ORIGINAL ARTICLE

Comparison of Registration Accuracy of Skin- and Bone-Implanted Fiducials for Frameless Stereotaxis of the Brain: A Prospective Study

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ABSTRACT

The registration accuracy of skin- and bone-implanted fiducials using a frameless stereotactic system were analyzed prospectively.

Twenty-eight patients underwent resection of intra-axial neoplasms after both skin- and bone-implantable fiducial markers were placed. Both sets of fiducials were independently co-registered to a magnetic resonance imaging data set acquired preoperatively using the ISG Viewing Wand™. Root mean square errors were recorded as an objective measure of registration accuracy of the two types of fiducials.

Root mean square errors of bone-implanted fiducials registration were lower than those of skin fiducials; however, this difference was not statistically significant ($p = 0.206$).

The registration accuracy of skin- and bone-implanted fiducials appears to be similar. Still, bone-implanted fiducials may be advantageous compared to skin fiducials when re-registration of the patient-image space is desired intraoperatively such as during major drift in the patient's position or after surgical repositioning.

KEYWORDS: Fiducial markers, frameless stereotaxis, registration accuracy

Computer-guided frameless stereotactic systems are used routinely for intraoperative neurosurgical navigation. Their use hinges on preoperatively acquired magnetic resonance imaging (MRI) and computed tomography (CT) studies that need to be matched precisely to the patient in the surgical position using a digitizer. This process, during which the patient's preoperatively acquired images (image space) are matched to the patient in the surgical position (physical space), is

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referred to as patient-image co-registration or patient registration.

Registration is usually accomplished by matching markers (fiducials) applied about the patient's head. These fiducials may be applied to the skin (skin fiducials) or may be tapped into the skull (bone fiducials).[1] Unless another set of images is acquired during the surgical procedure,[2] the accuracy of the system depends, all else being equal (e.g., technical accuracy of imaging device and neuronavigation system, intraoperative brain shift), on the accuracy of the original registration.[3] It has been suggested that bone fiducials constitute a more accurate platform for image-guided surgery (IGS) than scalp fiducials because the former, being rigidly fixated to the cranium, are subject to less motion.[4–6] The purpose of this investigation was to compare prospectively in the same patients the registration accuracy of skin- and bone-implanted fiducials using a frameless stereotactic system.

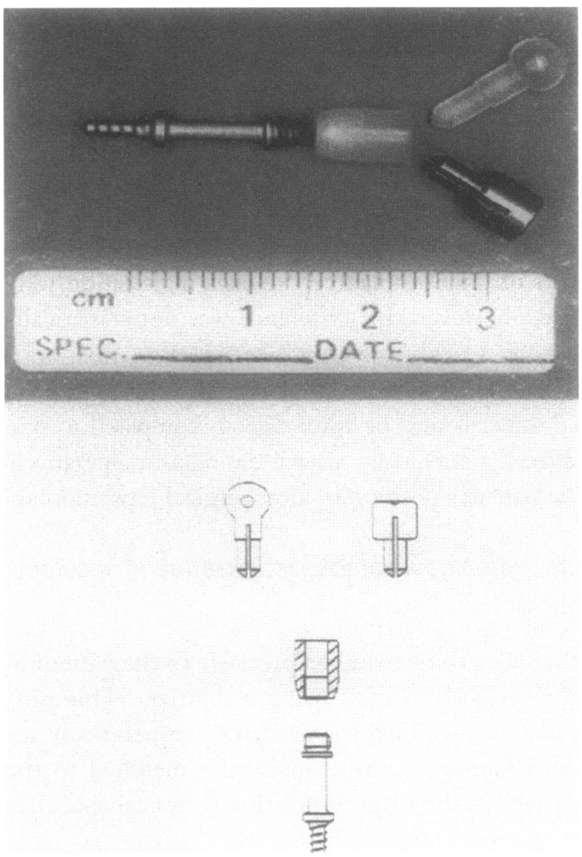

Figure 1 Magnified schematic drawing (bottom) and photograph (top) of bone-implantable fiducials. The interchangeable contrast cap and registration cap fit into the base placed onto a fiducial screw.

CLINICAL MATERIAL AND METHODS

After obtaining Institutional Review Board approval and informed consent from each individual, we studied 28 patients undergoing surgery for intra-axial neoplasms. Patients received both skin- and bone-implanted fiducials before preoperative scanning as described below. Preoperative planning was based on MRI studies.

Placement of Fiducial Markers

Five or six bone fiducials were applied before surgery. After the scalp incision was made, a rechargeable power drill with a 7-mm long, 1.5-mm diameter bit was used to penetrate the outer table of the skull. Immediately, a bone fiducial screw, 13 mm long, (Marker System for Stereotactic Navigation, Howmedica Leibinger Inc., Dallas, TX) with a preapplied plastic cup, (marker base) was screwed to the hub of the screw taper (Fig. 1). The MRI fiducial contrast caps were then snapped into the bases of the screws and filled, using a #25 gauge needle, with 0.1 cc of fresh gadopentatate dimeglumine (Magnevist, Berlex Imaging, Wayne, NJ) 1:200 dilution in saline. The fiducial caps were hand-sealed with warm bone wax. All bone fiducials were checked for stability and lack of bubbles. Six or seven skin fiducial multimodality markers (IZI Medical, Baltimore, MD) were placed on the scalp using tincture of benzoin. The scalp was marked at the center and at the rim of each skin fiducial with a pen to detect possible fiducial movement. The location of the skin and bone fiducials on the patient's head was similar. All fiducials were applied in a noncollinear fashion, trying to keep the centroid of the fiducials as close as possible to the target.

Patient Imaging

We used a gadolinium contrast-enhanced head MRI (General Electric Signa, 1.5 Tesla superconducting magnet with version 4.8 software) acquired as a slab-volume acquisition, 256 × 128 matrix of slices 2 mm thick without gaps. We used an echo delay (TE) of 5 ms and a repetition time (TR) of 34 ms with a 35-degree flip angle over one excitation. The field of view was 24 or 28, depending on the size of the head and the reach of the bone-implanted fiducials. The MRIs were viewed on the monitor to verify the visibility of fiducials. Scan image data were transferred to our departmental UNIX server via a file transfer protocol and later to the operating room computer. Files were modified using proprietary scripts for the ISG Viewing Wand™.

Surgical Positioning

Patients were positioned for surgery in a 3-point Mayfield headrest fixation device.

Patient-Image Registration

Before registration, the contrast-filled caps of the bone fiducials were replaced with fiduciary localization caps. Both sets of fiducials were registered after surgical positioning to achieve suitable registration accuracy (root mean square error (RMS) < 2 mm). Bone-implanted fiducials were registered by placing the tip of the probe in the straightest possible orientation to the small divot on the fiduciary cap. Skin fiducials were registered in a similar fashion, using the center as the focus and trying not to deform the skin surface (Fig. 2). Anatomical and surface accuracy was checked using the two registration data sets. Preoperatively the tip of the viewing wand was placed on a known anatomical point (nasion, inner canthus of the eye, anterior and superior aspect of the external auditory meatus), and the correlation between the physical space and the image space was assessed subjectively.

Intraoperative Landmarks

Skin fiducials were removed and the head was prepared for surgery as usual. Craniotomies were performed aided by the trajectory views of the ISG Viewing Wand™. Bone-implanted fiducials were removed when they prevented optimal replacement of the scalp flap, after its retraction, directly into the same hole at the same depth and using the same trajectory. A craniotomy was planned using the stereotactic arm. Immediately after the scalp flap was raised, multiple bone intraoperative landmarks were made just external to the planned craniotomy using a Midas Rex™ C-1 bit (Midas Rex™, Fort Worth, TX).

Intraoperative landmarks were registered to the same degree of accuracy as fiducial registration (tip-to-landmark < 2 mm). A precise measurement of distance representing the actual stereotactic arm tip (placed in the intraoperative landmark) from the computer's known coordinates of the landmark was displayed as the "tip-to-landmark." These tip-to-landmark measurements were checked after landmark registration and before each use of the wand. Ideally, tip-to-landmark measurements should be zero. The surgical table was not moved until all landmarks were registered. The most accurate fiducial system registration (smallest RMS) was used to provide stereotactic information for intraoperative landmark registration. All intraoperative landmarks were re-registered when the tip-to-landmark measurement was greater than 2 mm. Bone-implanted fiducials were not removed in case it became neces-

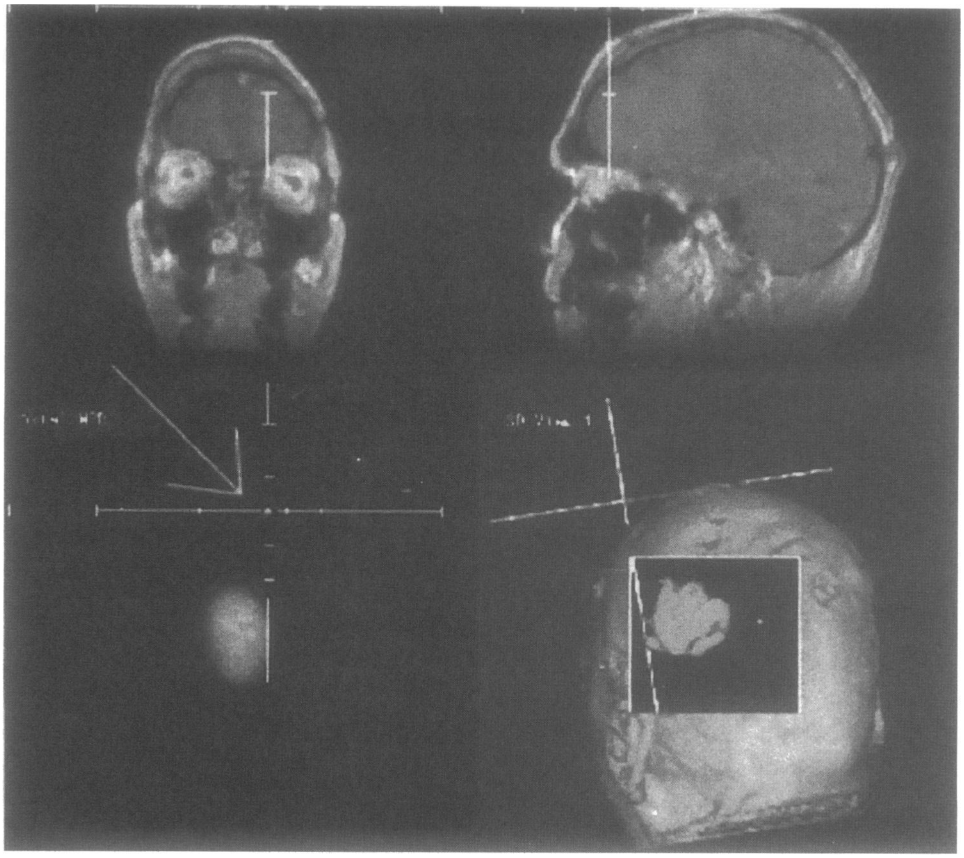

Figure 2 Software "screen shot" from ISG Viewing Wand™ computer monitor showing a three-dimensional and three planar views of MRI-acquired and reformatted images from a patient in the study. The cross-hairs are centered on a bone fiducial point for registration (arrow).

sary to re-register the fiducials before acquisition of the bony landmarks or when the tip-to-landmark value was greater than 2 mm despite re-registration of the landmark.

RESULTS

The mean RMS values were 2.76 ± 1.19 mm for skin fiducial registrations and 2.25 ± 0.95 mm for bone-implanted fiducial registrations. These values were not statistically different (paired *t*-test, $p = 0.206$).[7,12] The preoperative anatomical and surface accuracy checks performed by touching the same anatomical point using the two registration data sets also showed no difference, thus validating the RMS results.

DISCUSSION

Accuracy of Fiducial Registrations

The RMS value for bone-implanted fiducial registration was slightly lower than but not statistically different than the RMS value of the skin fiducials. Our results are similar to those reported by Alp et al.[4] However, they used different types of fiducial registration in different patients while we compared the accuracy of registering bone and skin fiducials in the same patients.

RMS represents variation in a three-dimensional volume based on points (fiducials) placed to best describe the volume. Some workers refer to this measure as the "sum of vectors" for each of three axes[7–9] or as registration error.[10] Although RMS is not an absolute measurement of error (and thus of accuracy),[11] and although it is possible to have a low RMS value and a high registration error, RMS has been accepted as an objective metric.[7,8,10–17] RMS is biased toward a "centroid" of the fiducials, which depends on the arrangement of the fiducials. Although we did not study the geometry of fiducial placement, like others[18] we found subjectively that widely spaced and diverse placement of the fiducials overlying the target improved accuracy, precision, and hence intracranial navigation. The lack of a significant difference between the RMS values derived from the two registration data sets was corroborated by the subjective finding that the accuracy checks were similar for the two registration data sets.

Validity of Intraoperative Bony Landmarks

Like others, we found bony markers to be useful landmarks.[7] They were reproducibly accurate (measured by "tip-to-landmark") and were easily re-registered when necessary. We checked the accuracy using the intraoperative bony landmarks' tip-to-landmark value with each use of the stereotactic arm. When the tip-to-landmark value decayed (> 2 mm) with multiple uses of the Viewing Wand™, we re-registered the intraoperative landmarks. We attributed the loss of accuracy to minor drift in components of the patient-headrest-table-stereotactic arm complex. When the tip-to-landmark value was greater than 2 mm despite re-registration of the landmarks, the original fiducials had to be re-registered. In these instances, we attributed the inability to obtain accurate tip-to-landmark values to major drift in the patient-headrest-table-stereotactic arm complex. Such major drifts probably reflected the use of power drills and adjustments of table height or slope. This re-registration of fiducials and thus of landmarks could only be performed for bone-implanted fiducials because skin fiducials were removed before antiseptic preparation of the scalp.

The main advantage of bone fiducials is that they may be re-registered during surgery. Thus the IGS system can be used effectively despite voluntary or involuntary movement of the patient-headrest-stereotactic arm complex. Theoretically, the superior registration of bone fiducials reported by us and others[4,9] may be advantageous when performing frameless stereotactic biopsies of small intracranial targets.

Caveat

Our study focused on comparing the accuracy of registration achieved with two types of fiducials. In addition to the technical accuracy of registration, the clinical accuracy of a neuronavigation system (i.e., the in vivo localization error in the operating room) also depends on the technical accuracy of the imaging device, the technical accuracy of the neuronavigation system, and the amount of intraoperative brain shift.[3]

CONCLUSIONS

Bone-implanted fiducial registrations have a slightly lower RMS value than skin fiducial registration. However, this difference is not statistically significant in a clinical setting.

Bone-implanted fiducials have advantages compared to skin fiducials. Because they are in the operating field during a craniotomy, they can be re-registered when the head of the patient is moved or when there is a major drift in the accuracy of landmarks.

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Commentary

Dr. Ammirati and his colleagues compared registration using skin fiducials and bone-implanted fiducials for cranial frameless intraoperative navigation. The study involved 28 patients who underwent a craniotomy for brain tumor resection. Each patient had both bone-implanted fiducials and skin-applied fiducials and served as his or her own control.

Registration accuracy was recorded as root mean square error (RMSE). The RMSE value represents the three-dimensional spatial error of fiducial distribution in image space compared to the physical "patient" space. Therefore, it is possible to have a low RMSE and a high actual registration error. This situation can occur if an axis shifts or rotates in such a way that the spatial distribution of fiducials did not change but the actual point-to-point inaccuracy was significant. The problem is real and prone to occur with spherical data sets such as fiducials around the head. It should be em-