Lack of agreement between direct magnetic resonance imaging and statistical determination of a subthalamic target: the role of electrophysiological guidance

EMMANUEL CUNY, M.D., DOMINIQUE GUEHL, M.D., PH.D., PIERRE BURBAUD, M.D., PH.D., CHRISTIAN GROSS, PH.D., VINCENT DOUSSET, M.D., PH.D., AND ALAIN ROUGIER, M.D.

Service de Neurochirurgie, Service d’Exploration Fonctionnelle Neurologique, et Service de Neuroradiologie, Hôpital Pellegrin, Bordeaux, France

Object. The goal of this study was to determine the most suitable procedure(s) to localize the optimal site for high-frequency stimulation of the subthalamic nucleus (STN) for the treatment of advanced Parkinson disease.

Methods. Stereotactic coordinates of the STN were determined in 14 patients by using three different methods: direct identification of the STN on coronal and axial T₂-weighted magnetic resonance (MR) images and indirect targeting in which the STN coordinates are referred to the anterior commissure–posterior commissure (AC–PC) line, which, itself, is determined either by using stereotactic ventriculography or reconstruction from three-dimensional (3D) MR images. During the surgical procedure, electrode implantation was guided by single-unit microrecordings on multiple parallel trajectories and by clinical assessment of stimulations. The site where the optimal functional response was obtained was considered to be the best target. Computerized tomography scanning was performed 3 days later and the scans were combined with preoperative 3D MR images to transfer the position of the best target to the same system of stereotactic coordinates. An algorithm was designed to convert individual stereotactic coordinates into an all-purpose PC-referenced system for comparing the respective accuracy of each method of targeting, according to the position of the best target.

Conclusions. The target that is directly identified by MR imaging is more remote (mainly in the lateral axis) from the site of the optimal functional response than targets obtained using other procedures, and the variability of this method in the lateral and superoinferior axes is greater. In contrast, the target defined by 3D MR imaging is closest to the target of optimal functional response and the variability of this method is the least great. Thus, 3D reconstruction adjusted to the AC–PC line is the most accurate technique for STN targeting, whereas direct visualization of the STN on MR images is the least effective. Electrophysiological guidance makes it possible to correct the inherent inaccuracy of the imaging and surgical techniques and is not designed to modify the initial targeting.

KEY WORDS • Parkinson disease • subthalamic nucleus • deep brain stimulation • stereotactic targeting • magnetic resonance imaging • electrophysiological monitoring

In cases of advanced Parkinson disease, the degree of improvement in motor symptoms attained by high-frequency stimulation of the STN depends, to a large extent, on the accuracy of electrode placement. The STN is normally located using an atlas of brain structures and preexisting data obtained by teams experienced in STN stimulation. The coordinates of the target are referenced to a line drawn from the AC to the PC. The location of the AC–PC line may be obtained either by using stereotactic ventriculography or 3D MR imaging reconstruction. A specific x-ray apparatus is needed to perform stereotactic ventriculography and this invasive procedure could be replaced by 3D MR imaging reconstruction, if equivalent precision could be obtained. Neither of these two techniques takes into account possible individual variations in STN localization according to the AC–PC-referenced positions, however, and thus direct identification of the STN on MR images theoretically seems to be the most suitable method if adequate MR imaging sequences are used. Because of the inherent imprecision of whatever imaging technique is used, however, microrecordings and intraoperative stimulations performed on multiple parallel trajectories are considered mandatory to improve localization of the optimal target site. Therefore, the targeting procedures are complex and time consuming, involving long patient immobilization and possible related complications.

By assessing the relative precision of each technique, the aim of this study was to alleviate the complexity of the targeting procedures and thus reduce, if possible, the duration of surgical procedures.

Clinical Material and Methods

Patient Population

Fourteen patients, each of whom had a long history of
Parkinson disease, underwent stereotactic bilateral implantation of a stimulating electrode into the STN. The study group consisted of nine men and six women with a mean age ± standard deviation of 60 ± 6.3 years. The onset of the disease occurred at a mean age of 43.9 ± 6.6 years, providing a mean disease duration of 15 ± 6.1 years in these patients. The mean Schwab and England stage was 40 ± 17.8 in patients during the off period and 82.3 ± 16.4 in the on period. All patients were evaluated in the morning after being deprived of antiparkinsonian medication since 5 p.m. on the preceding day. Following this evaluation, the patients were given a single dose of levodopa that corresponded to 150% of their usual standard morning dose and again were evaluated. The mean Unified Parkinson’s Disease Rating Scale Part III (motor) score was 54.5 ± 14 and 15 ± 8.5 during off and on periods, respectively. Seven patients were unable to walk alone in the off condition, whereas all patients could do so in the on situation. Treatment of all patients included levodopa (mean dose 914 ± 375 mg/day) and dopaminergic agonists (mean dose of Requip 11.4 ± 6 mg/day). Five patients occasionally used subcutaneous apomorphine and four of them were treated with tolcapone.

Procedures for STN Targeting

Reference System of Spatial Coordinates. A Leksell frame was positioned after the patient had been given a local anesthetic agent. Ear bars were used to match, as far as possible, the median axis of the brain with the median axis of the stereotactic frame. Thereafter, the x (lateral), y (anteroposterior), and z (superoinferior) coordinates of brain structures were referenced into the Leksell system, whatever the source of images (MR images or x-ray films).

Acquisition of MR Sequences. Magnetic resonance imaging was performed using a 1.5-tesla unit, which was equipped with a Leksell G stereotactic frame support and had been adjusted to reduce image distortion to a minimum. Three sequences were performed successively. The first was a 3D T1-weighted acquisition of 120 contiguous axial slices, 1.3-mm thick, which was obtained using 3D gradient-echo imaging (TR 20 msec, TE 4.6 msec, flip angle 30°, number of excitations 1, matrix 256 × 256, field of view each contact. At the end of this period, the best contacts were selected on each side. In some patients, an optimal result was obtained using a combination of two or more contacts for one electrode. In these cases, the effective stimulation point was considered to be located at an equal distance between the two effective contacts. No bipolar stimulation was used in any patient. In all patients, except three who declined, sustained-release levodopa (daily dose 250–375 mg) was given secondarily. Patients were reevaluated at 1 month postoperatively. Adjustments in stimulation parameters were rarely necessary. Three months later, all patients performed a complete levodopa clinical test.
230 mm, and acquisition time 10 minutes 25 seconds). The goal of the second acquisition was to identify the STN directly. This sequence was a double-echo $T_2$-weighted acquisition of 13 coronal slices obtained using two-dimensional spin-echo imaging (TR 2200 msec, TEs 50 msec and 120 msec, number of excitations 2, matrix $205 \times 256$, field of view 260 mm, and acquisition time 13 minutes 41 seconds). For all three sequences, the phase-encoding direction and frequency encoding were set up right to left and feet to head, respectively.

The slices obtained were 4 mm thick because at a smaller thickness the STN was not visible. The 4-mm thick coronal slices are efficient for determining superoinferior or lateral coordinates, but not for determining anteroposterior coordinates because of their thickness. The third acquisition was a $T_2$-weighted axial sequence obtained to visualize the anterior boundary of the red nucleus. This boundary defined the anteroposterior coordinate of the STN, which was not determined by the former coronal $T_2$-weighted MR imaging acquisition.

**Stereotactic Ventriculography.** The position of the frame was adjusted in an orthogonal teleradiographic apparatus. To refer spatial coordinates obtained from x-ray films in the Leksell system, frontal and lateral teleradiography was performed using an adaptation of the Leksell CT scan box. Two landmarks visible on x-ray films were indicated on the CT scan box as they corresponded, respectively, to the point defined by the coordinates $y = 100$ and $z = 100$ on the lateral view and the point defined by the coordinates $x = 100$ and $z = 100$ on the frontal view (Fig. 1A and B). Thus, spatial coordinates of brain structures observed on x-ray films may be converted into the Leksell system by superimposition of the ventriculographic image and the marked x-ray film (Fig. 1). To avoid brain shift by modifications of ventricular volumes, an equivalent volume of cerebrospinal fluid was withdrawn before injecting the contrast agent.

**Determination of STN Coordinates**

**Direct STN Identification.** The lateral and superoinferior coordinates (x and z values, respectively) of the STN were determined on coronal $T_2$-weighted MR images (Fig. 2A). Because of the thickness of the slices, it was impossible to determine accurately the anteroposterior STN coordinate (the y value). Thus, the anteroposterior STN coordinate was defined according to the position of the anterior border of the red nucleus on the axial $T_2$-weighted MR imaging, as described by Bejjani, et al. (Fig. 2B).

**Indirect Localization Achieved Using Ventriculography.** The STN coordinates were considered to be 10.8 mm anterior to the PC on the AC–PC line, 3.3 mm under the AC–PC line, and 12 mm lateral to the AC–PC line. The targets were defined on the x-ray film and the x, y, and z values were calculated according to the frontal and lateral landmarks of the CT scan box (Fig. 1C and D).

**Indirect Localization Achieved Using the AC–PC Line-Based MR Imaging Reconstruction.** The 3D MR images were transferred to workstations. The AC–PC line was identified after sagittal 3D reconstruction. Parallax errors were corrected using specific software. This made it possible to adjust the reconstruction to the AC–PC line (Fig. 3A). The STN target was defined using the same coordinates that were selected for ventriculography (Fig. 3B).

**Surgical Procedure**

The averaged values of the x, y, and z coordinates obtained from the different methods of targeting were used to define the central trajectory. The trephination opening was obturated by surgical wax to avoid any leaking of cerebrospinal fluid. Four parallel outer trajectories, separated by 2 mm from the central one, were determined using a custom-made apparatus. Single-unit neuronal microrecordings were performed from 5 mm above to 5 mm beyond the theoretical target. The final implantation site of the electrode placed for long-term stimulation was guided by the discharge frequency, neuronal pattern, and presence of the sensory receptive field as well as by clinically positive or adverse effects induced by the stimulations. The mean duration for bilateral implantation was 10 hours. Electrodes were connected to a pulse generator (Itrel II for the first five patients and Kinetra for the nine others) 6 days after implantation.

**Image Fusion and Coordinate Conversion**

The cerebral CT scan was obtained 3 days after implantation of the electrodes to identify their locations. The acquisition consisted of contiguous 3-mm slices with a matrix of $512 \times 512$ and a field of view of 250 mm under conditions of neuronavigation (gantry tilt of 0°). Images were
combined with the preoperative $T_1$-weighted 3D MR images by using image correlation software on a workstation (Fig. 4). These fusions were accepted only if the mean errors calculated by the software were less than 0.7 mm. Coordinates of the most efficient plot were calculated into the preoperative Leksell reference system to compare targets and electrode location. To allow comparisons between patients, coordinates of targets defined by the three different methods and the coordinates of the plot of the electrode providing the best clinical result were recalculated so that they could be referred to the PC position, which was considered an invariant point. The conversion from the Leksell system of reference to the PC position required the design of a specific algorithm detailed in the Appendix. Thus, it was possible to calculate the positions of the targets obtained using the three imaging methods according to the position of the electrode contact that provided the best clinical result.

The distance between targets and the final position of the electrode was not calculated using absolute values. In this way, it was possible to determine the direction of variation by the positive or negative result. When calculating means, values of opposing signs could cancel each other, thereby giving the erroneous impression that the initial targets and electrodes could be superimposed. Fortunately, by using ANOVA we were able to check this hypothesis. If they were not superimposable, the variation between the target position and the electrode would be great and vice versa.

**Statistical Analysis**

Variances were compared using the F test. Mean coordinate locations of each target were compared using ANOVA or the paired Wilcoxon signed-rank test if the variances were different. To correct for the number of analyses and to avoid type I errors, a probability value of 0.01 was considered significant.

### Results

**Comparison of the Distances Between the Target Defined by the Optimal Functional Response and the Targets Defined Using Imaging Methods**

The divergences varied according to the imaging method used. Mean distances between the target defined by the optimal functional response (best clinical response) and those defined by the three imaging methods were 2.61 ± 1.17, 2.85 ± 1.19, and 3.92 ± 1.92 mm (mean ± SEM) 3D MR imaging, ventriculography, and direct target MR imaging, respectively. The distance between the target defined by the optimal functional response and the targets defined by 3D MR imaging or ventriculography were significantly shorter than the distance between the target defined by the optimal functional response and that directly identified by MR im-

### Table 1

**Analysis of target coordinates with respect to the PC**

<table>
<thead>
<tr>
<th>Target</th>
<th>Coordinates (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Lat</td>
</tr>
<tr>
<td>statistically determined</td>
<td>12</td>
</tr>
<tr>
<td>theoretical target†</td>
<td></td>
</tr>
<tr>
<td>functional response</td>
<td>12.33 ± 1.34</td>
</tr>
<tr>
<td>direct MR imaging</td>
<td>12.86 ± 1.82</td>
</tr>
<tr>
<td>ventriculography</td>
<td>12.14 ± 0.92</td>
</tr>
<tr>
<td>3D MR imaging</td>
<td>12.04 ± 0.35</td>
</tr>
<tr>
<td>result of MLA (p value)‡</td>
<td></td>
</tr>
<tr>
<td>between i &amp; f</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>between f &amp; v</td>
<td>0.44</td>
</tr>
<tr>
<td>between v &amp; i</td>
<td>0.07</td>
</tr>
<tr>
<td>variance analysis (p value)§</td>
<td></td>
</tr>
<tr>
<td>between v &amp; f</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>between v &amp; i</td>
<td>0.011</td>
</tr>
<tr>
<td>between i &amp; f</td>
<td>&lt;0.001</td>
</tr>
</tbody>
</table>

* Values are expressed as means ± SEMs. For lateral coordinates the larger the value, the more lateral the target. For anteroposterior coordinates a positive value indicates the target is anterior to the PC. For superoinferior coordinates a negative value indicates the target is below the AC–PC line. Abbreviations: f = indirect target localization attained using the AC–PC line defined by 3D MR imaging reconstruction; i = direct STN identification on MR images; MLA = means location analysis; v = indirect target localization attained using ventriculography.

† Determined by Benabid, et al.
‡ Obtained using the paired Wilcoxon signed-rank test.
§ Obtained using an F test.

### Sources of Supplies and Equipment

The Leksell stereotactic frame was purchased from Elekta Instruments (Stockholm, Sweden). The MR imaging unit was obtained from Philips (Best, The Netherlands). The Surgiplan computerized planning workstation (Elekta Instruments) and the StealthStation workstation (Medtronic Sofamor Danek, Minneapolis, MN) were both used for indirect localization of the STN during 3D MR imaging reconstruction. Medtronic (Minneapolis, MN) provided the deep brain stimulator (DBS model 3389 electrode) as well as the Itrel II and Kineta pulse generators. ImMerge image correlation software, which was used on the StealthStation, was acquired from Zmed, Inc. (Ashford, MA).
Targeting the subthalamus for stimulation in cases of Parkinson disease

aging \(p = 0.003\). Thus, the use of the aforementioned STN coordinates according to the AC–PC line was more reliable than coordinates representing direct identification of the STN on MR images. Reconstruction of the AC–PC line by using 3D MR imaging was more reliable than using ventriculography, although the difference between these two methods was miniscule (inframillimetric) and not significant.

**Comparison of STN Coordinates Providing the Different Methods of Targeting**

The study of the three axes of divergence located in the PC-referenced system showed that the target directly identified by MR imaging was located significantly more lateral to the AC–PC line than the target defined by the 3D MR imaging (12.86 ± 1.82 and 12.04 ± 0.35 mm from the AC–PC line, respectively \(p < 0.01\), and that the target was located significantly more anterior to the PC than the other targets (10.30 ± 0.99 mm compared with 8.78 ± 1.18 for the target directly identified and 8.8 ± 1.19 for the target defined by ventriculography \(p = 0.001\), respectively) (Table 1).

The variances (that is, the square of the SEM) were used to study the precision of the targeting technique. These variances were calculated using absolute coordinates in the PC-referenced system. The divergences varied according to which imaging method was used. The variances of the target coordinates defined by direct MR imaging on the lateral (x) and superoinferior (z) axes determined by T1-weighted coronal MR imaging were significantly greater than those of the target defined by 3D MR imaging (2.32 mm for the x and 4.1 mm for the y axis compared with 0.12 mm for the x and 0.1 mm for the z axis, respectively \(p < 0.001\)), but not greater than those on the anteroposterior (y) axis, which was determined by the anterior border of the red nucleus; that remained an accurate landmark for targeting. The variances of the target coordinates defined by 3D MR imaging on the lateral (x) and superoinferior (z) axes were significantly lower than those defined by ventriculography (0.12 mm for the x and 0.1 mm for the z axis compared with 0.84 mm for the x and 1.98 mm for the z axis, respectively \(p < 0.001\)), because of the adjustment of the 3D reconstruction to the AC–PC line.

**Role of Electrophysiological and Clinical Guidance**

Electrophysiological and clinical guidance modified electrode implantation for 14 (50%) of approximately 28 electrodes: in 10 cases electrodes were implanted in the 2-mm posterior track and in four cases in the 2-mm medial track. Despite these implantations, target coordinates defined by electrophysiological and clinical guidance were close to the statistically determined target defined by Benabid \(^4\) (differing by only 0.33 mm in the lateral axis, 0.1 mm in the anteroposterior axis, and 0.6 mm in the superoinferior axis; Table 1), and there was no statistical difference between the coordinates of these two targets.

The fact that the final target selected after electrophysiological correction was close or similar to the preoperative target raises questions regarding the role of intraoperative electrophysiology. The aim of intraoperative electrophysiology is not to define a target that is different from that established during preoperative planning. If this were the case, the final target selected after electrophysiological correction would be different from the preoperative targets and would be located farther from them. The definitive electrode would therefore be at a distance from the target at least equal to that of the correction obtained from the electrophysiology, that is, 2 mm. This was not the case, and thus electrophysiology made it possible to rectify the error and to place the electrode as close as possible to the initial target. This has one of two consequences: 1) if the targets localized by preoperative planning and electrophysiology are the same, there is no difference between anatomical and functional targets; and 2) if the surgical technique induces an error, it is corrected by electrophysiology.

**Discussion**

The results of this study show that the target directly defined by MR imaging was located more lateral and the target defined by 3D MR imaging more anterior than the other targets. The distance between the targets defined by imaging methods and the target defined by the optimal functional response was greatest when direct MR imaging was used and smallest when 3D MR imaging was used. Analysis of variance showed that targeting accuracy was best when 3D MR imaging was used for targeting and worst when direct visualization by MR imaging was used. The coordinates of the target after electrophysiological and clinical guidance were close to the statistically determined coordinates defined by Benabid, et al.\(^4\)

Direct visualization of the STN on MR images was well described by Bejjani, et al.,\(^2\) who relied on coronal T1-weighted MR images to obtain superoinferior and lateral coordinates. The present study confirms that it is possible to localize the STN by using coronal T1-weighted MR imaging, but the localization obtained is less accurate than that attained using other techniques with regard to the variance value, which is always larger in these two axes. On the other hand, determination of the anteroposterior coordinate of the STN, based on the anterior border of the red nucleus on axial images, seems to be very effective. The target defined using this technique is more lateral than other STN targets. Although such a difference (approximately 1 mm) is not important for localization of the globus pallidus internus because of the size of that nucleus, the same is not true for the STN, which is small and ovoid.\(^2\)

In our opinion, using the AC–PC line to define the target is the gold standard technique.\(^3\) There are two different methods available to determine target based on the AC–PC line: ventriculography, which is the oldest and most invasive examination, and MR imaging with 3D reconstruction, which is less invasive and can correct head tilt or rotation of the head in the stereotactic frame. For Schuurman, et al.,\(^18\) there is no difference between the two techniques. This supposes that the stereotactic frame is aligned parallel to the AC–PC line.\(^15\) Because the statistical formulas for target locations defined by ventriculography and 3D MR imaging are the same (10.8 mm anterior to the PC), the significant difference between these two targets on the anteroposterior axis shows the importance of rotation correction on the 3D reconstruction. Thus, an adjustment of the 3D reconstruction to the AC–PC line may be used to correct head ro-
tation in the stereotactic frame. This cannot be corrected using ventriculography for target definition.

We determined the functionally optimal target, which is defined by the best contact of the definitive electrode implanted under electrophysiological and clinical guidance. It is impossible to prove this without intraoperative microrecordings, and certain proof will be possible only when autopsy studies are performed. If we accept the hypothesis that clinical effects are due to STN stimulation, however, in view of the volume of brain that is explored using electrophysiology and clinical testing, we can surmise that the most effective contact of the definitive electrode is in the anatomical STN. Thus, electrophysiological and clinical guidance for definitive electrode positioning may be used to correct the target from the stereotactically derived location of the STN to its anatomical location. A number of teams use electrophysiological guidance to localize lesions or electrodes correctly in the thalamus, subthalamus, or globus pallidus internus.1,6–8,12,16,17 For Gross and colleagues11 there is a mean change and become located farther from the statistically determined ventriculography for target definition.

There are three possible explanations for this mismatch between preoperative targets and the anatomical STN is the functionally optimal target. For Voges and associates19 these two targets are different and the latter is a few millimeters above the anatomical STN. In our opinion, it is difficult to prove this without intraoperative microrecordings, and certain proof will be possible only when autopsy studies are performed. If we accept the hypothesis that clinical effects are due to STN stimulation, however, in view of the volume of brain that is explored using electrophysiology and clinical testing, we can surmise that the most effective contact of the definitive electrode is in the anatomical STN. Thus, electrophysiological and clinical guidance for definitive electrode positioning may be used to correct the target from the stereotactically derived location of the STN to its anatomical location. A number of teams use electrophysiological guidance to localize lesions or electrodes correctly in the thalamus, subthalamus, or globus pallidus internus. For Gross and colleagues there is a mean change and become located farther from the statistically determined ventriculography for target definition.

There are three possible explanations for this mismatch between stereotactically derived or MR imaging–defined targets and electrophysiological determination or anatomical targets. 1) Target coordinate determination is not adequate and, thus, electrophysiology may correct this inaccuracy. This opinion is held by many; however, according to this hypothesis, after electrophysiological guidance the targets change and become located farther from the statistically determined target defined by Benabid, et al.4 This hypothesis cannot explain why targets selected after electrophysiology and statistically determined targets have the same location. 2) The mismatch between preoperative targets and the target selected after electrophysiology might be due to a shift in brain structures during the surgical procedure; however, unlike the cortex, the gray nucleus cannot shift location during the surgical procedure. 3) The accuracy of target coordinate determination is efficient, but the surgical technique performed using the frame or the duration of surgery induces an inaccuracy that is corrected by electrophysiology. The latter hypothesis might explain why the target is close to the statistically derived target after electrophysiological guidance.

**Conclusions**

Statistical determination of the coordinates of STN location remains the gold standard, but the use of 3D MR imaging to determine the location of the AC–PC line could replace the use of ventriculography, because the former is less invasive and can correct head rotation within the stereotactic frame. Direct determination of STN coordinates based on coronal T1-weighted MR imaging is the least effective technique. After electrophysiological guidance the target that is finally selected is close to the statistically determined target.

**Appendix**

**Transcription of the Stereotactic Frame Coordinates (O, x, y, and z) into AC–PC Coordinates (PC’x’, y’, and z’)**

If the coordinates of the PC, AC, and up points have these coordinates in the stereotactic frame reference PC (x0, y0, z0), AC (x1, y1, z1) and, up (x2, y2, z2), if the unitary axis vectors from the AC–PC reference system (PCs’x’y’z’) are i’, j’, and k’ and if the unitary axis vectors from the frame reference system (Oxyz) are i, j, and k.

To transcribe frame coordinates into AC–PC coordinates, we need to use the vectors i’, j’, and k’, in the Oxyz system: $i' = ai + bj + ck$, $j' = ai + bj + ck$, and $k' = ai + bj + ck$.

To determine $i'$, the norm of the AC–PC vector is $n = \sqrt{(x_1 - x_0) + (y_1 - y_0) + (z_1 - z_0)}$

so that: $a_i = (x_1 - x_0)n$, $b_i = (y_1 - y_0)n$, and $c_i = (z_1 - z_0)n$.

To determine $k'$:

$k' = n' \cdot (CP_{up} - (CP_{up})^*) \cdot j'$, which is called V where $CP_{up}$ is the scalar product named $s$.

$s = (x_1 - x_0) \cdot a_i + (y_1 - y_0) \cdot b_i + (z_1 - z_0) \cdot c_i$.

thus, $V = (x_1 - x_0 - s \cdot a_i)i + (y_1 - y_0 - s \cdot b_i)j + (z_1 - z_0 - s \cdot c_i)k$.

The norm of V is named $n'$.

$n' = \sqrt{(x_1 - x_0 - s \cdot a_i)^2 + (y_1 - y_0 - s \cdot b_i)^2 + (z_1 - z_0 - s \cdot c_i)^2}$

thus, $i'' = \sqrt{V} \cdot n'$ so that:

$a_i = (x_1 - x_0 - s \cdot a_i)n'$, $b_i = (y_1 - y_0 - s \cdot b_i)n'$, and $c_i = (z_1 - z_0 - s \cdot c_i)n'$.

To determine $j''$:

$i''$ is the vector product of $j'$ and $k'$ (we could use $-i''$) so that:

$a_i = b_i * c_i - b_i * c_i$, $b_i = a_i * c_i - a_i * c_i$, and $c_i = a_i * b_i - a_i * b_i$.

To determine the $x'y'z'$ line matrix of coordinates in the new AC–PC reference system, we can determine the rotation matrix R:

$R = \begin{bmatrix} a_i & a_2 & a_3 \\ b_1 & b_2 & b_3 \\ c_1 & c_2 & c_3 \end{bmatrix}$

If R is the inverse matrix of R,

$\begin{bmatrix} x' \ y' \ z' \end{bmatrix} = R^{-1} \begin{bmatrix} x - x_0 \ y - y_0 \ z - z_0 \end{bmatrix}$

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**References**


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Address reprint requests to: Emmanuel Cuny, M.D., Service de Neurochirurgie, Hôpital Pellegrin, CHU de Bordeaux, Place Amélie-Raba-Léon, 33076 Bordeaux, France. email: emmanuel.cuny@chu-bordeaux.fr.