Purpose: The purpose of this study was to evaluate the accuracy of a new version of the ExacTrac X-ray (ETX) system with statistical analysis retrospectively in order to determine the tolerance of systematic components of spatial uncertainties with the Novalis system.

Methods and Materials: Three factors of geometrical accuracy related to the ETX system were evaluated by phantom studies. First, location dependency of the detection ability of the infrared system was evaluated. Second, accuracy of the automated calculation by the image fusion algorithm in the patient registration software was evaluated. Third, deviation of the coordinate scale between the ETX isocenter and the mechanical isocenter was evaluated. From the values of these examinations and clinical experiences, the total spatial uncertainty with the Novalis system was evaluated.

Results: As to the location dependency of the detection ability of the infrared system, the detection errors between the actual position and the detected position were 1% in translation shift and 0.1° in rotational angle, respectively. As to the accuracy of patient verification software, the repeatability and the coincidence of the calculation value by image fusion were good when the contrast of the X-ray image was high. The deviation of coordinates between the ETX isocenter and the mechanical isocenter was 0.313 ± 0.024 mm, in a suitable procedure.

Conclusions: The spatial uncertainty will be less than 2 mm when suitable treatment planning, optimal patient setup, and daily quality assurance for the Novalis system are achieved in the routine workload. © 2009 Elsevier Inc.

Spatial uncertainty, Image-guided radiotherapy, Geometrical accuracy, Patient setup, Stereotactic radiotherapy.

INTRODUCTION

Patient localization accuracy is significant for providing a highly focused beam to a target volume (1–9). Therefore, spatial uncertainties in the radiotherapy process have to be reduced with daily quality assurance (QA) and quality control (QC) (10–12). The delivery of radiation at a sufficient dose to a planning target volume (PTV) is an ideal of external beam radiation therapy.

In the late 1990s, new image-guided patient positioning devices were developed for a clinical linear accelerator (LINAC). In addition, BrainLAB (Germany) recently manufactured a Novalis radiotherapy system which was dedicated to highly precise radiotherapy. The Novalis system for stereotaxy consists of a micro-multileaf collimator (m3) and an ExacTrac X-ray (ETX) positioning system. The characteristics of a micro-multileaf collimator were reported by many scientists and physicists, and its usefulness for clinical application has already been proven. The ETX system of the Novalis system is a kilovoltage X-ray-based two-dimensional-to-three-dimensional image fusion-guided target localization device dedicated to stereotactic radiosurgery and stereotactic radiotherapy. Two X-ray tubes and two flat-panel detectors are at a fixed position in the treatment room, suspended from the clinical LINAC. The ETX system is one of the commercially available patient positioning devices produced by BrainLAB. The ETX system combines an infrared (IR)-based tracking system with a X-ray-imaging-based system. Two IR cameras are fixed to the ceiling. Two kilovoltage X-ray beams are projected from the two X-ray tubes in oblique directions for the purpose of verifying patient localization. The procedure for patient setup with the ETX system consists of three steps: in step one, the initial patient setup according to the IR body markers is performed.
Normally, the IR body markers are placed asymmetrically on the patient’s body surface. The placement of each IR marker is detected by two IR cameras, and then the IR-based patient localization is completed by the automatic couch movement. In step two, two X-ray images are taken and compared with a digitally reconstructed radiograph (DRR) by the registration software for the purpose of calculating the setup error. In step three, X-ray image-based patient localization is completed by the automatic couch movement.

Clinical experiences with the Novalis system were reported by several investigators (9, 13–16). Many procedures of these studies were done with a previous type of ETX system (Qualisys type). The present upgraded ETX system is version 5, and the geometrical system has been changed to a Polaris type, which is smaller and simpler than the previous type (Fig. 1). The source-to-isocenter distance and the source-to-detector distance of the Polaris type ETX are 2.2 m and 3.5 m, respectively. The purpose of this study was to evaluate the mechanical accuracy of a new ETX system and its spatial uncertainty in the radiotherapy workload with the Novalis system.

METHODS AND MATERIALS

As a fundamental study of geometrical accuracy with the Novalis system, three factors of the patient setup with ETX system were evaluated.

Location dependency of the IR system

Six IR-reflective spherical markers, each with a diameter of 15 mm, were placed asymmetrically on the graph sheet, fixed on the exact couch top (Fig. 2). A front pointer was put on the gantry head, and then the vertical direction was aligned by the front pointer. The gantry angle, the couch angle, and the collimator angle were each set to 0°. A reference position was defined on the origin of the graph sheet. After the intentional offsets of the couch shift/angle were set to the exact couch angle, the actual locations were compared to the ETX detective locations under each condition. The actual location was measured on the enlarged image of the graph sheet with a highly precise digital camera. The intentional movements of couch shift were 0, 50, and 100 mm in longitudinal and lateral directions. The intentional couch angles were tried at 0°, 45°, and 90°.

Accuracy of the patient verification software

After five IR-reflective spherical markers were placed asymmetrically on a lumbar phantom (Hologic), the phantom was placed horizontally on the CT table (Fig. 3). Simulation CT scanning was performed under suitable conditions. The slice thickness, the tube voltage, and the field of view of CT were 1.25 mm, 120 kV, and 500 mm, respectively. A CT-based treatment plan was designed by Brainscan, and then the reference point was placed at the center of the lumbar phantom. After the coordinate data were transferred to the ETX system, the lumbar phantom was set up at the isocenter by the ETX system and kept at its position. Correction and verification procedures were repeated many times under different X-ray image conditions. After automatic verification was repeated 50 times via

Fig. 1. Comparison of two types of ETX system.
because the ETX system exists independently of a Novalis linear accelerator. The range of deviation among the coordinates depends on the calibration procedure used for the ETX system (Fig. 4). Therefore, calibration accuracy based on two types of X-ray calibration phantoms were evaluated as a comparative study. The size and implant marker placement of each phantom were basically the same. A hollow X-ray calibration phantom (Phantom A) has a hole at the center, and a solid X-ray calibration phantom (Phantom B) does not have a hole (Fig. 5).

Routine Winston-Lutz tests were performed with a Winston-Lutz kit (BrainLAB) as daily QA in our hospital. Routine isocenter verification and X-ray calibration were performed every day and two times per week, respectively. In addition, a WL-module test, a special program used to check the offset distance between the mechanical isocenter and the ETX isocenter, was applied, calculation of which depended on the calibration of the coordinate that was defined by a pinhole camera model algorithm by the following formula:

\[
\begin{align*}
    u &= \frac{p_{11}X + p_{12}Y + p_{13}Z + p_{14}}{p_{31}X + p_{32}Y + p_{33}Z + p_{34}}, \\
    v &= \frac{p_{21}X + p_{22}Y + p_{23}Z + p_{24}}{p_{31}X + p_{32}Y + p_{33}Z + p_{34}}
\end{align*}
\]

Where \(X, Y, \) and \(Z\) are three-dimensional coordinates of a point in the imaging object, \(u\) and \(v\) are two-dimensional coordinates of its projection on the kV X-ray images, and \(p_{ij}\) are unknown project parameters determined by a dedicated phantom.

For this study, the WL-module test was done constantly during every Winston-Lutz test (Fig. 6). Phantom A and Phantom B were used for X-ray calibration for the initial 3 weeks and for the next 4 weeks, respectively. The Winston-Lutz test depended on the mechanical isocenter, which was defined as the cross-line point of the in-room laser alignment. The deviation between the mechanical isocenter and the ETX isocenter based on vertical, longitudinal, and lateral directions was evaluated by the WL-module test (Fig. 7). Total deviation of coordinates between the mechanical isocenter and the ETX isocenter was defined by the root sum of the square of each direction. That is,

\[
D_t = \sqrt{D_x^2 + D_y^2 + D_z^2}
\]

where, \(D_t\) is the total deviation between the mechanical isocenter and the ETX isocenter; \(D_x\) is the observed value in the lateral direction; \(D_y\) is the observed value in the longitudinal direction; and \(D_z\) is the observed value in the vertical direction. The geometrical accuracy with each phantom was evaluated by the retrospective statistical analyses of these data.
RESULTS

Location dependency in the IR system

Results of the examination for location dependency in the IR system are shown in Table 1 and 2. As the results of examination with the intentional translation shift are shown in Table 1, the location dependency of the IR system with translation shift was evaluated. All actual locations after the intentional movement were confirmed by the enlarged image of the graph sheet with the digital camera. On the other hand, the detected location of the ETX system, which meant the IR coordinate of the ETX system, was confirmed by the IR camera. The deviation of each coordinate was calculated by subtraction from the IR coordinate to the actual coordinate. The deviation between the IR coordinate and the actual coordinate was observed in each (lateral/longitudinal) direction. The deviation in the longitudinal direction was larger than in the lateral direction; especially the deviation at the +100 mm shift point in the longitudinal direction was 1.08 mm (1%) as the maximum value. On the other hand, the misdetection of the table angle in each intentional movement ranged within ±0.1°.

As to the results of examination with the intentional couch angle are shown in Table 2, the location dependency of the IR system with the couch angle movement was evaluated. All intentional angles, which defined actual angles, were confirmed by the enlarged image of the graph sheet and a protractor with the digital camera. On the other hand, the detected locations of the ETX system, which meant the IR-based
angles, were confirmed by the IR camera. The deviation of each angle was calculated by subtraction from the IR-detected angle to the actual angle. The deviation of the front pointer meant the error from rotation center.

An offset of the front pointer was less than 0.3 mm, and errors of the detected position of the ETX system were within 0.4 mm on the translation shift. The detection error of the couch angle was less than 0.7°, and the maximum value was detected at 45° of the couch angle.

Accuracy of the patient verification software

Results of an examination for the purpose of clarifying the calculation accuracy of the patient verification software are shown in Fig. 8. The purpose of this examination was to evaluate repeatability and deviation of the setup verification value in the patient registration as determined by the image fusion. The image fusion was tried 50 times per each setup verification. Each calculated value was analyzed statistically. The graduation and the section of bar graph mean the average and the standard deviation of 50 trials, respectively. From the results, the values of 100 kV are smaller and more stable than under other conditions. On the other hand, the values of 60 kV and 80 kV are larger and more variable than under the 100-kV condition. This tendency appears in all directions and couch angle settings.

Deviation of the coordinates between the ETX isocenter and the mechanical isocenter

Results of the WL-module test during the Winston-Lutz test are shown in Table 3. By using the WL-module test, an offset distance between the center of a microsphere and the center of the ETX origin was evaluated. This value means a deviation of the coordinate between the ETX origin and the mechanical isocenter. The deviation values calibrated by Phantom A and Phantom B were 0.455 ± 0.088 mm and 0.313 ± 0.024 mm, respectively. These values mean a sphere of 95% confidence level with each calibration phantom. Sample numbers of Phantom A and Phantom B were 14 and 18 times, respectively. The accuracy of the calibration for the ETX system with Phantom B was better than with Phantom A, with an advantage of approximately 0.1 mm.

DISCUSSION

As to the location dependency in the IR system, results of the first examination are divided into two categories: (1) those in which the error of detection is increased in longitudinal translation shift, and (2) those in which the error of detection exists in couch rotation. The stereoscopic angle of the Polaris type on the isocenter is sharper than the previous system because the distance of each IR camera became shorter. As a result, the detection accuracy of the Polaris type in longitudinal direction and/or couch rotation was worse than with the previous ETX system.

As to the accuracy of the patient verification software, results of the second examination are divided into two categories: (1) those in which calculation accuracy is precise when the tube voltage is set to 100 kV, and (2) those in which calculation accuracy at 0° of couch position was better than at 45° and 90°. The verification error is thought to be improved when the image contrast is suitable because it is easy to detect bony structures or implant markers. In the couch rotation, however, there were some uncertainties such as marker placement and mechanical error, etc.

The preliminary study of the previous type of ETX system was reported by Verellen et al. in 2003 (14). That study used the previous ETX type and reported that results of preclinical verification of the system and clinical validation were limited to the DRR fusion approach based on bony structures. That study also evaluated the intrinsic uncertainties of the IR tracking system, DRR fusion tests, and an overall deviation within the ETX system. From their data, the authors found that the average deviations between the IR tracking measurements of the isocentric position and the actual position of the hidden target with respect to the treatment isocenter were −0.24 ± 0.33 mm, 0.45 ± 0.55 mm, and −0.49 ± 0.59 mm in the vertical, longitudinal, and lateral directions, respectively. Their experiment featured an intrinsic uncertainty from the...
That study concluded that the ETX system was designed to support automated patient positioning based on anatomical data such as bony structures and/or implanted radiopaque markers by the automated registration of X-ray images and DRRs. Anthropomorphic phantom measurements showed that submillimeter three-dimensional treatment setup accuracy could be achieved within an acceptable time frame. Our data were acquired under corresponding conditions similar to that study. The average deviations obtained from our data at the second examination, with 0° of couch angle, were 0.18 ± 0.14 mm, 0.25 ± 0.08 mm, and 0.26 ± 0.25 mm in the vertical, longitudinal, and lateral directions, respectively. Comparing our results to those of the study by Verellen et al. (14), the verification accuracy with the Polaris type ETX system compared to the new version of the registration software was better than the previous type. However, the detection uncertainty of the IR marker in the longitudinal direction with the Polaris type ETX system was larger than that of the previous type. Therefore, the detection error of the IR marker via the patient motion and/or marker placement should be decreased for precise patient localization with the ETX system.

Liu et al. (16) reported optimal marker placement with a photogrammetry patient positioning system. An actual target registration error and fiducial registration error in IR-based patient positioning with the previous type of ETX system were evaluated with the anthropomorphic phantom. That study concluded that a reduction of approximately 50% in target registration error had been achieved by using the optimal configuration compared to the random configuration. The authors stated that these data demonstrated that the optimization of a fiducial configuration could result in improved tumor targeting ability. We carried out each examination described by that study’s recommendations, each marker that was put on phantom asymmetrically for the reduction of registration error depended on IR marker placement.

The ETX system consists of an IR system and two floor-fixed kilovoltage X-ray tubes on the LINAC side that project obliquely from lateral to medial, from the floor to the ceiling, and from the LINAC side to the couch side, as the vertical, longitudinal, and lateral directions, respectively, onto two corresponding flat-panel detectors mounted on the ceiling. Therefore, the Novalis system has three coordinate scales, the LINAC-based mechanical coordinate scale, the IR-based coordinate scale, and the X-ray image-based coordinate scale. It is very important for precise radiotherapy that these coordinate scales coincide. The coincidence of the coordinate scales was completed by the ETX calibration procedure. In general, the LINAC-based coordinate scale and IR-based coordinate scale are coincident with the calibration phantom at the isocenter. Next, the IR-based coordinate scale and X-ray image-based coordinate scale are aligned by the X-ray calibration tool as the weekly routine QA. We suspect that this procedure has some uncertainty because two different phantoms are used in the calibration procedure. In the calibration step between “LINAC-based scale to IR-based scale” and “IR-based scale to X-ray image-based scale,” the phantom is replaced manually from the calibration phantom to the X-ray phantom. Therefore, an immediate check for coincidence between the LINAC-based scale and the X-ray image-based scale is necessary to reduce geometrical uncertainty because patient localization is finally verified by the fusion of X-ray images and DRRs. A WL module test during the Winston-Lutz test is a simple and feasible method for checking the coincidence at the isocenter as routine QA. In addition, results of a third examination suggest that the solid X-ray phantom should be used to calibrate the ETX system for the purpose of reducing the deviation between the mechanical isocenter and the ETX isocenter.

Radiation therapy committee task group 24 of the American Association of Physicists in Medicine (AAPM) recommended that the tolerance of the spatial uncertainty resulting from machine inaccuracy and patient motion should be within 10 mm in conventional radiotherapy (18). In

### Table 1. Results of translation shift movement*

<table>
<thead>
<tr>
<th>Intentional couch shift</th>
<th>Lat(mm)</th>
<th>Lng(mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vert (mm)</td>
<td>0</td>
<td>-100</td>
</tr>
<tr>
<td>Lng (mm)</td>
<td>0.01</td>
<td>0.03</td>
</tr>
<tr>
<td>Lat (mm)</td>
<td>0.01</td>
<td>-0.07</td>
</tr>
<tr>
<td>Lat (deg)</td>
<td>0.0</td>
<td>-0.46</td>
</tr>
</tbody>
</table>

Abbreviations: Vert = vertical direction; Lng = longitudinal direction; Lat = lateral direction.

* The deviation between IR detected location and the actual location.

### Table 2. Results of couch rotation*

<table>
<thead>
<tr>
<th>Intentional couch shift</th>
<th>Vert (mm)</th>
<th>Lng (mm)</th>
<th>Lat (mm)</th>
<th>Lat (deg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>05</td>
<td>0.01</td>
<td>0.12</td>
<td>-0.02</td>
<td>-0.03</td>
</tr>
<tr>
<td>45</td>
<td>-0.02</td>
<td>-0.25</td>
<td>-0.34</td>
<td>-0.31</td>
</tr>
<tr>
<td>90 (deg)</td>
<td>0.01</td>
<td>0.57</td>
<td>0.41</td>
<td>0.39</td>
</tr>
</tbody>
</table>

Abbreviations: Vert = vertical direction; Lng = longitudinal direction; Lat = lateral direction.

* The deviation between IR detected location and the actual location.
addition, spatial uncertainty is divided into two factors: (1) displacement of several fields relative to a target volume at a nominal distance related to the isocentric accuracy, the light field agreement, the jaw alignment, and the focal spot alignment, and (2) error in setup and position of target volume due to patient or organ motion, including setup error and breathing organ motion other than breathing. Figure 9 shows the tolerance model, which is spotlighted to the ETX system, of spatial uncertainties with the Novalis system in our hospital. This model is divided into the same two factors as the AAPM model: (1) geometrical uncertainty with ETX-guided patient setup, and (2) error in setup position of target volume patient organ motion. To satisfy the tolerance of the total spatial uncertainty within 5 mm, two factors of tolerance have to be within 2.5 mm and 4.0 mm, respectively. Geometrical uncertainty with the ETX-guided patient setup was characterized by four factors: uncertainty due to coordinate deviation of ETX, uncertainty due to the simulation CT, uncertainty due to the registration error by the verification system, and uncertainty due to marker detection. Yan et al. (15) reported that slice thickness of the simulation CT had a significant effect on the positioning accuracy of ETX-guided patient localization (15). The authors investigated positioning errors of the planned isocenter, using five different sets of CT scans. They concluded that positioning errors increased significantly when the slice thickness of the simulation CT was larger. Reference CT image data are usually used for dose calculation, marker detection, and construction of DRRs. Therefore, it is important to keep the image quality high and the effective slice thickness thin. The image slice thickness test and the positioning accuracy of nonhelical scanning with our simulation CT were better than with helical scanning. In our hospital, 1.25-mm slice thickness of nonhelical simulation CT is basically used for the reference CT. In commissioning data, the localization uncertainty due to the simulation CT is less than 0.2 mm. In addition, this value agrees with the tendency reported by the study by Yan et al. (15). Based on this value and the present paper’s results (17, 19–20), we can summarize the total geometrical uncertainty with the Novalis system with the following formula:

$$\text{Uncert}_{\text{total}} = \sqrt{E_{\text{ETX}}^2 + E_{\text{CT}}^2 + E_{\text{verify}}^2 + E_{\text{marker}}^2 + E_{\text{other}}^2} = 1.36 \pm 0.32\text{mm},$$

where, $\text{Uncert}_{\text{total}}$ is total geometrical uncertainty with Novalis system; $E_{\text{ETX}}$ is the uncertainty due to the coordinate deviation of ETX; $E_{\text{CT}}$ is the uncertainty due to the simulation CT; $E_{\text{verify}}$ is the uncertainty due to the registration error by the verification system; $E_{\text{marker}}$ is the uncertainty due to the marker detection; and $E_{\text{other}}$ is the uncertainty due to other factors (e.g., head structure).

Patient localization with the Novalis system has been completed with image-guided technology, and the setup error (from landmark structures) is able to hold to within 1 mm. Therefore, the systematic component of spatial uncertainty is decreased if the internal target volume is defined enough to cover the patient’s internal motion. We propose two very

<table>
<thead>
<tr>
<th>The type of the X-ray phantom</th>
<th>The total deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Phantom A</td>
<td>0.455±0.088 (mm)</td>
</tr>
<tr>
<td>Phantom B</td>
<td>0.313±0.024 (mm)</td>
</tr>
</tbody>
</table>
important points for consideration for using the Novalis system: (1) to reduce the geometrical uncertainty with ETX-guided patient setup (20) and (2) to include internal motion as well as possible at the time of defining the internal tumor volume (ITV) (21). In fact, the ITV is defined by several respiration-phase CT images at our hospital, for the purpose of including all internal motions of the target. An evidence-based setup margin, which means the leeway to enlarge from ITV to PTV, should be decided by daily QA/QC and the statistical analysis of the clinical data in the routine workload. The formulas for defining the setup margin have been reported by several investigators (7, 22, 23). The favorable condition for these formulas is basically to reduce uncertainty in the radiotherapy process. If uncertainties in the image-guided technology are not ensured, confidence in the calculated values of the setup margin will be lost. From our examinations, the setup margin with the Novalis system will be able to be reduced compared to that of the conventional system through two significant steps of QA/QC for the geometrical accuracy and the united definition method of the ITV are necessary and sufficient conditions.

**CONCLUSIONS**

The spatial uncertainty of the Novalis system was evaluated with several examinations related to the ETX system. Some factors of spatial uncertainties depended on ETX accuracy. In this study, these uncertainties were within 2 mm, which was secured by the submillimeter three-dimensional patient setup with the ETX system and daily QA/QC related to the radiotherapy procedure and mechanical stability.

**REFERENCES**


