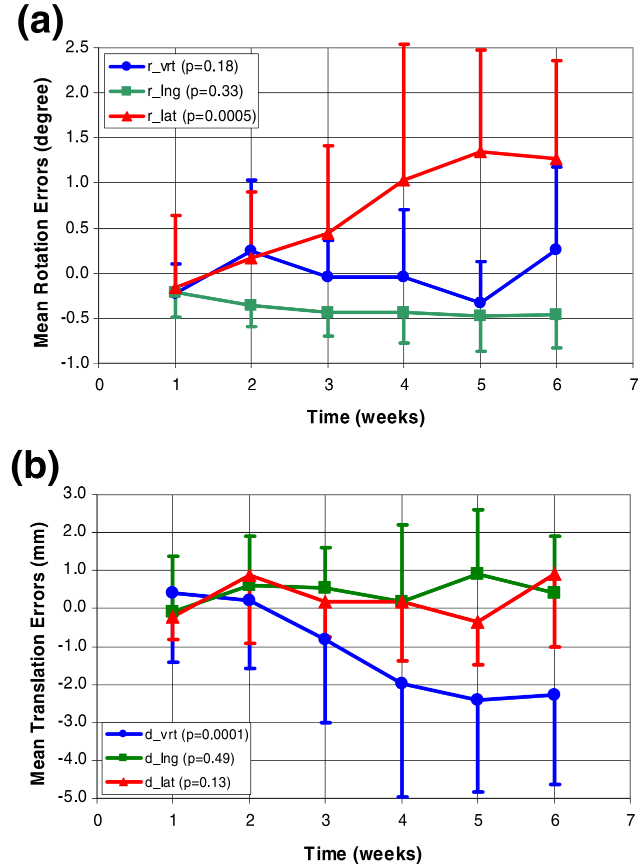

Fig. 3. Rigid realignment accuracy: (a) the rotational means, in degrees and (b) the translational means, in mm, are plotted as a function of time, in weeks. Shown in the legend are the p values from within-subject repeated measure ANOVA. Error bars are 1 standard deviation (SD).

surface instead of the whole surface for the registration for these 3 patients. The selected surface consisted of regions that are less prone to tumor shrinkage, *e.g.*, forehead, cheekbones, nose, and ears. The new registration accuracy is summarized in the middle portion of Table 2. Noticeable improvements were observed compared to those without selections of regions of interest (ROIs), as shown in Table 2, especially in *r_lat* and *d_vrt*. Not only was the mean error reduced, the standard deviation was also significantly reduced. At 90% confidence level, the rotation and translation accuracy levels were 1.1°, 0.8°, and 1.3° and 3.1, 2.7, and 2.4 mm in vertical, longitudinal, and lateral axes, respectively. One-way ANOVA showed patient specificity only in the *d_lng* axis.

Non-rigid realignment accuracy

Table 2, bottom, also summarizes the nonrigid registration accuracy, ΔU_k, as derived in Eq. 5. Standard deviations are much larger than those for the head only and can be as large as 2.7° for rotations and 6.3 mm for translations. At 90% confidence level, the accuracy levels were 1.9°, 2.4°, and 4.5° and 10.1, 11.9, and 6.9 mm. Therefore, we consider this not clinically acceptable.

Discussion

The advantages of the camera system over standard CT are the zero-radiation dose and quick response time. Previous evaluation studies of the AlignRT system included many other tumor sites. However, no published study exists that directly evaluates the accuracy for HN cancer patients. One possible reason is that HN cancer patients are frequently immobilized with a thermoplastic mask, which prevents the camera from visualizing patient skin directly. If CT with the mask and independently acquired surface images without the mask were compared, an invalid comparison may occur because they represent two snapshots of the patient position that may change with time. In this study, we overcame this obstacle by extracting the surface images from the exact same CT datasets. We want to point out that only the surface registration algorithm was evaluated in this study, although this is a very important component of the system. This is the first step to systematically evaluate the system, and more investigations of the whole system's performance, including image acquisition, are necessary prior to clinical implementation.

The accuracy of the AlignRT system's surface registration algorithm was found to be highly accurate, using a single rigid head. The accuracy for rigid alignment of 11 patients with repeated CTs was acceptable (2° in rotation and 3 mm in translation at 90% confidence level). We noticed that the *r_lat* and *d_vrt* values were detected with lower accuracy than others. They were also time-dependent and patient-specific. This may be caused by the changes in skin surface due to weight loss and tumor shrinkage. Selecting ROIs that are less prone to shrinkage could

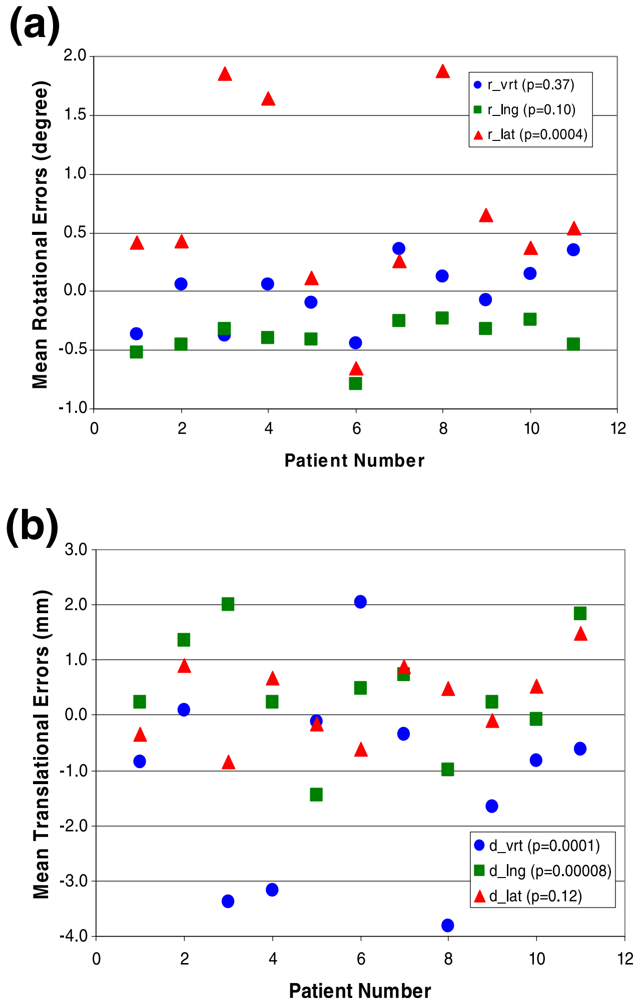

Fig. 4. Rigid realignment accuracy: (a) the rotational errors and (b) the translational errors detected by AlignRT around the vertical, lateral, and longitudinal axes are shown for11 patients. Shown in the legends are the *p* values from one-way ANOVA.

significantly improve registration accuracy. The optimal use of the surface imaging system and CT scans depends on the requirement for accuracy and imaging dose. One possible protocol is to take infrequent (such as weekly) CBCT or helical CT images. These CT images are used for replanning to account for weight loss and tumor shrinkage (11, 16). They can also be used to derive updated reference images for surface imaging alignment. Doing so will reduce the effect of weight loss and improve the online registration accuracy. For the 3D surface imaging system to be used in the clinic for HN-IMRT patient setup, alternative immobilization methods or modified masks need to be explored. Because the response time of the surface imaging system is on the order of a few seconds, it can be used for the evaluation of immobilization and intrafraction motion monitoring during treatment.

However, when the nonrigid setup error was evaluated, the discrepancies between AlignRT and Pinnacle[3] were considerably larger. This may be caused for a number of possible reasons, including registration errors in Pinnacle[3], registrations errors in AlignRT, and actual differences between skin and bone in the shoulder region. In Pinnacle[3], the vertebrae in the shoulder region that were used were very posterior, and the shoulder itself was not a rigid body. They could not be represented accurately by the anterior skin surface, which AlignRT uses for registration. Other anterior bony structures such as the clavicles can be used for registration; however, they were motion prone. Furthermore, the discrepancies could be caused by weight loss, which is more pronounced in the shoulder region than in the head region. Therefore, we do not consider the AlignRT system alone can be used for the detection and correction of nonrigid patient setup yet.

Conclusions

Future studies include validating the fact that the surface image directly acquired is equivalent to the ones derived from skin contours from CT for online image guidance; investigating the effect on registration accuracy if the mask is removed or modified; and investigating patient intrafraction characteristics for typical treatment duration, using the optical system's monitoring capability.

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