EFFECT OF CHANGING PATIENT POSITION FROM SUPINE TO PRONE ON THE ACCURACY OF A BROWN-ROBERTS-WELLS STEREOTACTIC HEAD FRAME SYSTEM

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OBJECTIVE: Despite the growing popularity of frameless image-guided surgery systems, stereotactic frame systems are widely accepted by neurosurgeons and are commonly used to perform biopsies, functional procedures, and stereotactic radiosurgery. We investigated the accuracy of the Brown-Roberts-Wells stereotactic frame system when the mechanical load on the frame changes between preoperative imaging and the intervention because of different patient position: supine during imaging, prone during intervention.

METHODS: We analyzed computed tomographic images acquired from 14 patients who underwent stereotactic biopsy, deep brain stimulator implantation, or radiosurgery. Two images were acquired for each patient, one with the patient in the supine position and one in the prone position. The prone images were registered to the respective supine images by use of an intensity-based registration algorithm, once using only the frame and once using only the head. The difference between the transformations produced by these two registrations describes the movement of the patient's head with respect to the frame.

RESULTS: The maximum frame-based registration error between the supine and prone positions was 2.8 mm; it was more than 2 mm in two patients and more than 1.5 mm in six patients. Anteroposterior translation is the dominant component of the difference transformation for most patients. In general, the magnitude of the movement increased with brain volume, which is an index of head weight.

CONCLUSION: To minimize frame-based registration error caused by a change in the mechanical load on the frame, stereotactic procedures should be performed with the patient in the identical position during imaging and intervention.

KEY WORDS: Image-guided surgery, Mechanical stress, Prone position, Stereotactic head frame system, Stereotactive radiosurgery, Stereotactic techniques, Stereotaxy, Supine position

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Despite the growing popularity of frameless image-guided surgery systems, stereotactic head frame systems are widely accepted by neurosurgeons and are still commonly used to perform stereotactic biopsy, functional procedures, and stereotactic radiosurgery (1, 10). Stereotactic frame systems generally include a stereotactic reference frame (head ring) that provides rigid cranial fixation with pins or screws and establishes a stereotactic coordinate system in physical space, a method for stereotactic image acquisition, and a stable mechanical platform (which typically includes an aiming arc assembly) for holding and directing a probe or other surgical instrument to a defined intracranial target point (10, 12, 17). Most current frame systems relate image space to the physical coordinate space established by the reference frame by attachment, just before image acquisition, of a localizing system consisting of three or more N-shaped fiducials (*Fig. 1*) (5, 6).

The accuracy of frame-based surgical procedures depends on many factors, including image resolution, geometrical fidelity of the images, localization error of the N-shaped fiducials, and the mechanical construction of the frame system (23). Substantial effort has been made to investigate and quantify some of these sources of error (3, 4, 7–9, 11, 14, 18–20, 24, 25, 29, 33, 34, 36, 37), but very little has

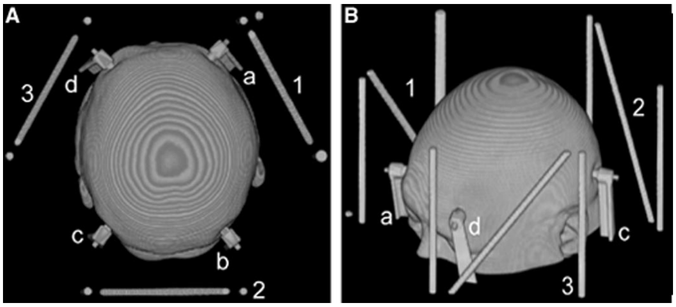

FIGURE 1. *Three-dimensional volume rendering of a CT image from a patient with an attached stereotactic head frame.* A, *view from cranial direction;* B, *view from left anterior oblique direction. The stereotactic reference frame or head ring (not visible) is attached to the head by four posts that are labeled* a *through* d. *Registration of the image coordinate system to the physical coordinate space established by the reference frame is achieved by attachment, just before image acquisition, of a localizing system consisting of three N-shaped fiducials. Each of these fiducials, often referred to as "N-bars," consists of two parallel and one diagonal rod; they are labeled* 1 *through* 3.

been reported about the effect of mechanical loading. The accuracy of a frame system depends on its rigidity and the perfect immobilization of the patient's head with respect to the reference frame or head ring and thus is limited by the construction details of the frame and the mechanical properties of the materials it is manufactured from. Most current stereotactic frame systems attach a reference frame or head ring to the head by four vertical posts by use of pins or screws. The weight of the head mechanically loads the frame, and the support posts deform. If the mechanical load is identical at the time of scanning and the time of treatment, then the effect is unimportant. If the load is different, the head will move rigidly with respect to the head ring (and the N-shaped fiducials of the localizing system), which defines the stereotactic coordinate system. Even when the patient's position is the same at the time of scanning and the time of treatment, there can be a different mechanical load if the body is supported differently in the scanner and the treatment room, as is often the case (the head can generate different force depending on how much the neck and shoulders are supported by the table; also, the head ring support can sit at different vertical heights). The worst case scenario is a supine position during scanning and a prone position during treatment, as is the case, for example, for posterior fossa biopsy and some types of radiosurgical treatment.

The voluntary standard performance specifications for cerebral stereotactic instruments, as issued by the American Society for Testing and Materials, state that the mechanical accuracy of a stereotactic system shall be submillimetric (2). Nonetheless, two studies using phantoms have reported errors of several millimeters caused by application of mechanical loads similar to the weight of a human head (19, 30). In this study, we used clinical data—computed tomographic (CT) images acquired from 14 patients who underwent stereotactic biopsy, deep brain stimulator implantation, or stereotactic radiosurgery—to investigate the accuracy of a common stereotactic head frame system, the Brown-Roberts-Wells frame system, when the mechanical load on the frame changes because of a change in patient position from supine to prone.

PATIENTS AND METHODS

The frame-based registration error caused by a change in patient position from supine to prone is equivalent to the movement of the head relative to the N-shaped fiducials caused by the change in mechanical load on the stereotactic frame. We analyzed CT images acquired from patients in both the supine and prone positions. Each supine and prone image was segmented into a head-only and a frame-only image. The segmented images were registered to produce head-only and frame-only supine-to-prone transformations. The difference between these transformations was used to compute the movement of the head relative to the N-shaped fiducials between the supine and prone positions.

Image Acquisition

We analyzed CT images acquired from 14 patients who underwent stereotactic biopsy, deep brain stimulator implantation, or stereotactic radiosurgery. On the morning of the surgical procedure, a stereotactic reference frame or head ring (Intubation Head Ring, Model HRA-IM; Radionics, Burlington, MA) was applied. A localizing system consisting of three N-shaped fiducials (Model BRW-LF; Radionics) was attached to the stereotactic frame just before image acquisition. Two CT images were acquired before surgery on the morning of the surgical procedure. One image was acquired with the patient in the standard supine position. For this image, the stereotactic frame was mounted to the scanner table via a special adapter. A second image was acquired with the patient in the prone position. Because the frame can mount to the table only in the supine position, for the prone images, the frame was taped to the scanner table, and the patient was instructed to remain as still as possible during the scan. All CT images were acquired on either a HiSpeed Advantage RP scanner (General Electric Medical Systems, Milwaukee, WI) or a Picker PQ5000 scanner

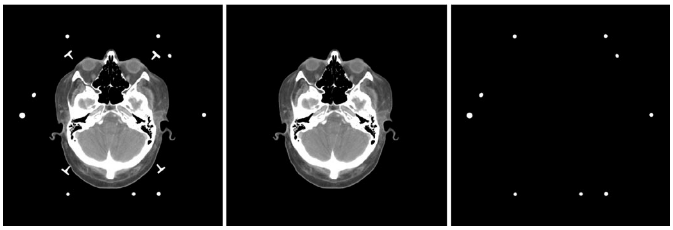

FIGURE 2. *Separation of original CT image* (A) *into head-only* (B) *and frame-only* (C) *images. The three N-bars appear as nine circles (the diagonal rods are ellipses) in a transverse (cross sectional) image slice such as the one on the left. The four posts used to attach the reference frame (head ring) to the head have a T-shaped cross section in a transverse image. These posts are removed from both the head-only and frame-only images. Thus, the frame-only image contains only the three N-bars.*

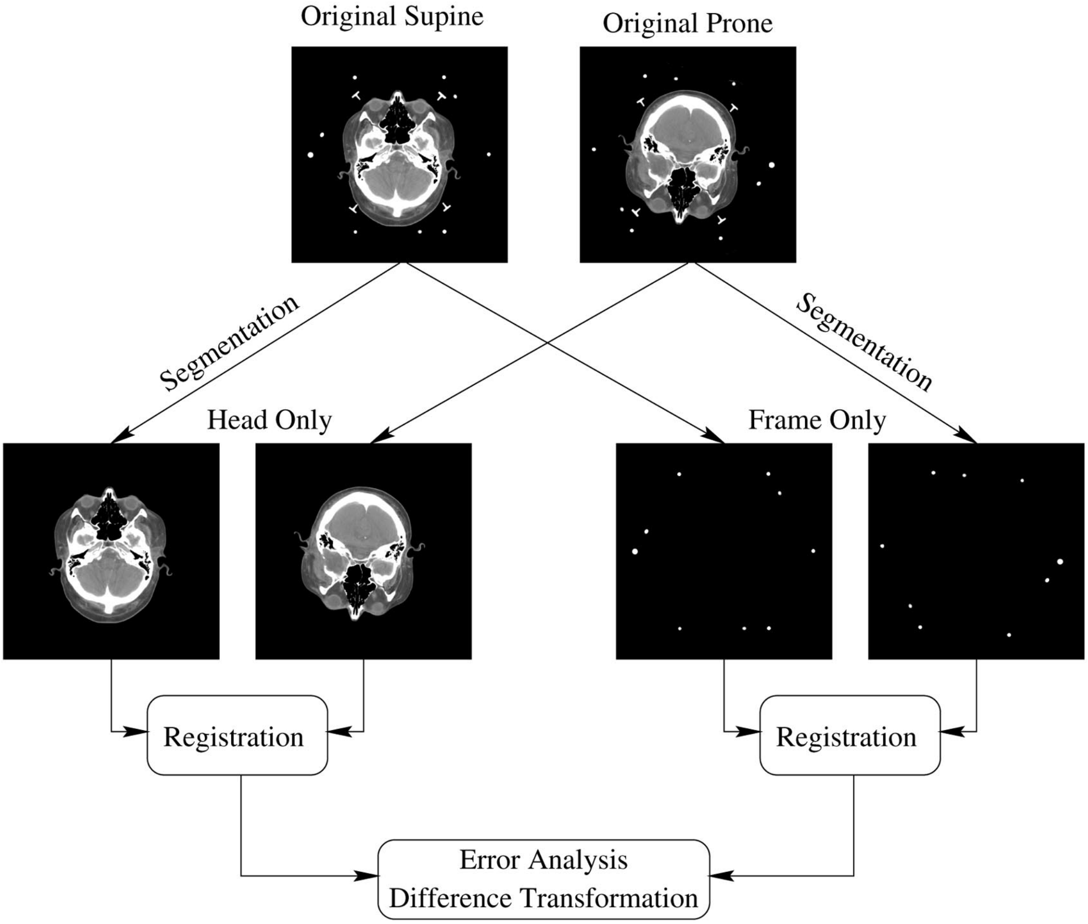

FIGURE 3. *Scheme of image segmentation, registration, and error analysis. The original supine and prone images are separated into head-only (*left branch*) and frame-only (*right branch*) images. The prone head-only image is registered to the supine head-only image. The same is done independently with the prone and supine frame-only images. The resulting transformations are then compared, and the error analysis is performed as described in the text.*

(Philips Medical Systems, Best, The Netherlands) with conventional table advance. Each image volume contains between 42 and 53 transverse slices with 512 × 512 pixels. The axial field of view begins just above the frame and ends at the top of the head. The pixel sizes are generally approximately 0.7 mm; slice thicknesses are 2 or 3 mm. All CT image volumes in this study are stacks of image slices with no interslice gap or slice overlap. The gantry tilt angle was zero.

Image Segmentation

Each original CT scan was separated into two distinct images by manual and semiautomatic (region growing) segmentation implemented in a locally developed software package. One of the resulting images contained only the patient's head (head-only image). The other image contained only the three sets of N-shaped fiducials of the localizing system (frame-only image). The segmentation is illustrated in *Figure 2*. The intensities of the remaining voxels of the segmented images were set to zero. The four posts used to attach the stereotactic frame (head ring) to the head had a T-shaped cross section in transverse image slices. These posts were removed from both the head-only and frame-only images. This is done because they are the part of the frame system that bears the mechanical load. Deformation of these posts is the cause of movement of the head relative to the stereotactic frame when the patient position changes from supine to prone. Also, image-to-physical registration is performed in all current stereotactic frame systems that we are aware of, including in particular the Brown-Roberts-Wells frame system, using only the N-shaped fiducials (5, 6, 13, 16). We wanted to compute the frame-based registration error caused by a change in patient position from supine to prone, which is equivalent to the movement of the head relative to the N-shaped fiducials caused by the change in mechanical load.

Image Registration

For the head-only and frame-only image data, the images in the supine and prone positions were registered to each other independently. This process is illustrated in *Figure 3*. We refer to the registration transformations determined with the head-only and frame-only images as the head-only and frame-only transformations, respectively. Registration was performed with an intensity-based rigid (six-degrees-of-freedom) registration algorithm. Our technique was based on the normalized mutual information similarity measure (32). The six parameters of the optimal rigid transformation were determined by a multiresolution optimization technique. The search algorithm was an independent and modified implementation of the method described by Studholme et al. (31). Our implementation incorporated several additions designed to improve the accuracy and computational efficiency of the original algorithm (26–28). Registration was started with an initial rotation by 180 degrees around the craniocaudal axis to account for the supine-to-prone relocation of the patient. The registration transformations were visually inspected by use of subtraction (difference) and fused (interleaved) images (*Figs.* 4 and 5).

Frame-based Registration Error Analysis

We calculated the frame-based registration error caused by a change in patient position from supine to prone, which is equivalent to the movement of the head relative to the N-shaped fiducials caused by the change in mechanical load, by using the head-only transformation as a reference standard. The head-only transformation was taken as the reference because we were interested in accurately registering the patient rather than the frame. Specifically, we calculated the error as the distance between the position of a point in the supine image mapped to the prone image by the reference head-only transformation and its position mapped by the frame-only transformation. The analysis is similar to the one performed by Maurer et al. (22). Let $\mathbf{x}$ be the position of a target point in the supine image. Let $\mathbf{T}_\mathrm{h}$ and $\mathbf{T}_\mathrm{f}$ denote the homogeneous 4 × 4 matrices representing the head-only and frame-only transformations, respectively. Then $\mathbf{y}_\mathrm{h} = \mathbf{T}_\mathrm{h}\,\mathbf{x}$ and $\mathbf{y}_\mathrm{f} = \mathbf{T}_\mathrm{f}\,\mathbf{x}$ are the positions of the target point in the prone image mapped by the head-only and frame-only transformations, respectively. Because $\mathbf{y}_\mathrm{f} = \mathbf{T}_\mathrm{f}\,\mathbf{x} = \mathbf{T}_\mathrm{f}\,\mathbf{T}_\mathrm{h}^{-1}\,\mathbf{y}_\mathrm{h}$, the error is

$$\Delta\mathbf{y} = \mathbf{y}_\mathrm{f} - \mathbf{y}_\mathrm{h} = (\mathbf{T}_\mathrm{f}\mathbf{T}_\mathrm{h}^{-1} - \mathbf{I})\mathbf{y}_\mathrm{h} \qquad (1)$$

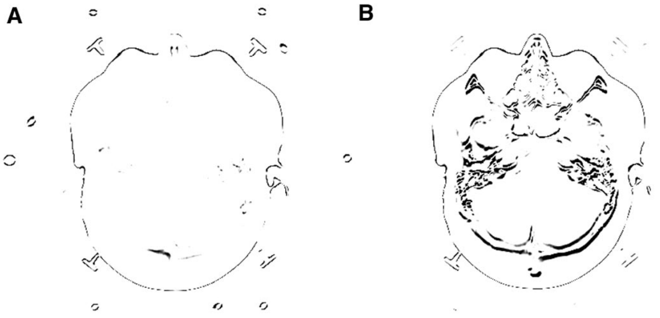

FIGURE 4. *Subtraction (difference) image slices of supine-and-prone study using head-only (*A*) and frame-only (*B*) registration transformations. The lack of artifact inside the head in the head-only registration subtraction image suggests that the head-only registration transformation has subpixel accuracy. The lack of artifact at the N-bar rod cross sections in the frame-only registration subtraction image suggests that the frame-only transformation accurately aligns the N-bars. The artifact inside the head in the frame-only subtraction image indicates that the head moves relative to the N-bars between the supine and prone positions. The artifact at the N-bar rod cross sections in the head-only subtraction image consists primarily of horizontal edges and is consistent with a predominant anteroposterior translation between the images acquired in the supine and prone positions. Artifacts are present at the skin surface and T-shaped attachment posts in both subtraction images, which suggests that these structures move (and deform) with respect to both the cranium and the N-bars.*

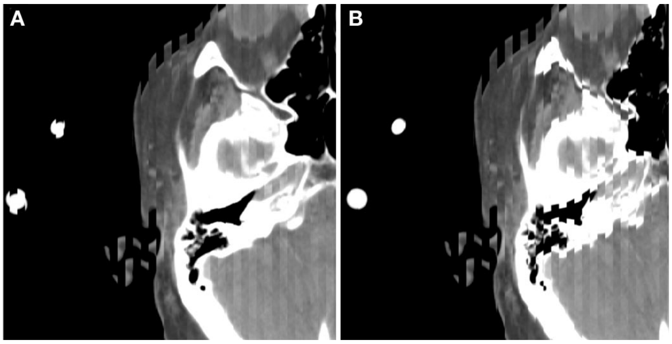

FIGURE 5. *Fused (interleaved) image slices of supine-and-prone study. Alternating vertical bars show corresponding areas of the registered images from both acquisitions.* A*, head-only registration;* B*, frame-only registration. This figure shows a zoomed region of the image slice used to generate the subtraction images in Figure 4. This figure shows, as does Figure 4, that the head-only registration accurately aligns the cranium and its contents; the frame-only registration accurately aligns the N-bars; the head moves relative to the N-bars between the supine and prone positions; and the skin, temporalis muscle, ears, and eyes deform.*

We computed the mean, minimum, and maximum values of $|\Delta\mathbf{y}|$, i.e., the scalar length of the error vector $\Delta\mathbf{y}$, at all voxels $\mathbf{x}$ inside the patient's brain in the supine study. To achieve this restriction to the interior of the cranium, the brains were segmented in the supine images. This was done to ensure that the computed errors represented clinically relevant areas. We also used this segmentation to estimate brain volume, which is an index of head weight. The brain volume values were used to investigate whether there was a relationship between the magnitude of the frame-based error and the (unknown) weight of the head. Because $\mathbf{T}_\mathrm{f}$ and $\mathbf{T}_\mathrm{h}$ are both rigid body transformations, the difference transformation $\mathbf{T}_\mathrm{f}\,\mathbf{T}_\mathrm{h}^{-1}$ is also a rigid body transformation. It can therefore be decomposed into the six common canonical parameters: three translations along the x, y, and z axes and three successive rotations around these axes. Comparing these parameters with those of the identity transformation (which all have the value zero) provides a more specific description of the nature of the registration error than the mere distribution of differences over the image volume.

RESULTS

The head-only and frame-only registration transformations were visually inspected by use of subtraction and fused (vertically interleaved) images (*Figs.* 4 and 5). The lack of artifact inside the head in the head-only registration subtraction suggested that the head-only registration transformation had subpixel accuracy. The lack of artifact at the N-bar rod cross sections in the frame-only registration subtraction suggested that the frame-only transformation accurately aligned the N-bars. The artifact inside the head in the frame-only subtraction indicated that the head moved relative to the N-bars between the supine and prone positions. The artifact at the

N-bar rod cross sections in the head-only subtraction consisted primarily of horizontal edges and was consistent with a predominantly anteroposterior translation between the images acquired in the supine and prone positions. Artifacts were present at the skin surface and T-shaped attachment posts in both subtraction images, which suggests that these structures move (and deform) with respect to both the cranium and the N-bars. The subtraction artifacts in *Figure 4* appear as sawtooth artifacts in *Figure 5*, which shows fused images in which vertical bars alternate between the registered supine and prone images. Both figures show that the head-only registration accurately aligns the cranium and its contents; the frame-only registration accurately aligns the N-bars; the head moves relative to the N-bars between the supine and prone positions; and the skin, temporalis muscle, ears, and eyes deform.

The results illustrated in *Figures 4* and *5* are typical of what we observed in 13 of the 14 patients. In one patient, however, we observed substantial misregistration for both the head-only and the frame-only transformations. The apparent cause of the misregistration was substantial patient motion during acquisition of the prone image: visual inspection of the prone image revealed multiple discontinuities in the N-bar rods. This patient was therefore excluded from further analysis.

The results of the quantitative analysis of the frame-based registration error between the supine and prone positions are listed for each patient in *Table 1*. The maximum error for all patients was 2.8 mm. The individual maximum error for each patient's brain was greater than 2 mm in two patients and greater than 1.5 mm in six patients. In nine patients, that is, in almost two out of three in our study, the individual maximum error was greater than 1 mm. In *Figure 6*, the mean and maximum errors for each patient are plotted versus the patient's brain volume, which we use as an index for the (unknown) head weight. There is a slight (the correlation coefficients of the mean and maximum error linear regressions are 0.61 and 0.64, respectively) but significant (t test on slopes of regression lines, $P < 0.05$) increase in registration error with brain volume.

The difference transformation $\mathbf{T}_f\mathbf{T}_h^{-1}$ between the frame-only and head-only registrations was computed and decomposed into the six common canonical parameters: three translations along the x, y, and z axes and three successive rotations about these axes. *Figure 7* is a box-and-whisker plot of the six difference transformation parameters over all patients (*Fig. 8* shows the orientation of the image coordinate system relative to the patient). Anteroposterior translation ("Translation Y" in *Fig. 7*) is the dominant component of the difference transfor-

TABLE 1. Frame-based registration error between supine and prone positions[a]

Patient no.	Brain volume (ml)	Registration error (mm)		
		Minimum	Maximum	Mean
1	1373	0.22	0.44	0.30
2	1582	1.07	1.53	1.27
3	1723	0.68	2.76	1.44
4	1570	0.93	1.18	1.05
5	1110	0.49	1.16	0.75
7	1285	1.11	1.58	1.34
8	1687	0.87	2.03	1.38
9	1094	0.57	0.81	0.69
10	1412	0.42	0.51	0.45
11	1398	0.42	1.52	0.94
12	1492	1.15	1.46	1.30
13	1282	0.61	0.67	0.63
14	1480	0.61	1.67	1.12
Mean ± SD	1411 ± 193	0.70 ± 0.30	1.33 ± 0.65	0.97 ± 0.38
Median	1405	0.61	1.46	1.05

[a] Patient 6 was excluded because the patient moved during the prone image acquisition. SD, standard deviation.

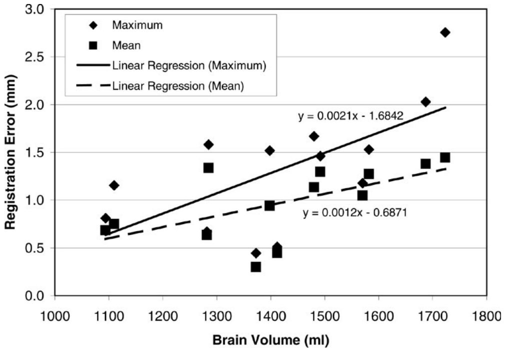

FIGURE 6. *Relationship between frame-based registration error (caused by a change in position from supine to prone) and brain volume. The relationship is approximately linear. The correlation coefficients of the mean and maximum error linear regressions are 0.61 and 0.64, respectively. Brain volume is used as an index of head weight.*

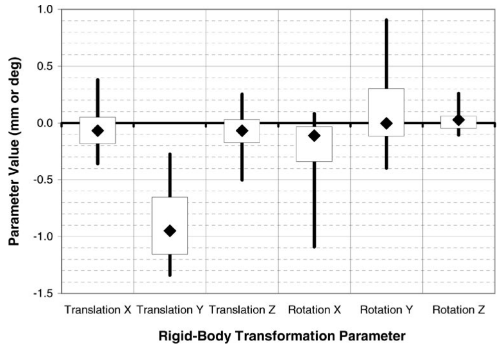

FIGURE 7. *Box-and-whisker plot of the parameters of the difference transformations between frame-only and head-only registrations. The* x, y, *and* z *axes are oriented in the right-left, anteroposterior, and craniocaudal directions, respectively (Fig. 8). The diamond denotes the median value of the respective parameter over all patients, the lower and upper edges of the box are the 25th and 75th percentile values, and the ends of the solid line are the minimum and maximum values over all patients. Anteroposterior translation is the dominant component of the difference transformation between the frame-only and head-only registrations for most of these patients.*

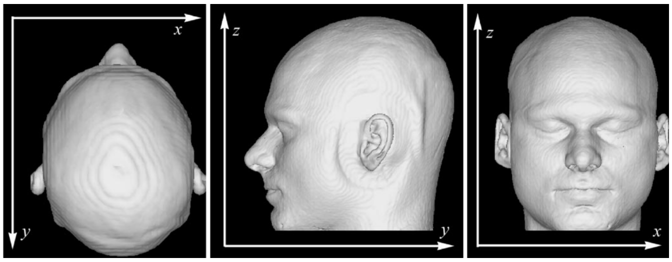

FIGURE 8. *Orientation of the image coordinate system relative to the patient. Axial planes are spanned by the* x *and* y *axes, sagittal slices are spanned by* y *and* z, *and coronal slices are spanned by* x *and* z.

mation between the frame-only and head-only registrations for most of these patients. This finding is statistically significant (two-sided paired t tests, $P < 10^{-5}$) and is not unexpected, because it corresponds to the direction of gravity. For one patient, there was a substantial rotation around the x axis, equivalent to a tilting of the head toward the anterior direction. Other translations and rotations showed a somewhat random distribution of relatively minor magnitude.

DISCUSSION

To assess the validity of our results, it is necessary to understand how accurately the intensity-based registration algorithm we used registers the frame-only and head-only images. Our registration algorithm was previously validated by use of the Vanderbilt data sets (26, 35). The median target registration error for CT-magnetic resonance (MR) registration is approximately 0.6 to 0.9 mm (the range covers different types of MR images). The head-only and frame-only registrations in this study are serial registrations of monomodality images rather than of multimodal images. An intensity-based registration algorithm similar to the one we used in this study was found to produce less than 0.2 mm error, which is approximately the threshold of visually detectable change in the difference images for serial MR registration (15). The error, which is really registration consistency, was evaluated as the difference between a composition of three transformations forming a cyclic closed loop around three images, $\mathbf{T}_{31}\mathbf{T}_{23}\mathbf{T}_{12}$, and the identity transformation, which is what the composition would produce if there were no registration error in each step. Another intensity-based algorithm, also similar to the one we used in this study, was found to achieve 0.4 mm error for registration of preoperative and postoperative CT images (our unpublished results). The error was evaluated by using as a reference standard the point-based registration transformation obtained with five bone-implanted markers (21). The ability of similar intensity-based registration algorithms to align serial CT and MR images very accurately and the lack of artifact observed in visual inspection of subtraction images such as those illustrated in *Figure 4* suggest that the head-only and frame-only registration errors are substantially smaller than the amount of measured movement of the head relative to the N-shaped fiducials. Furthermore, the difference transformations between the frame-only and head-only registrations are consistent with what one expects physically: anteroposterior translation, which corresponds to the direction of gravity, is for most patients the dominant component of the difference transformation. The mechanical load, and thus the magnitude of the error, should and does increase with head weight. Finally, errors in the z direction are of an order of magnitude of 0.15 mm and thus are substantially smaller than the resolution of the image data in this direction (slice thickness is 2 or 3 mm). This indicates that no relevant computational errors were induced by between-slice interpolation.

Thus, we think that the observed effect of changing patient position from supine to prone is real and that the values of the frame-based registration error between supine and prone that we measured in this study are valid. The error is presumably a result of the change in mechanical load that accompanies a change in patient position from supine to prone. The maximum frame-based registration error between the supine and prone positions was 2.8 mm; it was greater than 2 mm in two patients and greater than 1.5 mm in six patients. Errors of this magnitude are sufficiently large to potentially cause clinically relevant targeting errors during stereotactic procedures that require submillimetric accuracy. We note that these errors are independent of, and thus potentially in addition to, other sources of error such as image resolution, geometrical fidelity of the images, localization error of the N-shaped fiducials, and the mechanical construction of the frame system (23).

CONCLUSIONS

We conclude that to minimize frame-based registration error caused by a change in the mechanical load on the frame that can accompany a change in patient position, frame-based stereotactic procedures should be performed with the patient in the identical position during imaging and treatment.

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COMMENTS

The list of potential pitfalls in stereotactic and functional neurosurgery is long. Prominent among these is the error introduced by stereotactic image acquisition used in operative planning. Aside from the intrinsic problems and the inaccuracies and distortions associated with imaging, this information is acquired with the patient in a specific posture and in an environment in which the frame and other attributes may introduce distortions and errors in the image. Another important source of error is the position of the patient during magnetic resonance imaging and the position during the surgical procedure. Rohlfing et al. have performed a well-designed study regarding the movements of the head with respect to the Brown-Roberts-Wells (BRW) frame during various stereotactic procedures. They have found that anteroposterior translation is a major source of error, particularly because of the differences in mechanical loading in different positions. This type of work emphasizes that those who rely on historical images acquired under a certain condition must use intraoperative physiological means, either stimulation or recording, to confirm that where they are in the operating room corresponds to where they think they are on an image acquired before surgery. Those who do not take into account these types of errors, so well exposed by these authors, do so at the peril of their patients.

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The authors point out and measure what most of us who use a stereotactic frame have observed in the operating room: there is a shift in the position of the head relative to the frame imposed by the weight of the head (or other stresses) as the position of the patient is changed. Although their study involves the BRW system, the same caveat can be extended to any stereotactic frame, but the effect on each system would have to be evaluated individually, because it would be influenced by mechanical factors inherent in each system design. Indeed, their *Figure 5* shows the shift of soft tissue surface, which would have an adverse effect on frameless systems that rely on surface fiducials. The shift that is important in that figure, however, is the shift of bony structures relative to the head ring, because there does not seem to be a significant shift of intracranial targets relative to the intact cranium.

Unfortunately, the authors have expressed the potential error as "maximum frame-based registration error," whereas the mean error should have been stressed. Perhaps to emphasize their point more dramatically, mean error was not mentioned, although it appears in *Figure 7* to be consistently less than 1 mm, that is, in the range of one pixel, with the shift most subject to gravitational stress the greatest.

Although one must be aware of the potential for such mechanical error, which may provide a significant problem in targeting a nucleus that is perhaps 2 to 3 mm wide, the adverse effect would be inconsequential if one were to biopsy a 4-cm glioma. The surgeon must ask how much accuracy is demanded by each individual procedure and how much error might be introduced by all influences combined.

Although the frame can be used to secure the patient in the scanner in the prone position by applying the frontal part of the ring to the patient's occiput (care being taken to interpret the coordinates in relation to the frame and not to the patient's head), scanning the patient in such a position is so uncomfortable that it could require general anesthesia, which might otherwise not be necessary or desirable.

Although the American Society for Testing and Materials standards state that the mechanical accuracy of a stereotactic system should be submillimetric, it refers to the unstressed frame itself, and the effect of mechanical stress from gravity is not addressed. I must take exception to the statement that "stereotactic procedures should be performed with the patient in the identical position during imaging and intervention," because that is often not possible and should not be expressed as standard procedure. Often, surgery requires the patient to be sitting or semireclining, positions that are not possible to maintain during imaging. The authors remind us once again that great care must be taken to be aware of and to compensate for inaccuracies that are introduced by the application of any image-guided or stereotactic technique.

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It is interesting to me that this study has not been done previously (to the best of my knowledge). Nonetheless, it is a logical concern: when a prone frame-based stereotactic procedure is planned, can we depend on a database acquired in the supine position? The authors have shown an average error of 2.8 mm between prone and supine databases acquired with the Brown-Roberts-Wells system. This is most likely a result of gravity-induced mechanical loads of the vertical supports of the cranial fixation system so that, in the supine position, the head drifts posteriorly with respect to the fiducial reference system attached to the base ring of the frame: the authors have assumed that its position should be constant irrespective of position (I agree). A 2.8-mm error would be very significant in posterior fossa biopsies, particularly in the brainstem.

Perhaps one problem in this study is that the base ring of the BRW frame is attached to the computed tomography table with the patient in the supine position and that the patient's head settles back on the posterior pins, whereas in the prone position with "the frame taped to the scanner table and the patient instructed to remain as still as possible during the scan," the head may not be settling on the anterior posts in a similar fashion. If it did, the error could theoretically be greater than measured here.

Are the authors' data relevant to other frame systems? They may be relevant to the Cosman-Roberts-Wells system, which uses a fixation system similar to that of the BRW. Could we have a similar problem with the Compass stereotactic system, which uses a different kind of head fixation? I do not know, but we will surely try to find out as soon as possible. With the Compass system, the base ring can be attached to the table in any position throughout 360 degrees of rotation.

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All neuronavigational systems based on preoperative imaging for stereotaxy are subject to error derived from differences in the spatial position of the brain during imaging and in the operating room. The problem most commonly manifests itself as brain shift after cyst decompression or large-volume tumor removal and can mislead surgeons by falsely indicating the intracranial location. In addition, framed-based systems must take into account the physical properties of the frame as they relate to image accuracy. Intimate familiarity with both the stereotactic frame and the imaging modality can separate a successful operation from an unsuccessful one by allowing the surgeon to adapt to situations as they arise.

Rohlfing et al. present an interesting analysis of the mechanical properties of the BRW frame. Their imaging analysis shows that there is a small but significant deformation of the frame when the patient's position is changed from supine to prone. The maximum difference was 2.8 mm. Most helpful was the breakdown of the planes in which the majority of deviation occurred and to what degree. As expected, the most significant change in position occurred in the anteroposterior plane. Although the series is small, the ability to judge how to change trajectory to troubleshoot suboptimal results in the operating room is invaluable. A larger series along these lines would help standardize this deviation and provide an important contribution to the stereotactic surgeon's armamentarium.

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Image-guided surgical techniques, whether frame-based or frameless, rely critically on the ability to relate preoperative images to the surgical field. Any mobility of the fiducials with respect to the targeted structure will lead to localization inaccuracies. As the authors have demonstrated, a major limitation of stereotactic frame systems is the decoupling of the fiducials from the patient's head. Theoretically, a perfectly rigid frame fixated so as to allow no movement would maintain a perfect relationship between the fiducials and the targeted structure, and registration error would be eliminated. However, as the authors have shown, the BRW system exhibits significant flexibility, as demonstrated by the relatively large displacement of the head in the anteroposterior direction when the patient's position is changed from prone to supine. It is logical to assume that gravity is the culprit, and the small but significant correlation demonstrated between the magnitude of anteroposterior registration error and brain volume supports this assumption.

Registration errors in other planes are perhaps more interesting to consider than the obvious case of anteroposterior error because of gravity. It makes sense that rotation about the z axis should be the smallest error, because this rotation occurs in the plane of all four pins. Rotations about the x axis represent head flexion and extension and are highest in the negative (flexion) direction, as might be expected. Rotation about the x axis, which represents side tilting of the head, seems surprisingly large but again makes sense because it occurs in a place perpendicular to the plane of the pins. It would be interesting to repeat this experiment with the head placed in flexion and extension, supported by the frame. From a personal viewpoint, having watched frames flex as patients are repositioned, we would not be surprised to see rotational errors even larger than the translational errors reported in this article.

Frame manufacturers can take this valuable information and use it to design systems using different geometrics and materials that are not so prone to deformation resulting from patient weight. The ultimate solution to the problem of frame deformation would be to do away with the frame completely, applying the fiducials directly to the cranium. As Maciunas et al. (1) and Maurer et al. (2) have shown, extreme levels of accuracy are obtainable by this method. The present study lends further evidence to the concept that frames may not be the most accurate intracranial targeting method after all.

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