Journal of Neuro-Oncology (2006) 76: 65–70
DOI 10.1007/s11060-005-2915-z

Clinical Study

Assessment of image guided accuracy in a skull model: comparison of frameless stereotaxy techniques vs. frame-based localization

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Key words: biopsy, frame-based localization, image guidance

Summary

Introduction: The use of image-guided systems (IGS) for brain biopsy has increased in neurosurgical practice. We sought to evaluate the accuracy of a plastic, disposable burr hole mounted guide for stereotactic biopsy using an IGS and compare the results of different targeting methods with those of frame based localization.

Methods: MRIs were performed on a skull model with mounted fiducials with a stereotactic frame in place and data was loaded onto the Stealth IGS. The model was placed in a Mayfield head holder and fixed to the OR table. Registration of imaging to physical space was carried out. Using three different targeting methods on the Stealth IGS, the distance between the target and the predicted position of the target, the offset error, was measured in three dimensions and confirmed by 2 observers. A sum of squares for the 3 offset errors in all planes was used to calculate the summed vector error. The same MRI dataset used with the Cosman–Roberts–Wells (CRW) stereotactic frame for comparison. The summed vector error was calculated in the same manner to compare the accuracy of targeting with these guides to the frame-based CRW system.

Results: For frameless stereotaxy using the "Straight- guide 4 2D" targeting method the mean error was 2.58 ± 0.51 mm ($n=12$). The vector error was 5.23 ± 0.54 ($n=4$). For the registration set and target using the "Offset- guide 4 2D" targeting method the mean error was 1.66 ± 0.36 mm ($n=12$). The vector error was 3.32 ± 0.72 ($n=4$). The best localization was obtained with the "probe's eye" planning and targeting. The mean error was 0.33 ± 0.16 mm ($n=12$). The vector error was 1.0 ± 0.28 ($n=4$). We found a statistical difference between the different techniques ($P<0.001$) (Kruskal–Wallis One Way Analysis of Variance on Ranks). An all pairwise multiple comparison procedure (Holm–Sidak method) found an overall significance level = 0.05. For the frame-based CRW the mean error from the target was 1.03 ± 0.19 mm ($n=18$) and the mean target localization error vector was 2.23 ± 0.14 ($n=6$). We found a statistically significant difference between NDT guide "Probes Eye" vs. the MR-CRW ($P=0.003$, Mann–Whitney Rank Sum Test).

Conclusions: These results indicate that using MR imaging, surgical planning software and the skull mounted Navigus-DT with the probe's eye view option for targeting, localization accuracy appears to fall within acceptable ranges compared with frame-based methods which have been the standards for stereotactic brain biopsy and functional neurosurgery. Furthermore, there may be considerable differences in accuracy between different targeting methods.

Introduction

Frame-based image guided technologies have been a mainstay in targeting deep structures in the brain in functional neurosurgery and in obtaining biopsies of deep brain tumors. Since the advent of frameless stereotactic systems, these technologies have come into greater use [1–3]. In recent years, there has been controversy regarding which system is most accurate and cost-effective for biopsing brain lesions [2,4]. In order for a system to be useful, it must be accurate in application as well as provide a mechanism for the precise and rigid support of instruments. Previous systems for image guided biopsy accomplished this with large flexible arms that connected directly to the Mayfield head holder or to the operating table. A plastic, disposable burr hole-mounted guide, the Navigus Biopsy Guide (NBG) (Image Guided Neurologics, Melbourne, Florida) was developed to improve the ease of use and accuracy of frameless image. We sought to evaluate the accuracy of this guide for stereotactic biopsy using the Stealth Station Treatment Guidance System (Medtronic Sofamor Danek, Minneapolis, MN) and compare the results of different targeting methods and Cosman–Roberts–Wells (CRW) frame-based localization.

Previous studies have shown using phantom studies that both CT and MR frameless stereotaxy with other fixation devices is accurate and safe [1,2,5]. Here we describe the results of a study that compared the localization accuracy of the NBG with those of framed-based localization. To our knowledge, no study has been conducted which has compared the accuracy of frame-based vs. frameless stereotaxy and within frameless stereotaxy which technique appears to be the most accurate. We have previously reported that these two methods have equivalent accuracy in an experimental *in vitro* skull model [6].

Materials and methods

Skull model and set-up

A plastic, MRI-compatible, skull model was obtained from Image Guided Neurologics. Ten MR compatible reference self-adhesive fiducial markers were placed on the surface. Three markers (copper sulfate-impregnated plastic tips of increasing diameter) were placed at the level of the clivus and were used as targets (Figures 1 and 2). The tip of the target and the base of the target were 2 and 3 mm in diameter, respectively. We measured the distance from the actual target to the location of the target predicted using the Stealth and the CRW system.

Image acquisition and transfer to the operating room

MRI scans were acquired of the skull model using a General Electric 1.5-Tesla MR scanner at the UCSF Medical Center. Our MR image guidance protocol included a sagittal T1 weighted localizer scan, axial 3D volume T1 and T2 weighted fast spin echo scan (TR = 3000/TE102) using 1.5-mm thick slices with no interscan spacing. For stereotactic calculations using the CRW, the X, Y coordinates of the vertical and diagonal rods on the MR localizer and the targets were determined from the imaging console. These coordinates were transferred to a Radionics SCS1 workstation (Burlington, Massachusetts) and the anterior–posterior (AP), lateral (LAT), and vertical (VERT) position of the three targets was determined based upon the nine localizing rods of the stereotactic localizer attached to the frame. The AP, LAT, and VERT position of the three targets at the skull base was calculated on the SCS1 computer using the MR algorithm developed specifically for the localizer system.

The same MRI data was transferred to a Stealth Station in the operating room. Because the same imaging set was used for both systems (frame based, image guided), any error related to slice thickness and other imaging techniques was eliminated. The skull model was placed in standard 3-point fixation to the operating room table. Multiplanar reformatted images were produced from the T1 and T2 3D datasets, a 3D model constructed, and registration of imaging to physical space were performed. The accuracy of the registration was confirmed using a "reserve" fiducial not included in the registration process. Localization accuracy at the skull surface of less than 2 mm measured was required for us to proceed with the next steps of target localization. The trajectory to the target was determined by defining the entry and target positions in the surgical plan and then the alignment of the biopsy probe along the defined trajectory was first done using the skull mounted NBG and the "4 2D" image set. A second method for aligning the trajectory to the targets was done using a "probes-eye" view option, whereby the surgeon tried to align the trajectory using a red dot (the trajectory) within a target grid where the target was at the center of the grid (bull's eye). For each attempt using the 2D image sets, a straight and bayonet-style image guided probe were used placed in a custom made adapter for the NBG. These two methods were then referred to as "straight" and "offset", thus indicating the type of probe used for the alignment process. We choose these larger probes because: (1) a biopsy needle with an affixed light emitting diode had not been approved for human use and; (2) we felt that any torque applied to the thin biopsy needle in aligning it to the desired path might bend it ever so slightly, decreasing the accuracy of target localization for the skull model experiment. The straight and bayonet image-guided probes were much thicker and could not be bent. For the image-guided targeting using the frame and the image guided system (IGS) the same 3 targets were used.

A CRW MR-compatible transitional base ring (Figure 3) was attached to the skull model with the same fiducial markers as targets. MRI images were obtained using the same MR scanner. The axial scan images containing the target tips were used to select the coordinates of the localizing rods of the stereotactic localizing box. The AP, LAT and VERT position of the target were calculated on the SCS1 workstation and the same

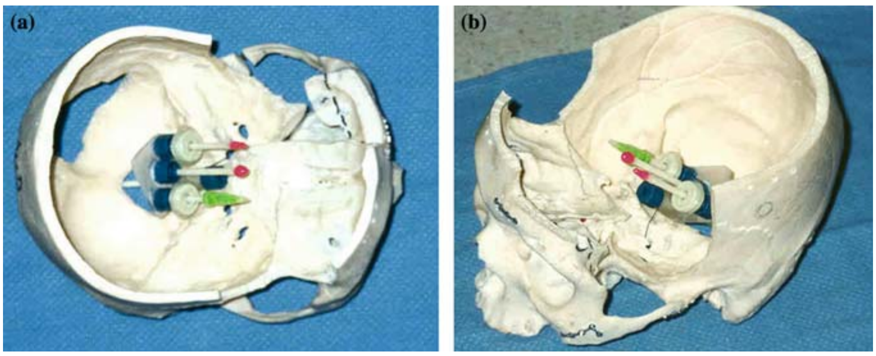

Figure 1. (a and b) Illustrate the three targets identified during surgical navigation. A plastic, MRI-compatible, skull model with MR compatible reference self-adhesive fiducial markers and three markers (copper sulfate- impregnated plastic tips of increasing diameter) were placed at the skull base (over the clivus) and were used as targets. The tip of the target was 2 mm and the base 3 mm in diameter. We measured off set to the tip of the target.

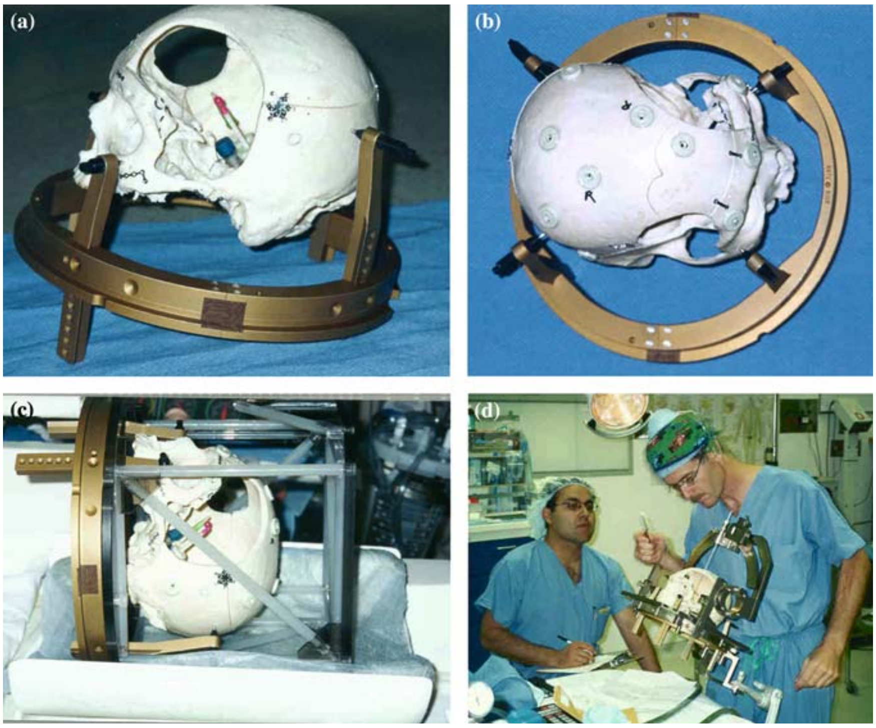

Figure 2. Frame-based set up. We applied the Cosman–Roberts–Wells (CRW) MR-compatible transitional base ring (a and b). Preoperative imaging was obtained (c). Using the phantom base and a Nashold brain biopsy needle the trajectory to the target was confirmed and the depth to the target set on the needle. The arc-ring system was then secured to the base ring and the needle passed down the needle guide to the set depth and then the AP, LAT and VERT offset, if any, was measured (d).

coordinates were used for the CRW stereotactic system. These coordinates were entered into the arc-ring CRW stereotactic system. Using the phantom base (Radionics) the AP, LAT and VERT coordinates were entered and the trajectory to the target position confirmed with a Nashold brain biopsy needle. The depth to the target was set on the needle. The arc-ring system was then secured to the base ring and the needle passed down the needle guide in the CRW arc to the set depth and then the AP, LAT and VERT offset, if any, was measured.

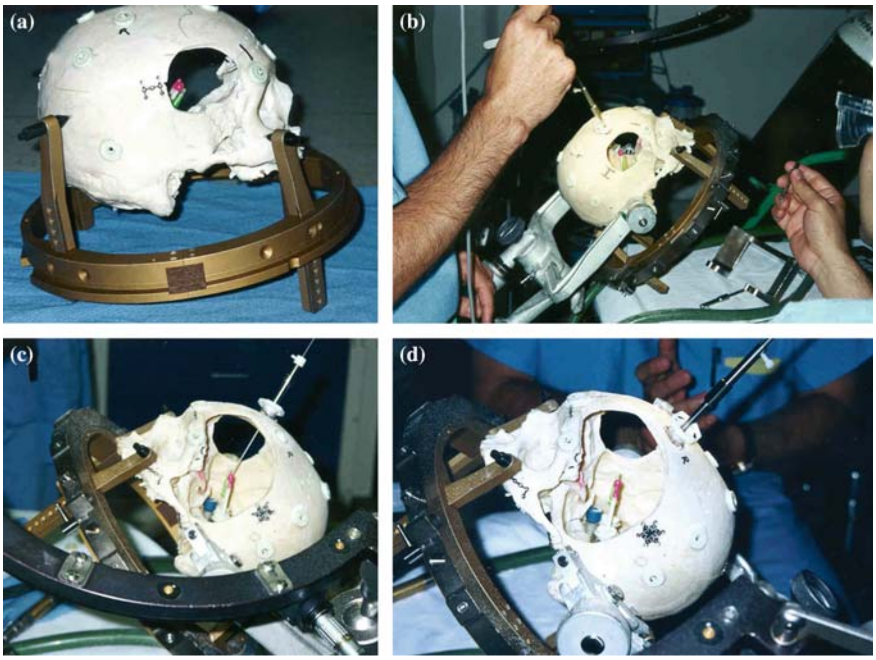

Figure 3. Frameless set up. (a and b) The CRW frame was left in place and the Mayfield holder was applied to the skull model. Preoperative MRI scans were acquired on a General Electric 1.5-Tesla MR scanner. The data was transferred to the operating room computer (Stealth System) where multiplanar reformatted images were produced from the T1 and T2 3D datasets. (c and d) Skull mounted for frameless target localization illustrates the Navigus DT.

Technique to determine the accuracy of the targeting

The distance between the actual target and its location as predicted by these protocols was measured in the anterior-posterior, medical-lateral and vertical plane to determine the offset error. The distances were confirmed by two observers. The average of these offset error in each plane determined the mean localization error (MLE). The square root of the sum of squares for the offset errors in all three planes was used to calculate the target vector error (TVE). This value was then used to compare the accuracy of targeting with these guides compared to the frame-based CRW system. This type of vector error gives more accurate 3D information regarding the error during target localization.

Statistical analysis

Statistical analysis was performed with Sigma Stat 3.0 (SPSS). Calculations performed included nonparametric statistical analysis using a rank sum test. Significance was established as $P \leq 0.05$. Values were reported as means ±standard error of the mean (SEM).

Results

Evaluation for bias based on approach

To determine if the side of approach introduced a bias, we used MR Stealth to approach targets from a right-sided burr holed, determined the mean errors and vector errors, and compared these results to those using a left-sided burr hole. For the MR phantom study using the Navigus and Stealth, the root mean square (RMS) error for registration was 0.7 and the real localization error using a reserved fiducial was 0, 1.35 and 0.7 mm. in the AP, LAT and VERT directions. Using the "4 2D" from a right-sided burr hole, using four trials for each of three targets, the MLE was 1.79 ± 0.21 mm ($n=36$; four measures in the AP, LAT, and VERT directions each). The TVE was 3.56 ± 0.36 ($n=12$). From a left-sided burr hole using four trials for each of three targets, the MLE was 1.65 ± 0.21 mm ($n=36$; four trials with measures in the AP, LAT, and VERT directions each). The TVE was 3.39+0.36 ($n=12$). We compared these two groups of measurements first using the raw data ($n=36$ in each group; $P=0.593$) and then using the vector data ($n=12$ in each group; $P=0.748$) and found no statistical differences between these two approaches (Mann–Whitney Rank Sum Test).

Comparison of accuracy of targeting

To assess the accuracy of frame vs. image-guided localization, a second registration was done. The RMS error for this registration of the MR phantom study was 1.0 and the real localization error using a reserved fiducial was 1.0, 1.0, and 0.5 mm in the AP, LAT and VERT directions, respectively. For the registration set and target using the "Straight- guide 4 2D" targeting method, the MLE was 2.58 ± 0.51 mm ($n=12$; four trials with measures in AP, LAT, and VERT directions each). The TVE was 5.23 ± 0.54 ($n=4$). For the registration set and target using the "Offset- guide 4 2D" targeting method the MLE was 1.66 ± 0.36 mm ($n=12$; four trials with measures in AP, LAT, and VERT directions each). The TVE was 3.32 ± 0.72 ($n=4$). The best localization was obtained with the "probe's eye" planning and targeting. The "probe's eye" planning had a MLE of 0.33 ± 0.16 mm ($n=12$; four trials with measures in AP, LAT, and VERT directions each). The TVE vector was 1.0 ± 0.28 ($n=4$). When these three computer localization techniques were compared, we found a statistical difference between the different techniques ($P<0.001$) (Kruskal–Wallis One Way Analysis of Variance on Ranks) favoring the "probe' eye" planning and targeting. An all pairwise multiple comparison procedure (Holm–Sidak method) found an overall significance level = 0.05 (Figure 4).

Frame-based CRW

The MLE from the target for the CRW was 1.03 ± 0.19 mm ($n=18$; six trials with measures in AP, LAT, and VERT directions each). The mean TVE was 2.23 ± 0.14 ($n=6$) for the MR-CRW. There was a significant difference in TVE of the NDT guide "probe's eye" vs. the MR-CRW ($P=0.003$, Mann–Whitney Rank Sum Test) (Figure 5), favoring the "probe's eye" view.

Discussion

The methods of sampling brain and tumor tissue for diagnosis have evolved from craniotomy for exploration based on symptoms and signs to stereotactic approaches using magnetic resonance and metabolic imaging [7–10]. The availability of image-guided surgical navigation systems has allowed surgeons to biopsy the brain without the use of stereotactic frames [1,11]. As a result both methods of biopsy for brain tumors are routinely practiced.

Here, we demonstrate the accuracy of the frame-based system (CRW) and the frameless system using different software techniques. Within the frameless system, different software techniques are used to help the surgeon align the actual trajectory with the planned trajectory. For frame-based systems, the alignment of the needle with the target is defined and maintained by the frame itself. To our knowledge, no study had evaluated the accuracy of different methods for aligning trajectories using IGSs, although many methods exist and are in some cases manufacturer dependent. We have shown that these techniques provide acceptable localization of targets to within a few millimeters; however, the probes eye technique appears superior to the other techniques tested. In our experience, there was no difference in the time to use each of these software techniques.

Because this is an *in vitro* study, there were several limitations in the interpretation of the data presented here. In this study, the fiducials placed directly on the surface of the skull. These markers remain fixed and

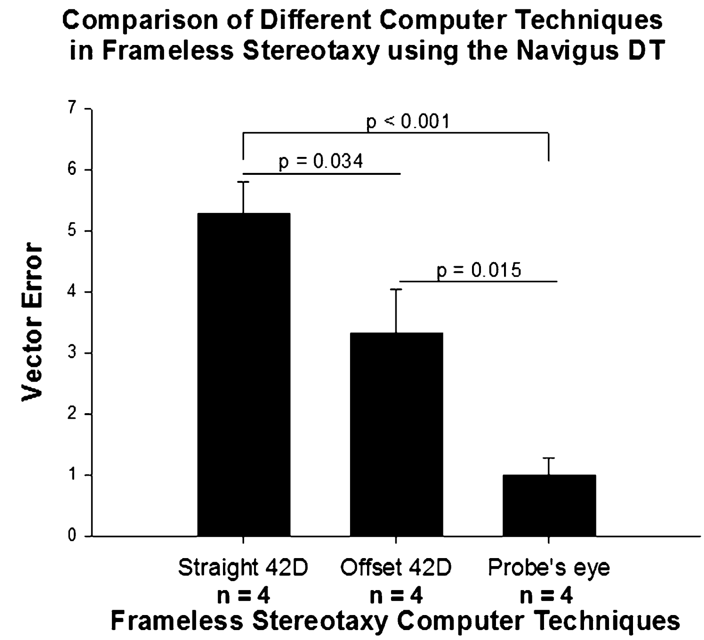

Figure 4. Comparison of different computer techniques in frameless stereotaxy using the Navigus DT biopsy guide. There were a total of 12 measures done in each group, 4 measures in each direction: AP, LAT, and VERT, respectively. We conducted a Kruskal–Wallis One Way Analysis of Variance on Ranks and found statistical differences in the mean values among the treatment groups ($P = 0.001$). All pairwise multiple comparison procedures were conducted by a subsequent Holm–Sidak method with an overall significance level = 0.05. Data presented as mean ± SEM.

care is taken to ensure that there is no movement from the time of the MRI until the registration of the Stealth station. The skull does not have the mobility of the skin and can potentially underestimate the actual error during the registration that is achieved in the human situation. Furthermore, the targets are also immobile but were placed at a depth corresponding roughly to the hypothalamus where little shift in any dimension would likely occur with a simple burr hole. This, however, does not accurately simulate biopsy conditions in which loss of CSF may allow the brain to move in a way predominantly influenced by gravity or friction from the entry of the probe may cause brain shift or slight movement of the target.

The application of frame-based biopsy has declined despite the equivalent accuracy and safety of the two procedures as documented by clinical studies [2,4]. Supporters of frameless systems encourage its use

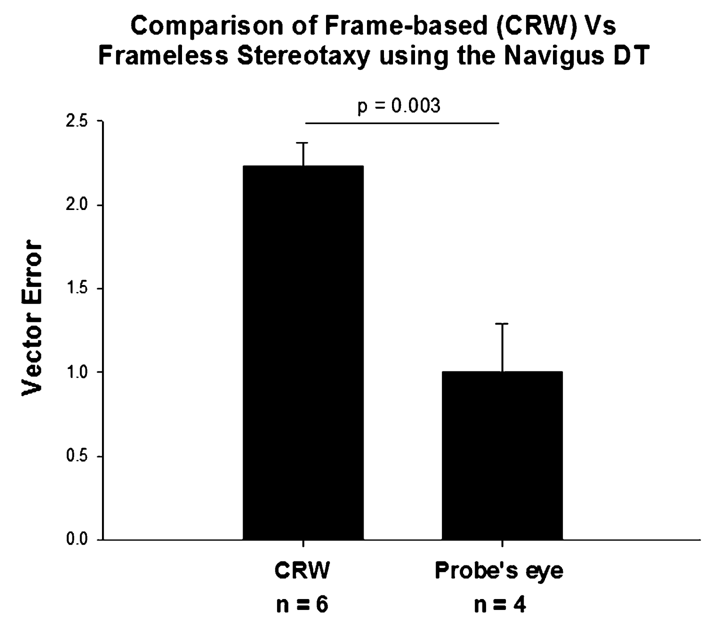

Figure 5. Comparison of frame-based (CRW) vs. frameless stereotaxy using the Navigus DT. There were a total of 18 and 12 measures done in the CRW and the frameless groups, respectively, 4 measures in each direction: AP, LAT, and VERT, respectively. We conducted a Mann–Whitney Rank Sum *t*-test and found statistical differences in the mean values among the two treatment groups ($P = 0.003$). Data presented as mean ±SEM.

because of its superior anatomic imaging using MRI, target visualization and the flexibility of the technique. These supporters argue that these benefits may translate into tangible advantages for safety, time and cost when compared with the current gold-standard of frame-based biopsy [2]. Frameless stereotaxy has continued to improve and its use continues to evolve. Our studies here have shown that image-guided target localization is as good as, and some times better than, frame-based localization. These techniques are presumed to be equivalent now in clinical practice, although frame-based biopsy is declining in popularity. The skull mounted NBG appears to provide a rigid and reliable method for maintaining a set trajectory to a defined target for biopsy methods. We also show that there are differences in the accuracy of the techniques of targeting with an IGS using different methods for aligning a trajectory. Although these differences may be small, surgeons should be aware of these differences and may want to use a method other than one that relies on 2D images for aligning a trajectory when targeting small lesions or those precariously close to vital structures.

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