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INSTRUMENTATION ASSESSMENT

Comparison of Frameless Stereotactic Systems: Accuracy, Precision, and Applications

Ethan A. Benardete, M.D., Ph.D.,
Michael A. Leonard, M.D., Howard L. Weiner, M.D.

Department of Neurosurgery, New York University Medical Center, New York, New York

OBJECTIVE: Frameless stereotactic systems have become an integral part of neurosurgical practice. At our center, we recently introduced for clinical use a small, portable, frameless stereotactic system, namely the Cygnus PFS system (Compass International, Rochester, MN). The purpose of this study was to compare the accuracy of the Cygnus PFS system with that of two larger systems that are also currently in use at our institution, i.e., the SMN system (Zeiss, Oberkochen, Germany) and the ISG viewing wand (ISG Technologies, Toronto, Canada). These systems represent three kinds of frameless stereotactic technologies that are commercially available. Each system uses a different method of spatial localization, i.e., mechanical linkage (ISG system), magnetic field digitization (Cygnus system), or optical technology (SMN system).

METHODS: Using a stereotactic "phantom," we measured the accuracies of all three systems with identical data sets. The errors in localization in three-dimensional space for nine targets were calculated by using 10 magnetic resonance imaging data sets. The precision of each system was also calculated.

RESULTS: With this experimental protocol, the Cygnus system attained a mean accuracy of 1.90 ± 0.7 mm, the ISG viewing wand system a mean accuracy of 1.67 ± 0.43 mm, and the SMN microscope a mean accuracy of 2.61 ± 0.99 mm. The precision values were not significantly different among the systems.

CONCLUSION: We observed only small differences in accuracy and precision among these three systems. We briefly review the advantages and disadvantages of each system and note that other factors, such as portability, ease of use, and microscope integration, should influence the selection of a frameless stereotactic system.

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Key words: Accuracy, Precision, Stereotactic techniques

With the advent of inexpensive computing power and the widespread availability of computed tomography and magnetic resonance imaging (MRI), the use of frameless stereotactic systems for real-time intraoperative guidance in neurosurgery is becoming standard (11). At our institution, we recently introduced a small, portable, frameless stereotactic system, the Cygnus PFS system (Compass International, Rochester, MN). Two other systems are already commonly used, namely the SMN system (Zeiss, Oberkochen, Germany) and the ISG viewing wand (ISG Technologies, Toronto, Canada). To determine the usefulness of the new Cygnus system, we have measured its accuracy, using the ISG and SMN systems for comparison.

Maciunas (14) has defined the accuracy and precision of a stereotactic system. Accuracy refers to the ability of the system to provide the true location of a point in space. The degree of precision reflects the variability of the stereotactic system in repeatedly localizing the same point in space. A system can be precise and still be inaccurate if there is a large degree of bias in its measurements. A stereotactic system is more accurate if it maximizes precision and minimizes the degree of bias.

There are numerous ways in which errors can be introduced into stereotactic systems (12). The essence of frameless stereotaxy is relating actual space to previously obtained images. The transformation from three-dimensional (3-D) space to image space is dependent on accurate digitization of 3-D space and precise computation. The quality of the imaging modality also affects target localization (15, 18, 19). In intraoperative use, factors such as brain shift and tissue displacement can have large effects on accuracy (7).

Using similar methods and identical data sets, we sought to measure the accuracy of these frameless systems. With all other factors being equal, the relative amount of error in localization can be attributed to the systems themselves. We acquired MRI data for a stereotactic "phantom," and identical images were then sent to each system. Multiple targets within the phantom were localized by each system. The difference between the localization by the system and the actual location of each target was measured. An overall estimate of the localization error of each system in 3-D space was then calculated. By making repeated measurements, we were able to estimate the precision of each system.

MATERIALS AND METHODS

Frameless stereotactic systems

The commercial versions of the three frameless stereotactic systems are currently in use at our institution. Each system had been inspected by a service representative and had been certified as being in working order within 3 months before this study.

SMN system

The SMN system (Zeiss) uses infrared light-emitting diodes (LEDs) and linear charge-coupled device cameras to localize both an operating microscope (Zeiss) and a 135-mm handheld probe (Image Guided Technologies, Inc., Boulder, CO) in 3-D space. The center of the focal plane of the microscope acts as the tip of the localizer in physical space. A workstation (Digital Equipment Corp., Boston, MA) performs the calculations for image registration, as well as intraoperative display of the imaging data. The localization accuracy of LED-based technology has been reported to be up to 0.1 mm in benchtesting (30).

ISG system

The ISG viewing wand (ISG Technologies) uses a six-jointed arm with electrogoniometers for interactive localization in 3-D space. We used the "short neuro" pointer for these studies (5). The image registration calculations are performed on a workstation (Hewlett-Packard, Palo Alto, CA), which also displays the images for interactive localization.

Cygnus system

The Cygnus system uses a magnetic field to localize a pointer in physical space (17). The calculations for the transformation between image space and physical space are performed with a 300-MHz laptop computer (Dell, Round Rock, TX).

Stereotactic phantom

A specially designed phantom provided a standard set of targets for testing each stereotactic system. The phantom is a cylinder (height, 17 cm; diameter, 14 cm) filled with copper sulfate solution (0.02%) for MRI (10). Inside the cylinder, nine targets are arranged at different distances from the base (*Fig. 1*). The lengths of the targets are 14.3, 13.9, 13.5, 13, 12.5, 12, 11.5, 11, and 10.5 cm. The phantom is mounted on a removable base ring that allows it to be fixed inside a MRI scanner. On the surface of the cylinder, eight or more standard, adhesive, fiducial markers (IZI Medical Products, Baltimore, MD) are mounted for MRI.

Image acquisition

Magnetization-prepared rapid gradient echo scans (TR, 12 ms; TE, 4 ms; inversion time, 300 ms; flip angle, 15 degrees; matrix, 180 × 256 pixels; field of view, 230 pixels) of the phantom were obtained with a Siemens Magnetom Vision scanner (Siemens AG, Munich, Germany) (13). The magnetization-prepared rapid gradient echo data set consisted of 128 sagittal partitions (1.2 mm). The imaging data were transferred to the SMN and Cygnus systems via a local

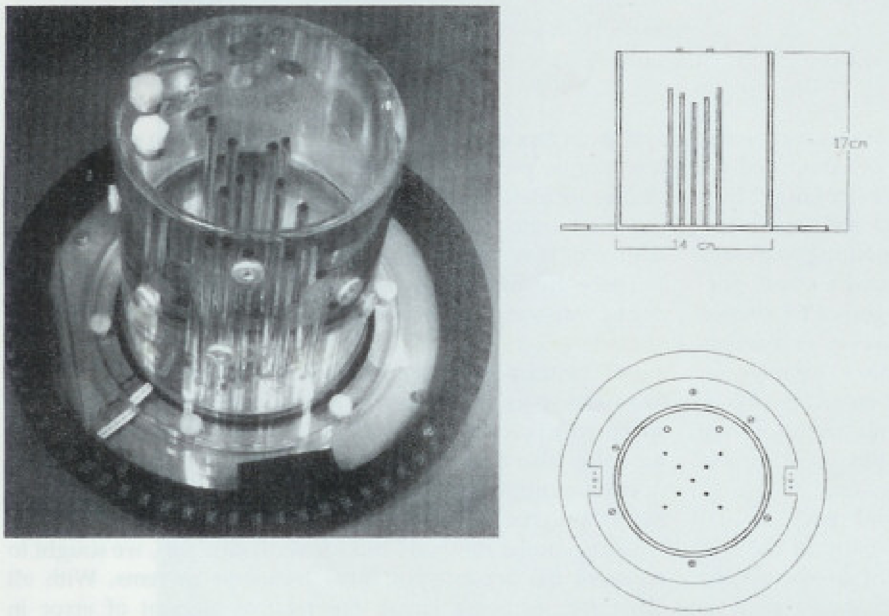

FIGURE 1. The phantom. The stereotactic phantom, which was used to perform the accuracy measurements, consists of a clear plastic cylinder containing nine targets of varying heights (from the base). The line diagrams indicate how the targets of varying heights are arranged.

area network. The data were transferred to the ISG viewing wand system on an optical disk.

Registration and measurements

After MRI, the error of each system was measured in one of two ways. In Method 1, the base ring of the phantom was mounted on a support frame (Compass International) that allows positioning of the phantom. In Method 2, the phantom was mounted in a three-pin headholder on a standard operating table and registered exactly as a patient would be registered intraoperatively (*Fig. 2*). The method of measuring the localization error is described in detail below. Both Methods 1 and 2 were used to measure the accuracy of the ISG and SMN systems. Only Method 2 could be used to measure the accuracy of the Cygnus system; the support frame (Method 1) distorts the magnetic field of the Cygnus transmitter and thus degrades the accuracy of the system. We observed that the difference between the measurements made by using the two different methods was less than 10% (see below).

Measurement Method 1

With the use of the support frame, worm gears with a hand crank allowed the phantom to be moved in submillimeter increments in the x, y, and z directions. The phantom was initially set at the origin ($x = 0$, $y = 0$, $z = 0$). For each system separately, eight fiducial markers on the outside of the phantom were registered. Each system then calculated a registration error, i.e., the root mean square (RMS) distance between the fiducials in physical space and the fiducials in image space. To proceed with target measurements, the system was required to indicate a RMS distance of less than 2 mm. As part of the protocol, each system was allowed up to three trials to obtain a RMS distance of less than 2 mm. If that degree of registration accuracy could not be obtained, then that MRI data set would be discarded. However, in each test, each

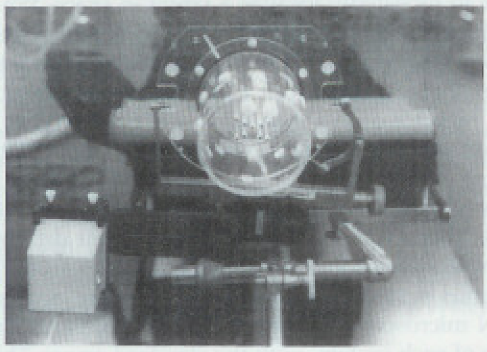

FIGURE 2. The phantom in the head frame. For Method 2, the phantom was mounted in a three-point headholder in a manner identical to the way in which a patient's head is positioned intraoperatively. The fiducials on the outer cylinder were used to register the imaging data, and then the outer cylinder was removed to provide access to the targets. Each frameless system was used to localize the tip of the target in space. The distance between the pointer and the tip of target was taken as the localization error.

system required only one or two trials to obtain a RMS distance of less than 2 mm, and no data sets needed to be discarded.

The outer cylinder of the phantom was removed, giving access to the inner targets. The SMN system and the ISG viewing wand both provide a hand-held pointer. The procedure for measuring the 3-D localization errors for these two systems, using their respective pointers, was as follows. On the basis of the computer display of each system, the hand-held pointer was brought onto the tip of each target. The localizer was then held fixed in space with a standard, flexible, retractor arm. A small distance typically separated the tip of the pointer from the tip of the target. The target was then translocated in space in the x, y, and z directions, by using the hand cranks, until the tip of the target was exactly on the tip of the pointer. By reading the scales of the x, y, and z slides, the errors in all three orthogonal axes were obtained (Δx, Δy, and Δz). The 3-D localization error, E, was then defined as

$$E = \sqrt{\Delta x^2 + \Delta y^2 + \Delta z^2} \quad (1)$$

which is the distance in 3-D space between the actual point in space and the calculated position of the target. For each system, 10 separate MRI data acquisitions were registered and error measurements were performed.

The precision of each system was tested by making multiple estimates of the target localization error, using each data set (see Results). This allowed us to determine the variability in the target localization. Two of the authors (EAB and MAL) made all of these measurements, after 10 previous MRI data sets had been used to practice the measurement method.

Because the SMN microscope uses the focal plane as the physical localizing device, a modification of the aforementioned procedure was required for measurement of the localization error. After registration of the fiducials and removal of the outer cylinder of the phantom, the tip of the first target was brought into focus in the center of the microscope's field of view, which was marked with a crosshatch. In general, this maneuver produces a small discrepancy on the computer display between the position of the microscope's focal point (marked by the intersection of a horizontal line and a vertical line on the computer screen) and the indicated tip of the target. The SMN system uses an infrared LED array to indicate the position of the surgical field. This localizing device is attached to the phantom; therefore, the position of the phantom can be manipulated as described above. The x, y, and z positions required to bring the tip of the target directly to the focal point of the microscope, as displayed on the computer monitor, are recorded. The amount of translation in the x, y, and z directions yields the errors in these orthogonal directions, i.e., Δx, Δy, and Δz. The 3-D target localization is then calculated as described above (*Eq. 1*).

Measurement Method 2

The phantom was mounted in a three-pin headholder, and the fiducials were registered as usual. The outer cylinder of the phantom was then removed and, as described above, the localizer of each system was brought in toward the tip of the target until the computer screen indicated that the localizer was exactly on the tip (*Fig. 3*). The distance between the tip of the localizer and the tip of the target was then measured, using 2.5× loupe magnification, with a digital micrometer (Mitutoyo, Japan) with a scale down to 0.01 mm and an accuracy of ±0.02 mm. To verify that Methods 1 and 2 yielded equivalent results, the ISG and SMN systems were tested with both methods. The distance between the target and the localizer was measured by using both Methods 1 and 2 for each data set. We observed that Methods 1 and 2 were in agreement within 8.6%, on average, for both the SMN and ISG systems.

To measure the precision of each system, a data set was registered and the errors in target localization were recorded three separate times. The statistical variance in the error was then calculated and averaged. This procedure was repeated with two different data sets, and the average variance was calculated. This statistical value yields an estimate of the variability in the localization of the target for each system (*Table 1*, last column).

RESULTS

The stereotactic phantom was imaged 10 separate times. Identical data from each of these sessions were transferred to each stereotactic system. The images were registered and the 3-D target localization errors were calculated as described above. *Table 1* summarizes the data from these measurements for each system. The first column of data presents the average, for all 10 data sets, of the image registration errors reported by each system. For the ISG system, this error was 1.25 ± 0.50 mm (mean ± standard deviation). For the Cygnus system, the error was 1.10 ± 0.32 mm. For the SMN system, the error was 1.53 ± 0.33 mm. The registration error was required to be less than 2 mm in each experiment for the measurements to be included in the study. The next column in *Table 1*, the mean error, is the average, for all 10 data sets, of the localization errors defined for each of the nine target points; therefore, this is the average of 90 separate measurements for each system. The ISG system exhibited a mean error of 1.67 mm, whereas the Cygnus system demonstrated a mean error of 1.90 mm. The SMN pointer exhibited a mean error of 2.26 mm, whereas the microscope exhibited a mean error of 2.61 mm. The next column in *Table 1* indicates the median of the same set of measurements for each system. The mean and the median were similar for each system, indicating there were no considerably outlying points in the data. Particularly for the SMN system, we checked whether there was any consistent bias in the degree of error in the x, y, or z direction. For the set of 10 experiments, the mean and standard deviation of each error were as follows: x, 0.96 ± 0.13 mm; y, 1.19 ± 0.18 mm; z, 0.63 ± 0.13 mm.

The fourth column in *Table 1* presents the standard deviation of the measured error for all data sets. This statistical value reflects the degree of variation in the error measured for each target. The standard deviation was least for the ISG system; however, the standard deviations for all systems were less than 1 mm and were not statistically significantly different.

The final column in *Table 1* presents the variance of the target localization error calculated for each system. This statistical value reflects the precision with which each system was able to repeatedly localize a target in space. We present these values for comparison among the different systems. The ISG system demonstrated a smaller average variance than did the other three systems, but all three systems exhibited an average variance of less than 0.5 mm. The difference in variances among the three systems was not statistically significant.

One-way analysis of variance was performed with the data sets (24). There was a statistically significant difference between these systems in terms of accuracy ($P < 0.05$). The ISG and Cygnus systems were significantly more accurate than the SMN microscope or pointer. *Figure 4* presents the mean accuracy of each system, with the standard errors. The difference in accuracy between the Cygnus and ISG systems was not statistically significant.

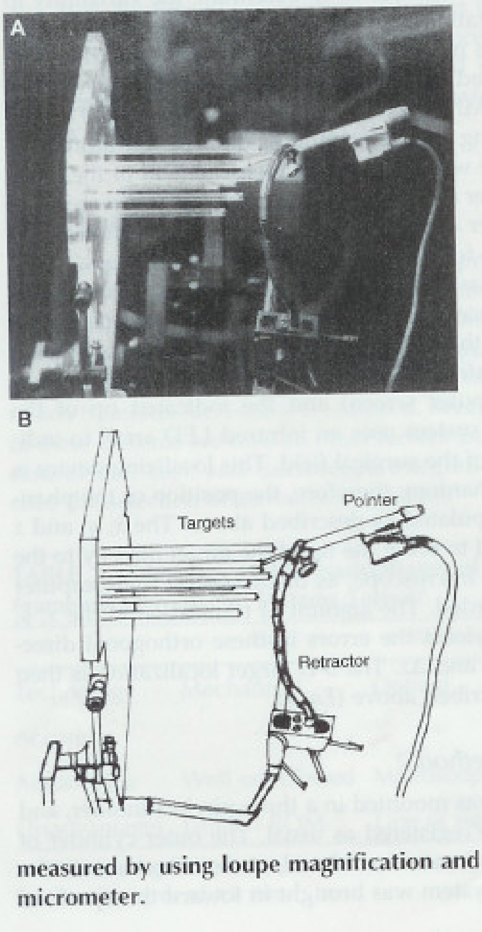

FIGURE 3. Localization of the targets. As indicated in the photograph (*A*) and the diagram (*B*), the tip of the pointer of the frameless system (ISG, SMN, or Cygnus system) was brought onto the tip of the target, as observed on the computer display of each system. The pointer was then held fixed in space with a standard retractor arm, and the distance between the tip of the target and the tip of the pointer was measured by using loupe magnification and a digital micrometer.

DISCUSSION

Frameless stereotactic systems

Several different technologies have been used in the development of frameless stereotactic systems for neurosurgery.

TABLE 1. Comparison of the Accuracy and Precision of Three Frameless Stereotactic Systems[a]

System	Registration Error (mm)	Mean Error (mm)	Median Error (mm)	Standard Deviation (mm)	Variance (mm)
ISG wand	1.25	1.67	1.62	0.43	0.20
SMN microscope	1.53	2.61	2.53	0.99	0.44
SMN pointer	1.53	2.26	2.29	0.83	0.36
Cygnus	1.10	1.90	1.72	0.70	0.34

[a] The registration error was reported by each system. The mean error and median error indicate the localization error for each system. The standard deviation of the localization error is also provided. The variance is a measure of the precision of each system. See text for details.

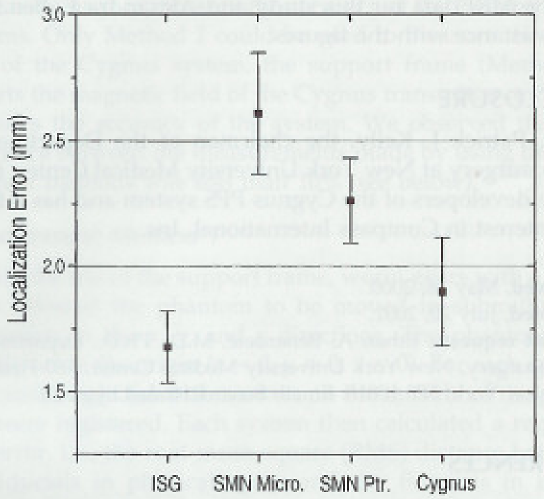

FIGURE 4. Localization accuracy. The localization accuracies of the systems were compared (see Materials and Methods). The error bars indicate 1 standard error of the mean for each measurement. As demonstrated, the Cygnus and ISG systems were significantly more accurate than the SMN pointer (*Ptr.*) or microscope (*Micro.*).

Early systems used tethered arms to localize positions in 3-D space (27). The ISG viewing wand is a descendant of these early systems. Sonic technology has also been used to localize a microscope or pointer, but corrections for the speed of sound in air and interference have made these systems more difficult to use (21). The sonic method has been refined to a reported 1.5-mm accuracy in bench-testing, however (21). The magnetic field digitizer in the Cygnus system provides a useful way to localize a point in space (4, 9). Optical technology with infrared LEDs, as used in the SMN system, has a reported accuracy of 2 to 4 mm (1, 8, 22, 23).

Accuracy

Numerous factors affect the intraoperative accuracy of stereotactic systems. Target localization depends on the technology of the localizer in 3-D space. The computer and software establish the correspondence between the images and the localizer data (2). Accuracy also depends on the stability of the target (28) and the ability of the localizer to reach the target in physical space. Few studies have carefully measured the target localization accuracy of frameless stereotactic systems, although the major frame-based systems have been compared (16). A direct comparison of multiple frameless systems has not been published.

Sipos et al. (26) and Golfinos et al. (5) previously reported the accuracy of the ISG viewing wand system. Sipos et al. (26) measured an accuracy of 2.5 mm by using surface fiducials. Golfinos et al. (5) observed that the target localization was within 2 mm. Although surface-fit registration methods can also be used with the ISG system, studies noted that fiducial methods are slightly more accurate (6). A similar articulated arm was reported to exhibit an intraoperative accuracy of 2.5 mm (3).

With an infrared LED-based pointer system, the target localization accuracy has been reported to be between 2 and 3.8 mm (23). The same group reported an intraoperative localization error of less than 2 mm with the frameless stereotactic microscope, after they had gained experience with it (22). Ryan et al. (25) reported an intraoperative accuracy of 4.8 mm, with a standard error of 3.5 mm, with an LED-coupled wand.

Overall, our accuracy measurements are close to those reported previously. We compared the accuracy and precision of three systems by introducing the same data set to each system. We observed that the three systems exhibited approximately the same degree of accuracy.

Advantages and disadvantages

Because of its portability and simplicity, the Cygnus system has begun to replace the other two systems for many applications at our institution. At New York University, 126 procedures were performed with the Cygnus PFS system between June 1998 and December 1999, for 117 patients. *Table 2* summarizes these data. The frameless stereotactic system was used primarily for tumor resection; approximately two-thirds of those procedures were to treat intra-axial tumors, and the remaining one-third were to treat extra-axial tumors. The majority of the extra-axial tumors were meningiomas, and the majority of the intra-axial tumors were gliomas of various grades. Four of the intra-axial tumors were intraventricular. Whereas 123 of the procedures were craniotomies, 3 burr hole procedures were performed with the system, for biopsy and aspiration of cysts associated with tumors. Craniotomies using frameless stereotaxy were performed in all possible locations, i.e., frontal, parietal, pterional, temporal, occipital, and suboccipital. The two most common locations were frontal

TABLE 2. Clinical Applications of the Cygnus System in 126 Cases during an 18-Month Period

Procedure	Craniotomy (123 cases)	Burr hole (3 cases)	Other (0 cases)
Diagnosis	Extra-axial tumor (33 cases)	Intra-axial tumor (91 cases)	Vascular (2 cases)
Craniotomy placement	Frontal (51 cases)	Temporal (28 cases)	Pterional/other (47 cases)
Operation	First resection (96 cases)	Recurrent (27 cases)	Biopsy/aspiration (3 cases)

and temporal. No complications related to use of the Cygnus system were reported.

Each of the tested systems has advantages and disadvantages (*Table 3*). The ISG viewing wand provides the standard of accuracy. However, the mechanical linkage arm can be cumbersome and has limited degrees of freedom. Infrared LED technology (as in the SMN system) yields good accuracy and, without a mechanical linkage, provides ease of movement in the surgical field. However, it does require that the line of sight between the charge-coupled device cameras, the probe, and the microscope remain unobstructed. Magnetic field digitizing systems (such as the Cygnus system) exhibit accuracy comparable to that of the other two systems. Mechanical arm or line-of-sight problems do not affect these systems; however, metallic objects in the surgical field can disturb the magnetic receiver. Intraoperatively, we have not found this factor to be a problem.

Given the range of accuracy of these frameless systems, it is clear that, for biopsy or resection of lesions in deep locations (such as the thalamus) and functional procedures for which greater accuracy is required, frame-based systems are still useful and necessary. In general, frame-based systems offer greater accuracy and precision (20, 29).

CONCLUSIONS

We observed that the accuracies and precisions of these frameless systems were comparable. For most applications, the small differences in accuracies among these systems would not be significant. At our institution, the Cygnus system has proven to be valuable in a variety of clinical cases for which frameless stereotaxy is required. Because the accuracies of these systems are similar, other factors (such as portability, ease of use, cost, and microscope integration) should influence the selection of stereotactic systems.

TABLE 3. Advantages and Disadvantages of the Three Frameless Stereotactic Systems Tested[a]

	ISG	SMN	Cygnus
Technology	Mechanical	Optical	Magnetic field
Accuracy	++	+	++
Advantages	Well established	Microscope	Portable
Disadvantages	Limited ROM	Line of sight	Interference

[a] ROM, range of motion; ++, localization error of <2 mm; +, localization error of >2 mm.

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DISCLOSURE

Dr. Patrick J. Kelly, the chairman of the Department of Neurosurgery at New York University Medical Center, is one of the developers of the Cygnus PFS system and has a financial interest in Compass International, Inc.

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Reprint requests: Ethan A. Benardete, M.D., Ph.D., Department of Neurosurgery, New York University Medical Center, 560 First Avenue, New York, NY 10016. Email: benare01@med.nyu.edu

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COMMENTS

This careful, well-designed study demonstrates the bench accuracy (i.e., point localization in space) and precision (i.e., the ability to repeatedly localize the same point in space) of three commercially available frameless stereotactic surgical navigation systems. This information is of practical interest because the three systems chosen for analysis rely on different localization technologies. Because the accuracy of these systems is roughly comparable, their usefulness in the surgical environment may depend principally on their convenience of use, portability, flexibility of application, and cost.

This study reveals a small difference in accuracy within a single commercial system, depending on whether a localizing pointer or microscope-based localization was used. The inherent inaccuracy in using the microscope's focal length as the source of the *z* coordinate does not seem to have contributed to reduced accuracy in the authors' laboratory environment. Although the more portable and inexpensive magnetic field-based localization system evaluated here performed very accurately in bench testing, further evaluation should be carried out in a "live" surgical environment that contains complex metal retractor systems, current-based coagulation devices, and other sources of magnetic artifact.

Kim J. Burchiel
Nathan R. Selder
Portland, Oregon

The authors have compared the accuracy and precision of three frameless stereotactic systems. This study is of particular interest because the systems are based on entirely different targeting principles—that is, an articulated arm, light-emitting diode fiducial detection, and an electromagnetic field.

As far as I know, all presently available commercial systems are accurate to within 2 mm, as were the systems that the authors tested. One must recognize, however, that in clinical use, other variables are introduced, and the final precision is nowhere near that measured in the laboratory. Perhaps the main source of error is imaging slice thickness, so the scanning technique must be tailored to the requirements of each case.

One must ask about the distortion of the magnetic field that may introduce error into the Cygnus PFS system (Compass International, Rochester, MN). The laboratory conditions under which testing was performed do not simulate the possible field distortion in the operating room, so the evaluation of that system must be interpreted with caution. The authors indicate that field distortion was not a problem in their experience.

All systems become inaccurate as soon as the dura is opened, a retractor is inserted, or the resection is begun. Even so, the use of image guidance allows the surgeon to approach the lesion safely and efficiently, obtain a maximum resection of abnormal tissue, and minimize trauma to the surrounding brain tissue, all of which are laudable goals in any resection.

The authors conclude that each system works with reasonable accuracy and reproducibility that are certainly within the requirements of most biopsies or image-guided tumor resections. Before each case, however, one must ask oneself, "How accurate do I need to be today?" A precision of 2 to 3 mm may be fine for the resection of a glioma (in which the edge of the tumor is not definable anyway) or a metastatic tumor (in which the edge is usually obvious once the tumor is found). It is not accurate enough, however, for most electrode insertions in functional neurosurgery. One must choose the system that meets one's immediate requirements, regardless of whether the system is frame-based or frameless. No matter which system is used, the clinical judgment of the surgeon ultimately guides the operation.

Philip L. Gildenberg
Houston, Texas

Benardete et al. have compared the precision and accuracy of three contemporary frameless stereotactic systems. All three systems seem to be quite similar with regard to precision and accuracy. I found this article to be quite useful in its guidance for neurosurgeons regarding the relative merits of different systems. To remove any potential appearance of bias in the interpretation of results, authors should disclose any financial interests in the companies whose products are being evaluated.

Andres M. Lozano
Toronto, Ontario, Canada

Self-portrait in Front of an Easel, **by Paul Gauguin, 1885. Private collection, Switzerland.**