Use of the LandmarX™ Surgical Navigation System in Lateral Skull Base and Temporal Bone Surgery

Hinrich Staecker, M.D., Ph.D.,¹ Bert W. O'Malley, M.D.,¹
Howard Eisenberg, M.D.,² and B. Emmerich Yoder, M.S.³

ABSTRACT

Despite the widespread availability of surgical navigation devices, their use in lateral skull base and temporal bone surgery has been limited. Problems with current systems include difficulty of use and inadequate accuracy. We present a series of cases using the LandmarX™ surgical navigation system as an adjunct for lateral skull base and temporal bone procedures. This infrared emitting diodes (IRED)-driven system has a post that carries the IREDs and bypasses the need to place the patient in a Mayfield head holder. This configuration allows greater mobility of the surgical field. Registration of the patient can include a combination of fiducial and anatomic landmarks that significantly increase accuracy compared to fiducial calibration alone. We introduced the use of the lateral process of the malleus as a landmark, thereby increasing accuracy within the temporal bone to a range of 0.9 to 1.5 mm. We used the system on encephaloceles, glomus tumors, meningiomas, and schwannomas, and revision surgery for chronic otitis media. It decreased operating time, allowed more effective use of "keyhole" approaches, and increased safety. As the availability and flexibility of these systems increase, their use should become the standard of care in revision temporal bone and lateral skull base procedures.

KEYWORDS: Lateral skull base surgery, temporal bone surgery

The principles of stereotaxy are more than a century old, but their viable application to most surgery was delayed until the development of computed tomography (CT) and magnetic resonance

imaging (MRI). During the 1980s frame-based stereotactic systems were developed to facilitate the efforts of neurosurgeons performing intracranial and spinal procedures. The development of frame-

Skull Base, volume 11, number 4, 2001. Address for correspondence and reprint requests: Hinrich Staecker, M.D., Department of Otolaryngology, Head and Neck Surgery, University of Maryland Medical System, 16 South Eutaw Street, Suite 500, Baltimore, MD 21201-1619. E-mail: hstaecker@surgery1.umaryland.edu. Departments of ¹Otolaryngology, Head and Neck Surgery, and ²Neurosurgery, University of Maryland School of Medicine; ³University of Maryland School of Medicine, Baltimore, Maryland. Copyright © 2001 by Thieme Medical Publishers, Inc., 333 Seventh Avenue, New York, NY 10001, USA. Tel: +1(212) 584-4662. 1531-5010,p;2001,11,04,245,256,ftx,en;sbs00237x.

less image-guided systems and the application of this technology to otolaryngology accelerated during the 1990s.¹ The use of this technology for procedures involving the paranasal sinus and anterior skull base has been the subject of many studies. Despite the widespread availability of surgical navigation devices, their use and study in lateral skull base and temporal bone surgery has been limited.²⁻⁹

Temporal bone and lateral skull base surgery holds the potential to benefit tremendously from frameless image-guided systems for four reasons. First, the anatomy of the temporal bone and lateral skull base is fixed along bony landmarks. Thus, structures are less prone to shift caused by intraoperative changes such as edema and the removal of cerebrospinal fluid (CSF).^{7,10} Second, the complex anatomy of the temporal bone and skull base contains numerous vulnerable structures. Surgery in this area is accompanied by a high risk of complications with possible damage to the facial nerve, cochlea, semicircular canals, dura, and carotid artery.¹¹ Third, the anatomy can be variable and subject to alterations caused by disease or prior surgeries. Therefore, anatomical landmarks used to guide temporal bone and lateral skull base surgery can be absent or misleading.² Finally, substantial time and effort during temporal bone and lateral skull base surgery are spent identifying and dissecting vital structures. More time-efficient and less invasive surgery may be possible if the location of vital structures can be ascertained with the aid of a surgical navigation device. Problems cited in the use of surgical navigation for temporal bone surgery include inadequate accuracy, cumbersome equipment, unsubstantiated additional costs, and added operative time.^{12,13}

This article presents our experience using the LandmarXTM surgical navigation system as an adjunct to temporal bone and lateral skull base procedures. The LandmarX is an optically based surgical navigation system that digitizes information gained from preoperative imaging with spatial information gained from the detection of infrared-emitting diodes (IREDs). The IREDs are attached

to various instruments and to a patient reference device consisting of either a skull post, a sinus head holder, or a Mayfield head holder. This system was used during the surgical treatment of encephaloceles, glomus tumors, meningiomas, and schwannomas as well as with revision surgery for chronic otitis media. This article addresses the advantages and disadvantages of using the system, describes techniques that can improve attainable accuracy under surgical conditions, compares the use of the skull post to the Mayfield head holder, discusses the effect of different registration strategies on accuracy, and outlines important areas for further research.

MATERIALS AND METHODS

This article details the experience of three surgeons at the University of Maryland Medical Center using the LandmarX surgical navigation system (Medtronic Xomed, Jacksonville, FL) during temporal bone and lateral skull base procedures. Included in the treatment group are encephaloceles, glomus tumors, meningiomas, schwannomas, and revision surgeries for chronic otitis media. Briefly, the LandmarX system consists of a Silicon Graphics O₂ workstation, optical digitizing camera, sterile surgeon interface touch screen, Y-shaped reference arc, planar passive probe, and fine probe. It can be used with a Mayfield head holder, skull post (Fig. 1), or sinus head holder.

The LandmarX system uses optical information to correlate a three-dimensional (3-D) computer image of a patient constructed from preoperative CT or MRI with real-time surgical space. Before surgery, each patient had 5 to 10 adhesive fiducials placed across the brow and behind an ear. Each patient was scanned in one of our hospital's four CT scanners (Toshiba Xpress/SX, GE High Speed Advantage HAS, GE Prospeed, and Siemens Plus4) or two MRI scanners using 1-mm axial cuts. The technicians were instructed to include the entire maxilla including the teeth in the scan.

Figure 1 Skull post (arrow) and infrared emitting diode (IRED). This unit is secured to the skull through a separate incision using three screws. It allows mobility of the surgical field and access to the temporal wall and lateral skull base.

The operating room was set up with the optical-digitizing camera array placed 6 feet from the operating table. Personnel and equipment were positioned so the camera had an unimpeded view of the surgical field. The workstation and sterile surgeon touch pad were positioned on the side of the room opposite the camera. Before the patient's entry into the room, the patient's radiological data were transferred to the surgical navigation system workstation. The images were reviewed for proper orientation and total inclusion of the surgical field. The threshold was adjusted so that the threshold line coincided with the desired anatomy, and the 3-D model was built. To complete the preoperative tasks, the 3-D model was edited as needed and our desired anatomical landmarks and fiducials were registered on the workstation using the cross-hairs on the three two-dimensional (2-D) views. The anatomic reference points used during the surgery include the tragus, antihelix, nasion, lateral canthus of both eyes, the groove of the incisors, nasal labial angle, and, in some cases, the lateral process of the malleus.

Five patients were placed in a Mayfield head holder, and six patients had a skull post placed. For the latter, an incision was made anterior to the at-

tachment of the temporalis muscle on the ipsilateral parietal bone while the patient was under anesthesia. The base of a specifically designed skull post was laid against the parietal bone. Three holes were drilled using a 2-mm stopbit in the corresponding hole in the post's base, and the skull post was attached to the cranium using 2-mm screws. Before drilling, the 3-D reconstruction of the skull was examined to assure that the thickness of the cortical bone at the drilling site was adequate. The skull post has a X-shaped reference arc with four IREDs (Fig. 1). The previously selected, computer-registered points were correlated with their actual physical points using the blunt probe to identify fiducials and anatomical landmarks on the patient. Reference points for which we were unable to obtain a reasonable reference error were eventually omitted. Before surgery began, accuracy checkpoints were selected and the accuracy of the system was tested with a surface landmark.

Intraoperatively, the blunt probe was used to identify structures and to outline the extent of the pathology. Accuracy was assessed approximately every 15 to 20 minutes using the computer-generated predicted accuracy, accuracy checkpoints, and known anatomic points to prevent surgical errors if the accuracy had degraded the system. For the purposes of this article, accuracy refers to the deviating distance from the surface accuracy checkpoint.

RESULTS

In the 11 temporal bone and skull base procedures in which the LandmarX was used, the surgeons found it to be useful (Table 1). During the four revision mastoidectomies, the system facilitated surgery by delineating the extent of the dehiscence of the tegmen, planning the approach, and identifying residual infected air cells. The system was particularly useful when operating on previously obliterated mastoid cavities. In the treatment of a glomus jugulare, LandmarX helped identify the fa-

Table 1 Image-Guided Lateral Skull Base/Temporal Bone Cases

Patient History	Diagnosis	Survey	Approach	LandmarX™ Use
44 year old with recurrent draining ear after previous mastoid surgery	Chronic otitis media and encephalocele	Revision mastoidectomy; middle fossa craniotomy	Skull post; CT	Delineation of area tegmen dehiscence allowing faster removal of disease
8 year old with chronic draining ear	Cholesteatoma with erosion into posterior fossa	Canal wall down mastoidectomy	Skull post; CT	Delineation of area of dehiscence
80 year old with preauricular mass and otalgia, history of radical mastoidectomy with bone dust obliteration	Neuroendocrine carcinoma of the temporal bone	Temporal bone resection	Skull post; CT	Identification of labyrinth in mass tumor and reformed bone
30 year old with pulsatile tinnitus	Glomus jugulare	Infratemporal fossa approach	Skull post; CT	Identification of facial nerve using image-guided nerve probe
50 year old with recurrent chronic otitis media with four previous operations	Chronic otitis media	Revision, mastoidectomy	Skull post; CT	Identification of residual infected air cells, identification of dehiscent tegmen
41 year old with chronic draining ear and otalgia	Chronic otitis media and petrous apex cyst	Canal wall down Mastoidectomy and drainage of petrous apex	Skull post; CT	Targeting of infracochlear approach
44 year old with orbital apex tumor	Meningioma	Orbitozygomatic craniotomy	Mayfield head holder; MRI	Identification of optic nerve
58 year old with hearing loss	Acoustic neuroma	Middle fossa approach	Mayfield head holder; CT	Localization of IAC in middle fossa
6 year old with facial nerve paralysis	Jugular schwannoma 5.5 cm	Translabyrinthine excision	Mayfield head holder; MRI, MRA	Localization of dehiscent carotid artery
68 year old with headaches	5-cm petrous meningioma	Retrolabyrinthine approach	Mayfield head holder; MRI	Delineation of tumor extension
70 year old with brain-stem compression	Pontine meningioma	Far-lateral approach	Mayfield head holder; MRI, MRA	Identification of vascular anatomy

cial nerve for preservation during the infratemporal fossa approach. In a temporal bone resection for a neuroendocrine tumor, the system helped identify the labyrinth in a mass of tumor and reformed bone. The system helped locate the petrous carotid artery in a large jugular foramen schwannoma

(Fig. 2). During a far-lateral approach to a pontine meningioma, the LandmarX system helped identify the vascular anatomy, providing greater assurance in avoiding neurovascular damage. During a retrolabyrinthine approach to a petrous meningioma, the system allowed more thorough removal

Figure 2 The surgical navigation system localizes the carotid artery in a large schwannoma of the jugular foramen, thereby defining the anterior limits of resection.

of the tumor by delineating the tumor extension. No major complications occurred during any procedure.

During our cases, the computer determined accuracy 10 cm from the centroid to be 2.0 mm to 3.2 mm in cases using fiducial registration with a Mayfield head holder and 1.2 mm to 2.4 mm in cases using combined anatomic landmarks/fiducial registration with a skull post. The combined use of fiducials and anatomic landmarks doubled accuracy compared to fiducial calibration alone. The use of the lateral process of the malleus as a landmark increased our accuracy to the submillimeter range with the temporal bone and to 0.9 to 1.5 mm within a 10-cm operating sphere (Fig. 3).

DISCUSSION

With the introduction of any new technology to a field, a period of adjustment is inevitable. Questions surrounding the proper use of the technology

need to be addressed, and shortcomings must be remedied before effective widespread use is possible. Surgical navigation systems and temporal bone surgery are no different. Since the beginning of anatomical study, surgeons have used anatomical landmarks to guide their efforts. With the emergence and improvement of this technology, stereotactic surgical navigation systems hold the promise of developing into a tool that will indicate a surgeon's exact location in the body during any part of a procedure.

The recurrent theme of additional cost, time, inconvenience, and effort related to use of stereotactic navigation highlights the importance of selecting proper cases for its use.^{4,12,13} When this technology is applied to endoscopic sinus surgery, surgeons have found it difficult to determine which patients would benefit from its use until surgery was in progress. Ideally, the device would be available for all patients.¹⁴ Bingaman et al. studied the cost-effectiveness of image-guided stereotactic craniotomies. Lengths of stay, hospital costs, and operative times were shorter in all cases except

Figure 3 Use of a combination of anatomic and stick-on fiducials results in predicted accuracy of 1 mm throughout the entire surgical field in the resection of an orbital apex-zygoma meningioma.

those involving gliomas. However, recurrent gliomas were treated more efficaciously with this technology than without it and only primary gliomas were treated less efficiently.¹⁵ These findings illustrate the importance of appropriate candidate selection. Likewise, image-guidance may be appropriate for revision mastoidectomies but not for primary mastoidectomies. Some surgeons believe that this technology is most useful when anatomy is distorted from disease or prior surgery.¹² However, most temporal bone procedures could benefit from surgical navigation systems by enhancing safety and confirming the location of vital structures. The appropriate indications for the use of this technology in lateral skull base and temporal bone surgeries have yet to be determined. In the current study the consensus among surgeons was that use of the system decreased operating times, allowed more effective and accurate use of “key-hole” approaches, and increased the margin of safety during all procedures.

Roth et al. outlined five criteria for an effective surgical navigation system as it relates to sinus

surgery: (1) 2- to 3-mm accuracy, (2) elimination of the second CT, possibly through surface marking, (3) computer updates for head movement, (4) sensors applied to suction and dissecting instruments for greater flexibility, and (5) easy-to-operate devices to remove the need for a technician.¹⁴ Most of these criteria hold true for temporal bone surgery although an accuracy of 2 to 3 mm is inadequate because of the size of most structures in the temporal bone. LandmarX system seems to fulfill most of these criteria. It was possible to proceed with only anatomic landmarks, thus eliminating the need for a second CT as long as the first CT has 1-mm cuts. The system compensated for head movements because the skull post is rigidly attached to the skull. The system also was compatible with suction, dissecting, and nerve monitoring probes, which increased the convenience for the surgeons. Finally, the set-up and operation of the system were so simple that residents could complete most preoperative tasks. Furthermore, a sterile touch screen interface allowed the surgeons to control the system completely from the sterile surgical field.

The skull post offered a tremendous advantage. Using the skull post resulted in greater accuracy than using a Mayfield head holder and made the system applicable to routine temporal bone surgery. With the skull post in place, the surgeon had the freedom to change the position of the head during surgery and did not have to work around the presence of a head holder. The application of the skull post took less than 20 minutes, although patients did complain of postoperative pain at the site. Others have noted a deterioration in accuracy during the course of procedures in which Mayfield head holders were used, likely due to movement of the head relative to the head holder.^{7,12} Theoretically, the skull post set-up should be less prone to such deterioration because it is rigidly attached to the skull. Furthermore, placement of pins can shift fiducials, thereby introducing additional inaccuracy. The skull post should not cause this problem.

All patients with a skull post underwent CT, whereas all patients placed in a Mayfield head holder underwent MRI as the imaging modality except for one who underwent CT. However, the accuracy of other authors using MRI has been superior compared to CT.⁷ Consequently, this discrepancy would be expected to increase not decrease accuracy in patients placed in a Mayfield head holder. Thus, increases in accuracy gained from using a skull post may be greater than our data indicate.

The main issue surrounding the application of surgical navigation systems to temporal bone surgery is their limited accuracy. The temporal bone is an area that requires submillimetric accuracy but the accuracy of most systems is only within 3 mm.^{4,7,9,12} Submillimetric accuracy in cadaveric models has been reported, but not during actual surgeries of the temporal bone.^{2,16} Our predicted accuracy varied between 2.4 and 0.9 mm depending on the set-up used. However, accuracy approached less than 1 mm when a skull post and a mixture of anatomic landmarks and fiducials were used. For all stereotactic procedures, accuracy is greatest at the center of the sphere generated by the

computer from the registration points. Our accuracy at the accuracy checkpoint was less than 1 mm. The predicted accuracy value indicates the positional uncertainty of the system at the surface of a sphere with a 10-cm radius. In our experience, the computer-generated predicted accuracy correlated well with the observations of our surgeons. However, it is actually a measure of how easily the computer can correlate points in image space and surgical space. Thus, the value may not take into account error that depends on such factors as a poor scan or registration error.

Many authors have indicated the process of fiducial registration as the major source of error.^{1,2,4,7} This error is inevitable but should decrease as surgeons become more familiar with the system. As much as human error during fiducial registration decreases accuracy, careful fiducial placement and selection of which fiducials and anatomic landmarks to use during registration can increase accuracy. The goal is to center the sphere of accuracy in the surgical field. These systems match the image space points to the surgical space points via two processes—rotation and translation. The coordinate systems are first placed in proper orientation by the computer and then matched as closely as possible to build the 3-D model. The error is reported in two forms—mean fiducial error and predicted accuracy. The mean fiducial error is the average discrepancy between image-space points and surgical-space points with the best-fit rotation and translation of the surgical-space coordinate system onto the image-space coordinate system. The workstation computes the predicted accuracy from the uncertainty involved in the rotation process. Thus, a collinear set of fiducials gives the worst predicted accuracy because of the absolute rotational uncertainty, and a sphere of points around the desired surgical space gives the greatest predicted accuracy because of the computer's increased certainty during the rotation and translation process. The greatest accuracy will be at the centroid where it should theoretically be zero because that is the point around which the coordinate systems are

rotated. Accuracy deteriorates with distance from the centroid. Therefore, the accuracy at the surface checkpoint may not be indicative of true accuracy if the accuracy checkpoint is outside the sphere defined by the registration points. The greatest effort should be placed on selecting registration points that center the sphere of accuracy on the most vital structures in a procedure. Thus, points close to the surgical field, such as the ipsilateral tragus and ossicles, are preferable to points far from the field that can drag the sphere of accuracy away from it. Ideally, a surgeon would be able to select registration points that completely surround the surgical field, but there are anatomic limitations (Fig. 3).

Previous authors have pointed out the importance of placing fiducials on areas where the skin is least mobile; we also have found this technique to be important.¹⁴ Fiducials placed near the back of the head were associated with the greatest registration error and often were omitted. This phenomenon is likely the result of the looseness of the scalp compounded by the deformation caused

by the patient lying on the back of the head in the scanner.

Using the lateral process of the malleus as a landmark increases accuracy substantially. This anatomical landmark has been used in cadaveric studies and has proven helpful in our surgical experience.² The ossicles provide registration points close to the surgical field in a different plane than most other registration points.

Additionally, the lateral process of the malleus is easily registered in image space using cross-hairs on the 2-D views and in surgical space using the fine probe. Use of the lateral process increases the overall accuracy of the system by centering the sphere of accuracy over the surgical field, bringing the greatest accuracy where it is needed most (Fig. 4). The use of the surface merge feature, however, did not improve accuracy.

Although we have outlined methods effective in maximizing the accuracy of this system, any surgical navigation system has limitations that surgeons must consider. As the technology improves,

Figure 4 The lateral process of the malleus provides a useful landmark for both registration and checking accuracy. It is easily localized on CT and serves to pull the sphere of accuracy (circle) over the surgical field.

so will accuracy; however, there is no substitute for a thorough knowledge of the anatomy. Navigation systems serve surgeons by orienting them during surgery and identifying structures but are only an adjunct to years of experience and training.

Another feature of this system with which we have had only cursory experience is the ability to merge MRI and CT data to create a 3-D model. In a review of 26 skull base tumors, Kraus et al. found a clear benefit from combining CT and MRI data during preoperative assessment, especially in cases involving bony invasion.¹⁷ Thus, when using this system with a tumor that invades the temporal bone or skull base, such as a meningioma, it would provide optimal guidance to have these modalities merged, which this system is capable of doing. Further study is needed to confirm this advantage.

During temporal bone or lateral skull base procedures, surgical navigation systems are useful for identifying vital structures. This situation holds true for revision mastoidectomies, during which navigation proved useful in identifying and directing the opening of unexenterated air cells. Nadol found that unexenterated tegmental and sinodural air cells complicate more than half of mastoidectomies that fail secondary to chronic otitis media.¹⁸ During our four revision mastoidectomies, the system assured complete opening of air cells, including tegmental and sinodural cells, while avoiding damage to sensitive surrounding structures.

Sargent and Bucholz described the use of image-guided surgery to uncover the internal auditory canal during the middle fossa approach to acoustic neuromas.³ Similarly, the guidance system allowed us to uncover and more thoroughly remove an acoustic neuroma with a smaller incision, to decrease operative time, and to limit dissection. This trend of more effective keyhole surgery proved true in all the tumor resections.

In our opinion, the greatest advantages for using this system are decreased operative times, smaller incisions, decreased need for dissection, more thorough removal of pathology, greater safety

during complex procedures, and guidance when normal anatomic structures are obscured. Robinson et al. described theoretical advantages: decreased complications from avoiding injury to neurovascular structures, decreased blood loss, decreased costs with decreases in rate of complications and length of stay, decreased rate of recurrence and need for reoperation, and increased functional survival.⁸ Outcome analysis studies are necessary to confirm such theoretical advantages. The perceived increase in safety warrants further application and study of image-guided navigation in temporal bone and lateral skull base surgery.^{2-5,7-9,14} These systems also help residents train and accelerate their learning curve for procedures. Image-guided surgical navigation systems are expensive, necessitate additional imaging, require specific positioning in the operating room, and increase set-up time. As this technology continues to develop, the cost will likely decrease, the systems will become easier to use, and the required set-up time will decrease. Still, cost-benefit analysis will be crucial in this era of managed care. As the availability and flexibility of these systems increase, they should become a standard of care in lateral skull base procedures. In conclusion, we advocate the application of surgical navigation technology to temporal bone and lateral skull base surgery. Our experience indicates a high level of accuracy is attainable with the use of a skull post and a combination of fiducials and anatomic landmarks. In addition, using the lateral arm of the malleus as an anatomic landmark enhances accuracy even more.

NOTE

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COMMENTS FOR PUBLICATION

We enjoyed reviewing the early experience of Staecker et al. with a frameless stereotactic navigation device used for skull base surgery. Neurosurgeons have progressed beyond the honeymoon

period with frameless stereotaxy and are now evaluating it with a jaundiced eye for its true utility and cost.¹ More than a few hastily purchased frameless stereotactic systems are gathering dust in the corners of operating rooms because of excessive complexity and the "fiddle factor," increase in time and labor per case, and low volume of cases requiring stereotaxy at all.

This review is an important reaffirmation of the utility of these systems in skull base surgery.³ In particular, the temporal bone has resisted the advances of frameless stereotaxy because of the extreme precision needed to avoid the many small and tightly packed delicate structures of the region. This anatomical complexity has spawned a generation of neuro-otologists so intimately familiar with the temporal bone as to question the ability of any mechanical device to match their precision and acumen.

The usual limitations of frameless systems are exposed in this paper. Until a more advanced surface-fitting technology is developed, surgeons will continue to rely on fiducial and anatomic landmark registrations. The authors note the problems with ill-placed fiducial markers. How they were able to select which fiducial to discard from the registration is not discussed. The use of the lateral process of the malleus for registration helps to center the registration more medially and is an important contribution. No discussion is given of the degradation in accuracy as skull base surgery proceeds toward the center of the head or as the length of surgery increases. In addition, short shrift is given to the Achilles' heel of infrared emitting diode-based systems: loss of line-of-sight as the field becomes cluttered with equipment, particularly the operating microscope. The differences in imaging techniques and registration methods render the comparison of the Mayfield and the skull bar invalid. It would be interesting to see the accuracy of registration using the Mayfield with MR imaging and fiducial-anatomic landmark registration. It might obviate the need for drilling additional holes in the patient's skull. The authors

claim that operative time decreased, but this statement does not reflect the full amount of time required per case with any frameless system. Any surgeon who has stood helplessly over an intubated patient while the system fails to load the MR image that loaded perfectly the day before recognizes the true effort required to use frameless systems.

Surgeons have made it clear that they will not adopt technology that increases the effort of operating, increases the time associated with an operation, is not user-friendly, and does not improve results or operative technique.² In their series, Staecker et al. demonstrate that the Land-MarX system can be a useful addition to temporal bone skull base surgery. We have doubts that any system will surpass a talented neuro-otologist in exposing the internal auditory canal from the middle fossa or in locating the facial nerve in a badly diseased chronic ear case. Then again, we never thought Garry Kasparov would lose to Big Blue in chess.

John G. Golfinos, M.D.
J. Thomas Roland, M.D.
New York, New York

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