Effect of Optical Digitizer Selection on the Application Accuracy of a Surgical Localization System—A Quantitative Comparison between the OPTOTRAK and FlashPoint Tracking Systems

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ABSTRACT  Application accuracy is a crucial factor for stereotactic surgical localization systems, in which space digitization camera systems are one of the most critical components. In this study we compared the effect of the OPTOTRAK 3020 space digitization system and the FlashPoint Model 3000 and 5000 3D digitizer systems on the application accuracy for interactive localization of intracranial lesions. A phantom was mounted with several implantable frameless markers which were randomly distributed on its surface. The target point was digitized and the coordinates were recorded and compared with reference points. The differences from the reference points represented the deviation from the “true point.” The root mean square (RMS) was calculated to show the differences, and a paired t-test was used to analyze the results. The results with the phantom showed that, for 1-mm sections of CT scans, the RMS was 0.76 ± 0.54 mm for the OPTOTRAK system, 1.23 ± 0.53 mm for the FlashPoint Model 3000 3D digitizer system, and 1.00 ± 0.42 mm for the FlashPoint Model 5000 system. These preliminary results showed that there is no significant difference between the three tracking systems, and, from the quality point of view, they can all be used for image-guided surgery procedures.

Key words: tracking system, application accuracy, frameless system, image-guided surgery, stereotactic neurosurgery

INTRODUCTION

Computer-assisted surgical localization requires very precise surgical tool tracking to guide neurosurgical procedures. These tracking techniques provide highly accurate intraoperative localization and allow the surgeon to resect a lesion in its entirety while sparing critical areas of the brain. The basic theory of this technique relies on establishing a three-dimensional (3D) coordinate system where any point of the patient’s anatomy can be precisely determined during surgical procedures. The application accuracy of space digitizing systems is therefore the key element of the whole system. In order to improve the application accuracy of the whole system, very precise tracking systems have to be used. The OPTOTRAK 3020 space digitization system (Northern Digital, Waterloo, Canada)
is a widely used motion analysis system not only in the medical field but also in industry (Fig. 1). It can track up to 256 pulsed infrared light emitting diode (LED) markers with a maximum sampling rate of about 3500 markers per second. Within a field of view of 1.0 m × 1.2 m at a distance of 2.0 m from the camera, it can locate each LED with an accuracy of 0.15 mm. The FlashPoint Model 5000 3D digitizer system (Image Guided Technologies, Inc., Boulder, CO, USA) is a relatively new system which evolved from the FlashPoint Model 3000 (Figs. 2 and 3). It can track up to 360 points per second or 25 data sets of 15 LEDs per second. Within a field of view of 1.0 m² at a distance of 1.5 m, the camera can locate each LED with an accuracy of 0.3 mm and a repeatability of 0.04 mm. Although the Polaris tracking system (Northern Digital, Waterloo, Canada) is also widely used, OPTOTRAK 3020 has a better accuracy, as documented by Northern Digital, and hence was used in this study. The purpose of this study was to quantitatively compare the application accuracy of these three tracking systems dynamically, i.e., with the tip of the probe digitizing the target point in space. The application accuracy of these tracking systems was evaluated using the frameless registration method which has been widely used in clinical surgical procedures. The application accuracy of the frameless implantable screw marker system has been proven to be as accurate as that of the frame-based system and even better in some instances.8

The accuracy of an image-guided surgical system ensures both unbiased and precise measurements. The repeatability of a tracking system refers to the precision of that system. There are two terms in image-guided surgery that need to be defined: mechanical accuracy and application accuracy. Mechanical accuracy refers to the accuracy of the navigational device, such as the different tracking systems. Application accuracy refers to the accuracy of these devices when used in their real-world setting, and can be expressed in terms of the mean error of localization. Application error applies to the entire system. The application accuracy of a surgical localization system is a function of its mechanical accuracy interacting with the selected parameters of the imaging studies chosen to visualize the lesion and its related anatomy. The overall accuracy (application accuracy) of a system is a sum of the individual accuracies of each of these components. However, mechanical accuracy is crucially important to navigation systems. Clinically, in addition to the mechanical limitations of the image-guided surgical system, the sources of errors related to the application accuracy are associated with many steps of image-guided surgery. These errors include imaging techniques, point selection, vector calculations, mechanical couplings and adjustments, and other related human errors. These
errors all contribute to the final application accuracy. In order to provide high levels of surgical localization accuracy, all of these error-related factors should be controlled and reduced to an extremely low level. When comparing different surgical localization systems, application accuracy is a very important component of the comparison. Theoretically speaking, the application accuracy of different tracking systems is directly related to their mechanical accuracy.

In the literature there are no quantitative comparisons between these three systems. We present our preliminary results comparing the application accuracy of the OPTOTRAK and FlashPoint 3000 and 5000 tracking systems with the use of implantable semi-invasive fiducial markers (Fischer-Leibinger, Freiburg, Germany) for the interactive intraoperative localization of intracranial lesions. The bench test was set up to reproduce as closely as possible a real surgical situation, but the interference from the surgical environment was not completely modeled, e.g., surgical lights were not used. Hence, this test setup closely reflected the application accuracy of an image-guided surgery system in the surgical environment.

**MATERIALS AND METHODS**

**Frameless Implantable Marker System**

The semi-invasive markers developed by Fischer-Leibinger consist of three parts: a titanium screw, a base, and an insert. Due to the varying thickness of the galea, the titanium bone screws are available in two different lengths, 10 mm and 18 mm, both with a thread length of 7 mm. The base has a thread on one end to attach to the screw, and a cavity for the insert at the opposite end. There are three types of inserts available: a CT angiogram-compatible insert, a multimodality image insert, and an intraoperative insert. The CT angiogram insert is a gold-filled sphere. The multimodality image insert can be filled with different substances, including radioactive isotopes for use with CT, MRI, digital angiography (DA), or positron emission tomography (PET) scans. The intraoperative insert has been created to replace the image insert for intraoperative registration. The image inserts are spherical in shape so the center is not accessible for intraoperative registration, while the intraoperative insert is flat, and its height corresponds exactly to the center of the spherical image insert (Fig. 4).

**Phantom Preparation**

A phantom was mounted with five semi-invasive screws of the frameless implantable marker system randomly distributed on the surface. A steel sphere 2 mm in diameter was then mounted on the phantom as a target point. The phantom was imaged using a Siemens Somatom-Plus-S CT scanner (Siemens, Erlangen, Germany). A stereotactic protocol was used for this study. The display field of view was set to 1.7 zoom and 0-degree tilt with 0-mm slice spacing. The scan thickness was set at 1 mm.
and the image resolution used was pixel size 0.59 \times 0.59 \text{ mm}. The images were transferred to a stereotactic computer. The Neurosurgical Planning System (NSPS) software developed at Wayne State University was used for image registration.\textsuperscript{14} The NSPS runs on a SUN SPARC 10 station (Sun Microsystems, Mountain View, California), and was used to achieve fast calculations and to reconstruct volumes from the imaging studies. The workstation was connected to the Detroit Medical Center’s central computer network, from which images derived from CT and MRI were transferred. NSPS allows image viewing and manipulation in real time both during preplanning and intraoperatively. The frameless implantable markers were randomly distributed on the surface of phantom. The intraoperative registrations were divided into two groups: a widely distributed marker group and a locally distributed marker group (in which the longest distance between the markers was less than 10 cm). The coordinates of the target point were recorded and saved in a file as a reference point (Fig. 5).

**Space Digitization System**

The OPTOTRAK space digitization system is a contact-less, precalibrated tracking system that is widely used for motion analysis. This tracking system is accepted as being very accurate for neurosurgical navigation. By attaching at least three markers onto a rigid body, its location and orientation in space can be determined. The system is precalibrated, reducing setup time and allowing for better tolerance to environmental changes. The limitation of the system is the need for a direct view between the camera and the LEDs. To overcome this limitation, we designed a special holder to allow for different heights and angulations. The OPTOTRAK system has the ability to define several rigid bodies, each of which is assigned a separate dynamic reference. It provides relative coordinates from the camera to any one of these rigid bodies’ dynamic references in real time by attaching them to the skull or other rigid bodies. By calibrating the relative coordinates, a homogenous transformation matrix is established. This eliminates the need for new matching during the neurosurgery procedure. The tracking system is controlled by a DOS-based software program running on a personal computer networked with a Unix workstation (Sun Microsystems, Inc., Mountain View, CA) which is used for image data acquisition/reconstruction and real-time instrument visualization. A single monitor provides all the information. In this study, the results from the OPTOTRAK tracking system were used as the standard for the application accuracy.

The FlashPoint 3D digitizer tracking system Models 5000 and 3000 were both compared with the OPTOTRAK system. The FlashPoint system is relatively new, and has an easy-to-move camera. Three high-resolution linear sensors are used to measure the location in space of up to 20 infrared light emitters. Each of the sensors returns to the digitizer a measurement of the angle of an LED relative to the sensor. Up to six sensors are supported, and they may be located anywhere within the digitizing volume. The location of a given point can be determined with the data returned from any three sensors. For a normal configuration, a contact-style probe with two LEDs is used to take
precise measurement from an object. The high-resolution sensors determine the exact location of the probe tip, then send the data to the computer. When using a probe, all its LEDs must be in sight of at least 3 sensors to compute the location of its pointer tip.

**Experimental Procedure**

For each camera group, the experimental procedure included image registration based on the frameless marker system, intraoperative registration of these markers, and digitization of the target point. For each camera, intraoperative registration was done three times in order to check the repeatability of the registration with the two localization systems. Only a registration error of less than 3 mm could be used for normal target digitization. In each registration, the target point was digitized 10 times. The coordinates of each digitization were recorded and saved in a file for off-line statistical analysis. These coordinates were compared with the coordinates of the reference point.

**Intraoperative Registration**

Registration is the process of defining special points based on the fiducial markers or anatomical landmarks from CT, MRI, or PET scan data. These points are then correlated with the points located on the head of the patient in the “real world” in the operating room. The goal is to match and correlate data from the medical images to the “real world” (i.e., the coordinate space of the surgical instruments). A tracking device is attached to the instruments to continually relay information regarding its position to the system. Coordinate matching ensures that any point seen in a medical image corresponds to an actual point in the patient’s anatomy.

The next step is to correlate the different images with each other. Each imaging modality displays anatomical structures and lesions in a unique way. This benefits the surgeon by providing several different ways to view the same anatomical structure, and requires the development of an interactive relationship between the images and the real world. Registration is used to build this relationship and enable the surgeon to use each imaging modality to its greatest advantage for localizing the anatomical structure.

**Intraoperative Digitization**

Intraoperative digitization using the OPTOTRAK and FlashPoint tracking systems was the most important portion of this study. These three systems consist of opto-electronics with LEDs. Three infrared sensors track target points defined by several miniature LEDs mounted in a predefined relationship on the surgeon’s operative instrument. This combination was referred to as a “surgical rigid body” or pointer. Another similar rigid body is mounted to the head holder or patient’s ring (“patient’s rigid body”). The patient’s rigid body is used to tell the system where the real patient is, and the surgical rigid body tells the system the position of the surgical instrument. Then the homogeneous transformation matrix is calculated and the unique coordinate system is set up. Each time the user moves the instrument, monitors mounted in the room display the instrument’s position on previously acquired and registered computer-generated images.

In the image registration phase, the image coordinates of each fiducial marker obtained from the CT scan were recorded in a file as the reference points (absolute image coordinates). Registration was performed for the semi-invasive fiducial markers by touching the tip of each one in order to form the appropriate transformation matrix for each system. The image coordinates were matched with the real-world patient’s anatomy. After intraoperative registration, the surgical tracking mode of the NSPS software program was used to track the surgical instruments. By touching the tip of each fiducial marker with the pointer (i.e., the surgical rigid body), the system recorded their spatial positions dynamically, and the Cartesian coordinates of the markers were determined.

**Statistical Analysis**

A systematic error analysis was performed by comparing the coordinates of target points on the medical images and the coordinates of intraoperatively digitized target points based on registration for each surgical localization system. Statistical analysis was performed on the experimental data.

A comparison was performed between the 3D \((x, y, z)\) coordinates of the target point from each experimental data set obtained with the fiducial markers and the absolute image coordinates. For each experiment, repeated measurements were made with each of the methods. This allowed testing of internal consistency of the measurements for each method. Statistical analysis pertaining to various comparisons between methods was performed on the average measurements.

The mean deviation from the absolute image coordinates was calculated from all 3D mean measurements \((x, y, z)\) of all experimental data for each tracking system, correlating the fiducial marker-based registration to the absolute image coordi-
nates. Also, the deviation from the target point in three directions (anteroposterior, lateral, and vertical) of each experimental data point was similarly calculated for the three tracking systems. Therefore, to assess the differences between the systems for each of the position measurements, a root mean square (RMS) representing the sum of the vectors was calculated. This represents the maximum distance between the coordinates of the reference point and the coordinates of the digitized point. For each group of data, it was calculated as follows:

$$\text{distance}_{ijk} = \sqrt{(X_{ij} - X_{ik})^2 + (Y_{ij} - Y_{ik})^2 + (Z_{ij} - Z_{ik})^2}$$

The calculation used is a simple method to calculate the distance between two points in Cartesian coordinates, where $i$ is the tracking system, $j$ is the coordinates of the reference point, and $k$ is the coordinates of the digitized point. This computation leads to a matrix of distances used for comparison purposes.

A paired t-test was applied to test the significance of the mean deviation between the OPTOTRAK and FlashPoint tracking systems, and was also used to compare the magnitude of differences in mean distances (delta values) between the fiducial marker-based registration and the absolute image coordinates.

A confirmatory nonparametric Wilcoxon test was also applied in case the normality assumption was violated. To estimate the average mean difference of the distance, a 95% confidence interval (95% CI) was obtained.

**RESULTS**

**Application Accuracy of the OPTOTRAK and FlashPoint Tracking Systems**

Anteroposterior, lateral, and vertical components of the target coordinates from each digitization were examined individually for error. The RMS was also calculated from these three components, and the results are shown in Table 1. Although the OPTOTRAK 3020 showed more accurate results, there was no statistical difference between the OPTOTRAK 3020 and FlashPoint 3000 tracking systems ($p = 0.09$), and no significant difference between the OPTOTRAK 3020 and FlashPoint 5000 tracking systems ($p = 0.36$). The FlashPoint 5000 tracking system was developed from the Model 3000: As tracking systems they are statistically equivalent, in terms of clinical application accuracy, to the OPTOTRAK 3020.

**Influence of Marker Position on the Application Accuracy**

It is commonly proposed that frameless system markers should be distributed as far as possible from each other to ensure application accuracy. However, it is difficult to determine what this distribution should be. As part of this study we tested two groups of distributions. One was localized around a $7 \times 7$ cm area close to the surgical area, making registration easy. The other group was distributed around the whole skull, and was supposedly more accurate than the locally distributed marker group (Table 1). The results are shown in Table 2. The widely distributed marker group showed a better application accuracy than the local marker group for all tracking systems. There was a statistically significant difference ($p = 0.03$) between the two groups with the OPTOTRAK tracking system, but there was no difference with the FlashPoint 3000 ($p = 0.26$) and 5000 ($p = 0.06$) systems.

**DISCUSSION**

Tracking systems used for stereotactic localization should have well-documented clinical application accuracy, and should attain a maximum mechanical accuracy before they can be really put into use.

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**Table 1. Comparison of the Application Accuracy of the Two Tracking Systems (CT Sections = 1 mm)**

<table>
<thead>
<tr>
<th>System name</th>
<th>X-direction ±</th>
<th>Y-direction ±</th>
<th>Z-direction ±</th>
<th>RMS ±</th>
<th>Max. error ±</th>
</tr>
</thead>
<tbody>
<tr>
<td>OPTOTRAK 3020</td>
<td>0.28 ± 0.32</td>
<td>0.32 ± 0.34</td>
<td>0.46 ± 0.38</td>
<td>0.76 ± 0.54</td>
<td>1.84</td>
</tr>
<tr>
<td>FlashPoint 3000</td>
<td>0.62 ± 0.34</td>
<td>0.46 ± 0.32</td>
<td>0.72 ± 0.46</td>
<td>1.23 ± 0.70</td>
<td>2.73</td>
</tr>
<tr>
<td>FlashPoint 5000</td>
<td>0.48 ± 0.38</td>
<td>0.42 ± 0.41</td>
<td>0.68 ± 0.42</td>
<td>1.00 ± 0.42</td>
<td>2.04</td>
</tr>
</tbody>
</table>

**Table 2. The Results of Localized Distributed Marker Systems**

<table>
<thead>
<tr>
<th>System name</th>
<th>X-direction ±</th>
<th>Y-direction ±</th>
<th>Z-direction ±</th>
<th>RMS ±</th>
</tr>
</thead>
<tbody>
<tr>
<td>OPTOTRAK 3020</td>
<td>0.62 ± 0.39</td>
<td>0.62 ± 0.54</td>
<td>0.54 ± 0.38</td>
<td>1.28 ± 0.51</td>
</tr>
<tr>
<td>FlashPoint 3000</td>
<td>0.86 ± 0.34</td>
<td>1.21 ± 0.62</td>
<td>0.62 ± 0.46</td>
<td>1.75 ± 1.32</td>
</tr>
<tr>
<td>FlashPoint 5000</td>
<td>0.68 ± 0.48</td>
<td>1.12 ± 0.68</td>
<td>0.58 ± 0.52</td>
<td>1.58 ± 0.86</td>
</tr>
</tbody>
</table>
However, the application accuracy of a tracking system is not equal to its mechanical accuracy and can be affected by many factors. In this study, we quantitatively compared the OPTOTRAK and Flash Point tracking systems, tried to find any significant differences between them, and also located the error sources. In frameless stereotactic procedures, during intraoperative registration, the transformation matrix is calculated from at least three fixed points on the fiducial markers. This is based on rigid-body mechanics. The frameless localization system showed better application accuracy in our previous study because the relative motion between the skull and screw was very small. This advantage will be helpful in improving the clinical application accuracy for the surgical localization system, which is why it was used for this study.

The clinical application accuracy is affected by many factors, being the sum of all related error. Bucholz et al. investigated the factors relating to image quality and target size, and found that the thickness of the scan is the most important factor affecting application accuracy. If treating a small lesion, it is best to reduce the thickness of the scan. We had similar results with small lesions in our previous study. In order to compare the different tracking systems under the same conditions, the thickness of CT scan used was 1 mm. As a cornerstone of the navigation system, the quality of the camera is an important factor that must be evaluated when setting up an image-guided surgery system.

The tracking system is also an important component of an image-guided surgery system, and its effect on the application accuracy of the whole system should not be ignored. Improvements in software cannot change the mechanical accuracy of the tracking system. The OPTOTRAK 3020 tracking system is a widely accepted tracking system for motion analysis in the medical field, and also in industry. This system has provided very good mechanical accuracy in many different applications. However, it is a heavy device, making it difficult to transport, and it is cumbersome to use in a crowded operating room. Another disadvantage is the price. In contrast, the newly-developed FlashPoint 3000 and 5000 tracking systems are light and easy to transport, and are also inexpensive. However, whether they can replace the OPTOTRAK system totally depends on whether they can achieve the same application accuracy as OPTOTRAK. At present, there is no comparative report in the literature. In this study, we used a frameless implantable marker system as the basic intraoperative registration method to compare these three tracking systems. The results showed that OPTOTRAK had a better application accuracy (smaller error) but, statistically speaking, there was no significant difference between these three tracking systems.

Registration methodology constitutes a basic process in image-guided surgery. As an alternative to conventional stereotaxis, a variety of frameless stereotactic systems have been developed to provide intraoperative surgical localization. They provide a reference interface, allowing for an unobstructed surgical approach and airway management. In recent years, several frameless navigational devices have been developed. Two methods are currently used most often for frameless stereotaxis; skin fiducial markers applied to the scalp, or semi-permanent fiducial markers rigidly fixed to the patient’s skull. When fiducial markers attached to the skin are used, the scalp may move relative to the cranial bones before or during the surgical procedure, deviating the fiducial points from their intended positions. These skin-attached fiducial markers are useful for some procedures, but do not provide the same level of accuracy obtained with rigid fixation. However, most frameless digitizing systems have been developed using non-invasive fiducial markers attached to the skin.

In order to achieve a higher degree of accuracy with frameless systems, a system of semi-permanent fiducial markers has been developed. These markers can be left in place for several days without risk of being displaced, and allow for staged procedures, as required in epilepsy surgery, for example, or in treating some skull-base tumors.

The distribution of the fiducial markers in the frameless marker system also has some influence on the application accuracy of these two tracking systems. From our experimental study, we found that wide distribution of markers can produce more accurate results than local distribution of markers. However, there was no statistically significant difference between the two groups for the three tracking systems evaluated. A more comprehensive study of marker distribution is required.

**CONCLUSION**

From this study there are two points that can be concluded:

1. There is no statistical difference between the OPTOTRAK and FlashPoint tracking systems from the application accuracy point of view, though OPTOTRAK showed a slightly better result.

2. The distribution of the frameless implantable marker system is an important factor.
that should not be ignored. Although there was no statistically significant difference between the widely-distributed marker group and the locally-distributed marker group, the former group did show a better result.

We believe that the semipermanent implantable fiducial marker system represents the next step in the application of stereotactic techniques in neurosurgery. Light, easy to transport, and cheap tracking systems will be increasingly popular as they can achieve the same application accuracy as bulky and expensive tracking systems. Interactive image-guided neurosurgery is evolving beyond the limitations imposed by the mechanically-based stereotactic frames systems designed at the turn of the century.

REFERENCES


