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Neuronavigation for Intracranial Meningiomas

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1. Introduction

According to its location, the surgical treatment of intracranial meningioma can be of considerable challenge for the neurosurgeon. Image-guided surgery essentially provides intraoperative localization for dynamic navigation and, also, improves the surgical planning. The continuous development of neuroimaging and computed technology promotes continuous improvement of navigation techniques and applications. In the last ten years, frameless image-guided surgery, also popularized as neuronavigation, is considered standard of practice by most neurosurgical centers around the world. Its usage can range from a simple craniotomy flap localization to a deep brain tumor resection respecting tract fibers, eloquent areas and neurovascular structures. In some cases, neuronavigation may not be necessary, but, if available, it should promote a safer surgery, as it has yet to become an integral part of intracranial procedures.

Computed tomography (CT), ultrasound images and magnetic resonance imaging (MRI) have detailed 3D images to guide intracranial surgeries. The intraprocedural tracking avoids accidental complications and offers less invasive craniotomies. Delimited relevant brain structures (i.e. vessels, cranial nerves, foramina, cerebral sulci), physiologic data such as PET or functional MRI and tumor limits can be localized with neuronavigation either, reducing the total surgery running time.

The application of neuronavigation for meningioma surgery is commonly related to tumor localization. However, this concept is applied only to convexity located lesions, where craniotomy location and size are of main interest. In other types of meningioma surgery, 'find the tumor' is not a frequent problem. Neuronavigation is particularly useful in the identification of neurovascular structures near the area of interest. It also optimizes tumor debulking avoiding critical damage to close structures the neurosurgeon can't directly see and, in large lesions, maximizes the extent of surgical removal staying within the limits of safe operability. The aim of this chapter is show how to enhance the neuronavigation usage for meningioma surgery.

2. Frame-based versus frameless image-guided surgery

Frame-based stereotactic resection was the first navigation method, rooted in cartesian coordinate system developed by Clarke and Horsley in the 1900s, and is still traditionally

applied to functional procedures and deep intracranial mass biopsies. Although useful for craniotomy guidance to intracranial targets, it provided limited anatomy identification and any 3D visual guidance during a surgical procedure. Along with the discomfort in the operatory field due to the frame itself, these disadvantages limited their application to craniotomy.

The era of image-guided systems began in mid-1980s, when Roberts et al described a neuronavigation device with a sonic based digitizer. In 1987, Watanabe described a frameless intraoperative device for intracranial localization. The use of light emitting diodes (LED) on surgery was introduced in 1993, by Bucholz et al. These devices offered an extended orientation and direct visual guidance better than frame-based stereotaxy and was increasingly being adopted into routine practice through the 1990s.

With the continuous developments of image-guidance technology, the frameless image-guided surgery offers accuracy similar (although there is a non-statistically advantage) to frame-guided stereotaxy. Both methods seem to work well if performed by neurosurgeons experienced in their use. Still, neuronavigation functionality enhance neurosurgeon's knowledge of anatomy and experience, promoting a safer and predictable procedure.

3. Pre-operative planning

To accomplish transoperative neuronavigation usage, preoperative images need to be acquired using a specific protocol and fiducials. Later, the data is transferred to a Workstation for surgery planning and then, transferred to neuronavigator. Although there are several different systems available, all of them works involving the same steps.

3.1 Image acquisition

The current image-guided systems rely on preoperative imaging. These data should be obtained a few hours or one day before surgery and must respect a standard protocol of image acquisitions. The accuracy of the information obtained from the navigation system is directly related to image quality and thickness. Artifacts and motion distortion should be strongly avoided in order to prevent target registration error. Contrast-enhanced T1-weighted 3D MRI (1.5 or 3.0 Tesla) and contrast-enhanced CT scan represents optimal choices for planning, as they assure tumor visualization. Both CT and MRI have particularities and both can be used to navigation. Image fusion between CT and MRI is particularly useful for skull base navigations, due to the relationship of bone to soft tissues (nerves, vessels). Also, image fusion with physiologic data or vascular imaging may help avoid potential damages.

The neurosurgeon involvement starts at the acquisition, the initial step for neuronavigation, in order to stay aware of data quality and, eventually, demands a new image acquisition.

After acquisition, images are transferred to the workstation over a local network or employing CD-ROM.

3.2 Planning in the workstation

Once in the Workstation, the data are analyzed and treated. Although surgical planning can be jumped, if meticulously performed, it offers neuronavigation optimization with additional and reliable details. When multiple sequences are available, they should be fused (figure 1).

In case of anatomical landmarks registration, these structures should be determined during planning: nasion, anterior nasal spine, medial and lateral angles of the eye, tragus and ear helix can be reliable skin landmarks for usage. In case of fiducials (adhesive or skull implanted) registration, these will be clearly shown in the image data (figure 2).

Usually demonstrated as homeogenic contrast-enhanced lesions, meningiomas can be easily delimited during surgical planning. Also, necrotic cavities, bleeding areas may be enfatized. Adjacent anatomy, such as cortical sulci and gyri, compression, adherence, and/or displacement of neurovascular structures should be analysed and, if necessary, delimited for a 3D demonstration (figure 3 and 4).

When surgical planning is done, the worked data are transferred to the neuronavigator.

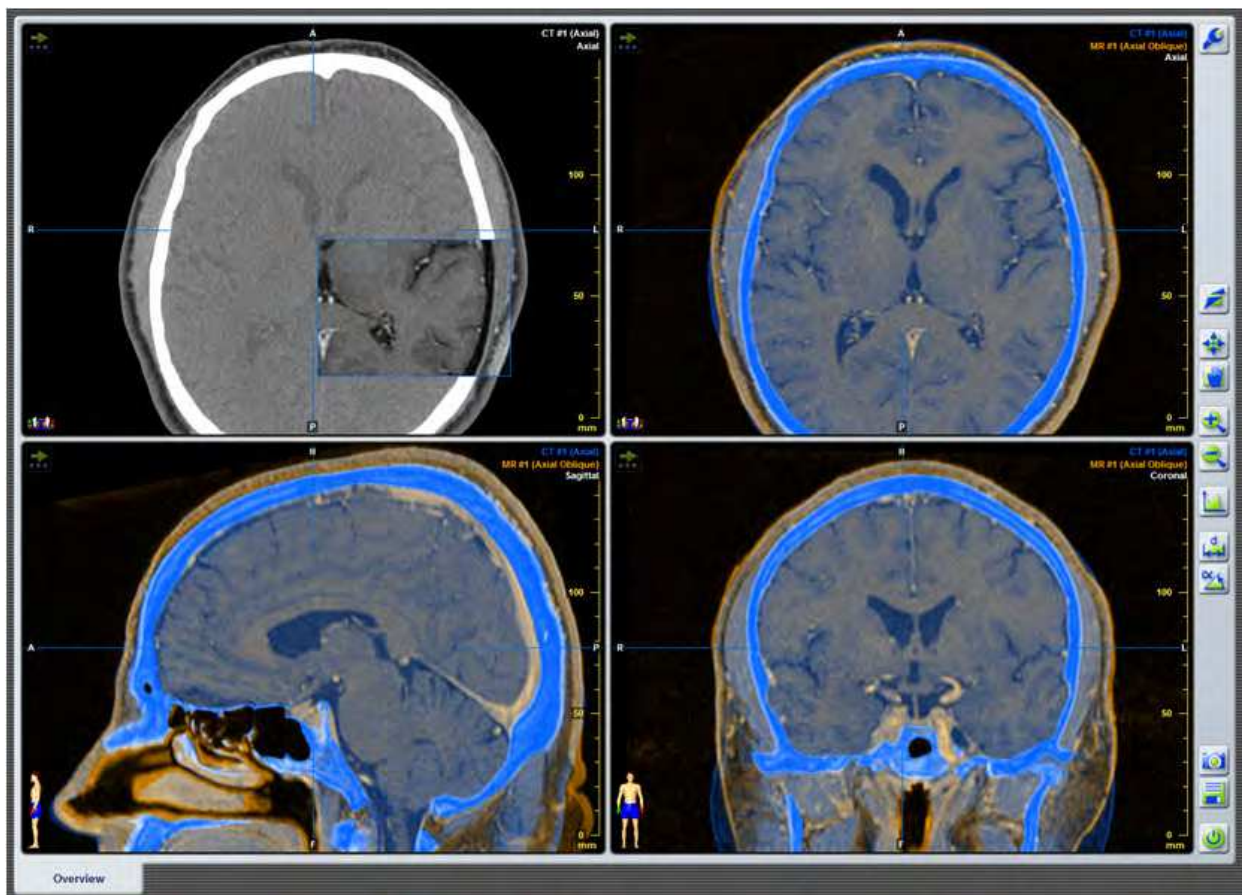


Fig. 1. CT/MRI fusion on Workstation

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Fig. 2. Markers for registration with skin anatomical landmarks

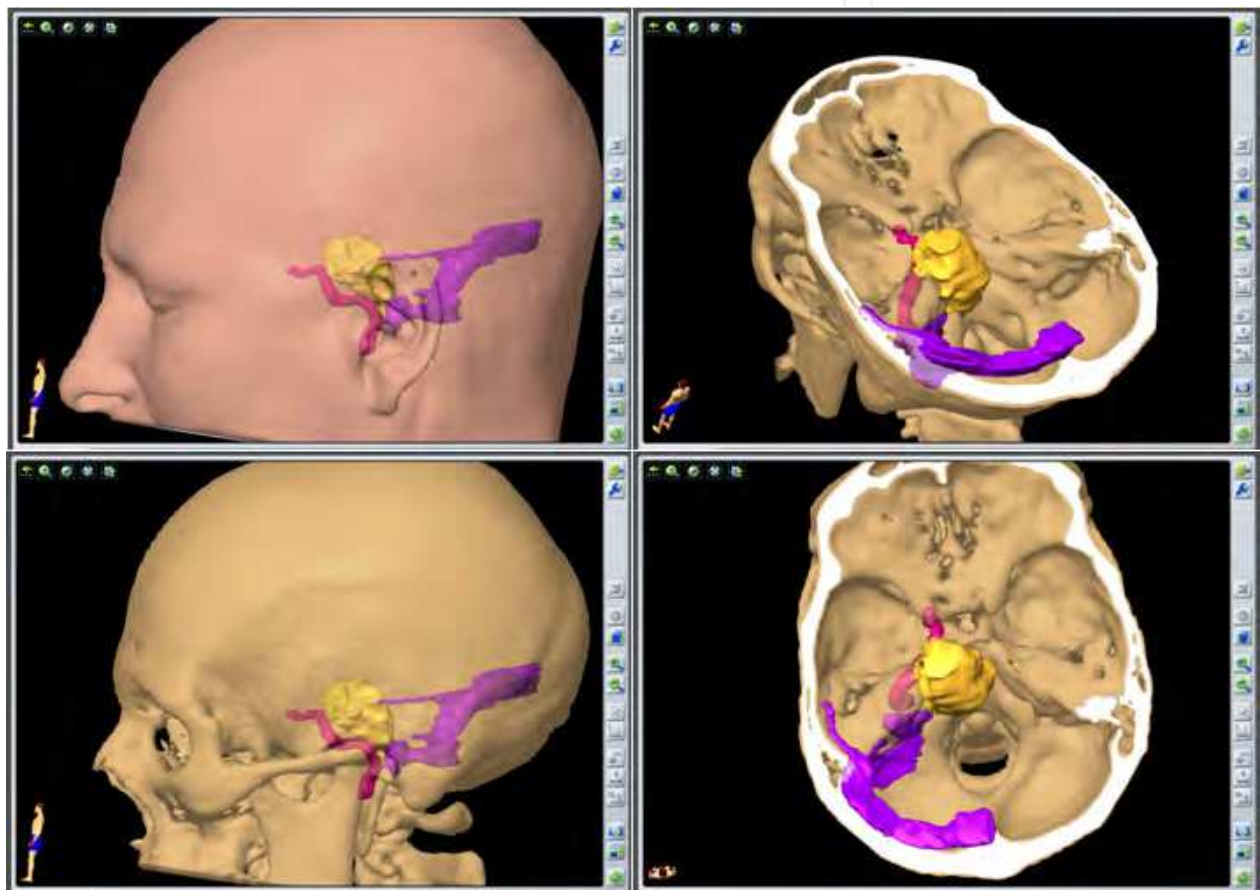


Fig. 3. Tumor (yellow) and vascular structures (purple and red) marked in the workstation for a petroclival meningioma surgery

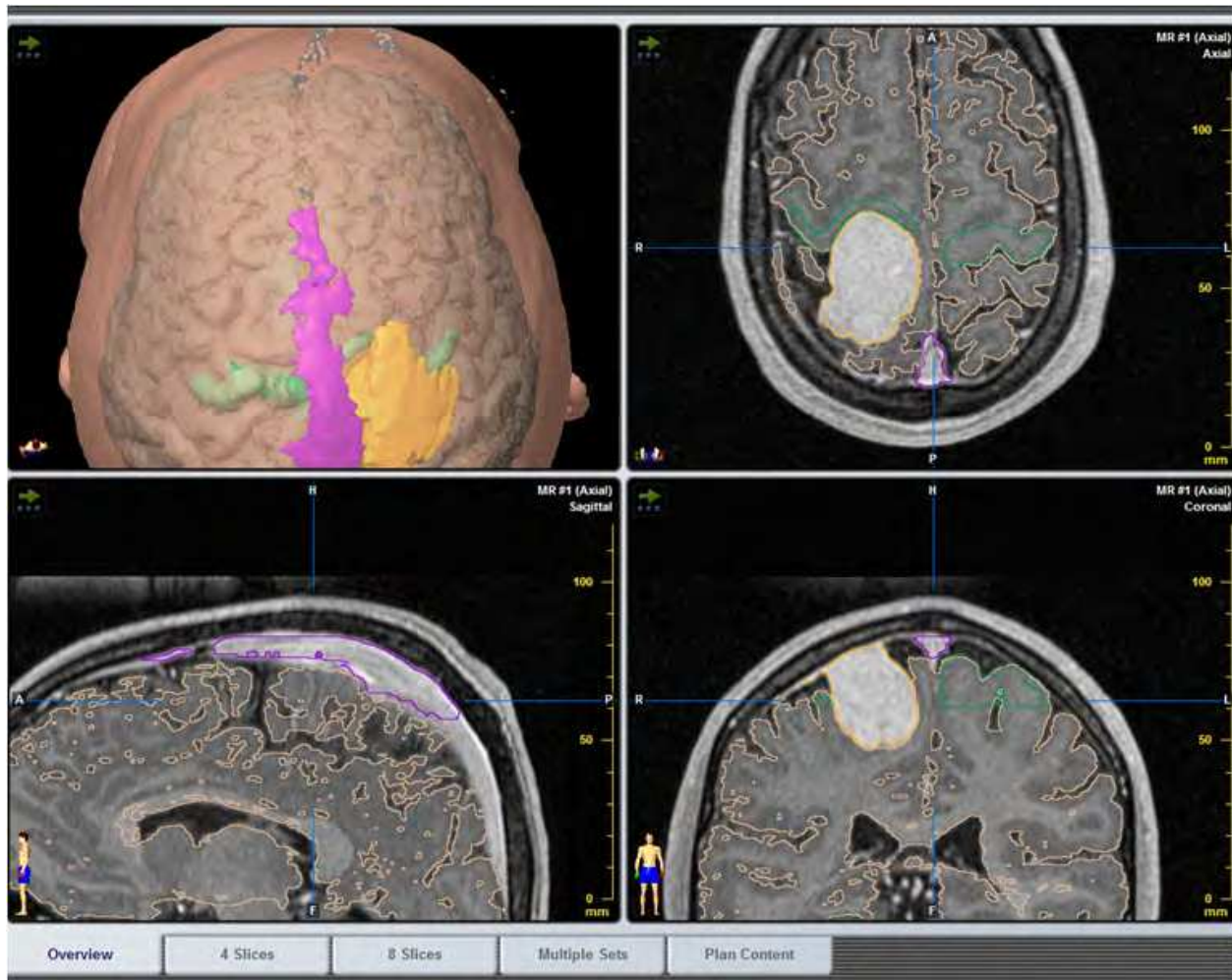


Fig. 4. A parasagittal meningioma (yellow), superior sagittal sinus (purple) and motor cortex (green) marked in the Workstation during surgical planning

4. Image-to-patient registration

In the operation room, after the patient's head is secured in Mayfield clamp with a reference star fixed in it and after positioning the neuronavigator camera array, patient-to-image registration is carried out (figure 5). There are three types of registration methods for navigation which should be designated according to the target area/tumor location. In some cases, as usually occurs in posterior fossa approaches, there is a common concept of major accuracy flaw due to image distortion and registration fiducials/anatomical landmarks too far from area of interest. However, these pitfalls may be avoided with a few considerations.



Fig. 5. Patient registration

Fiducials (figure 6 and 7) is the most frequently method of registration. It consists in the use of 4-8 (usually 6) fiducials placed in predetermined positions (usually near the area of interest) upon patient's scalp and imaging with standardised protocols. These fiducials may be skull implanted, which is invasive 'gold standard', with an accuracy flaw below 2 mm; or adhesive to the skin, and carried out the day before surgery or sometimes immediately prior to surgery. Consequently, fiducials usage demands time, delaying surgery, and adds extra costs.



Fig. 6. Fiducials on patient's scalp

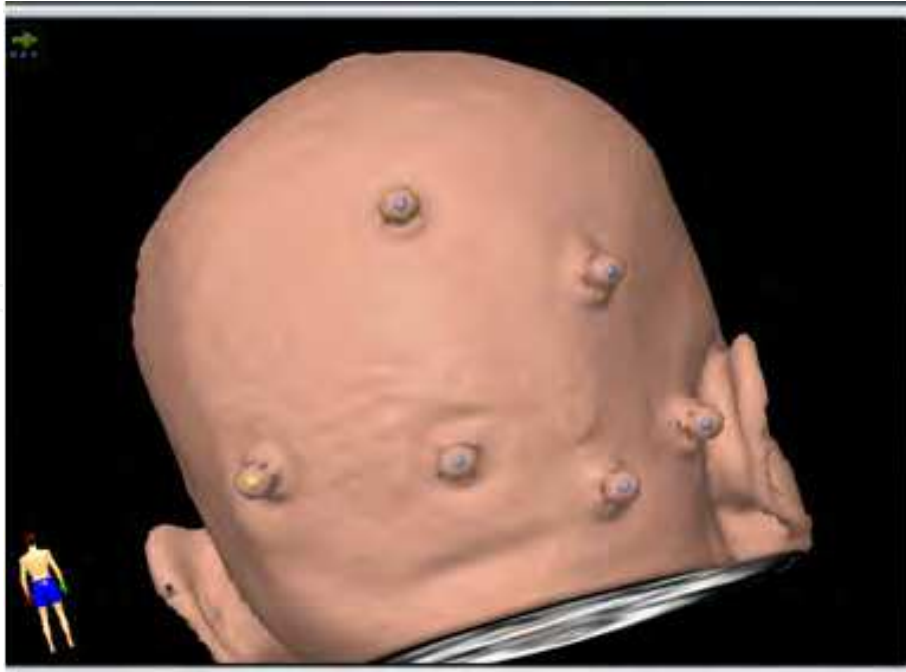


Fig. 7. Fiducials on patient's scalp in workstation

Skin surface based registration (figure 8) consists of a LASER pointer registration over patient's forehead, nose and around eyes. These method usually provides a reliable accuracy for craniofacial or anterior skull base surgery. Due to image distortion, there's an increasingly accuracy flaw posterior to coronal suture/ear. Although limited usage, it doesn't demands a preparation during surgical planning and may be complemented with anatomical landmarks acquisition to enhance the registration.

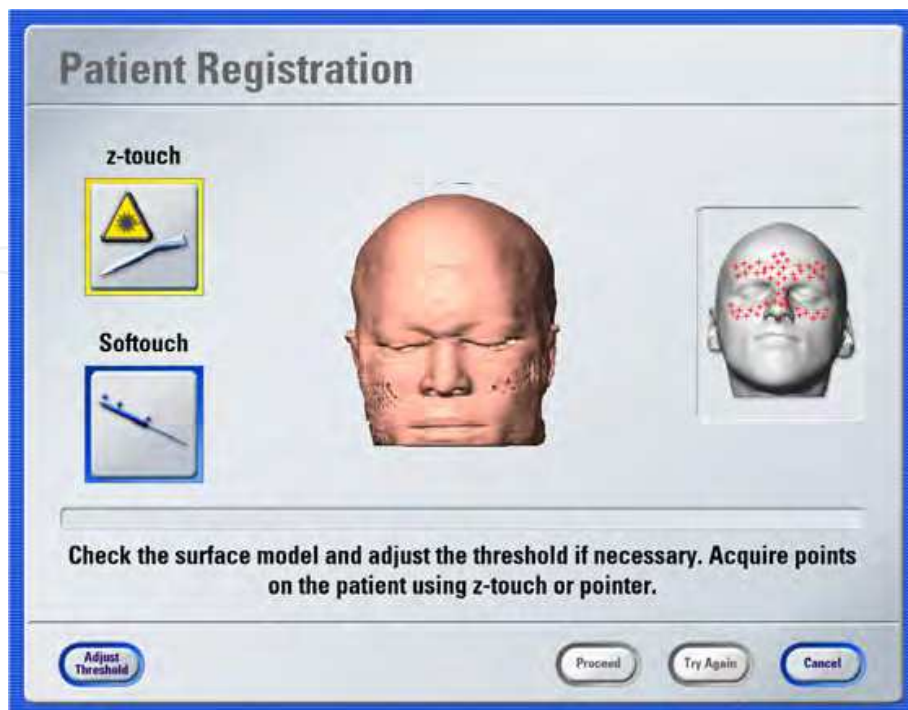


Fig. 8. Surface matching registration (navigator screen)

Registration with anatomical landmarks consists in the use of anatomical landmarks instead of fiducial markers. In patients face, these landmarks can be nasion, anterior nasal spine, medial and lateral angles of the eyes and other points carefully chosen in order to avoid distortion or too mobile areas. It may be the most operator-dependent method of registration and still the possibility of registration using bone instead of skin anatomical landmarks. Foramina, angles and sutures on bone anatomy (figure 9 and 10) usually offers reliable landmarks for registration and are performed after skin incision. This method is often used during navigation in spinal procedures. Once the necessary landmarks are exposed on the operatory field, registration can be and provides a more logical consistency in anatomical landmarks usage. As these points are closer to the area of interest than any skin fiducials, it favors the registration to a better accuracy for targets in deep structures.

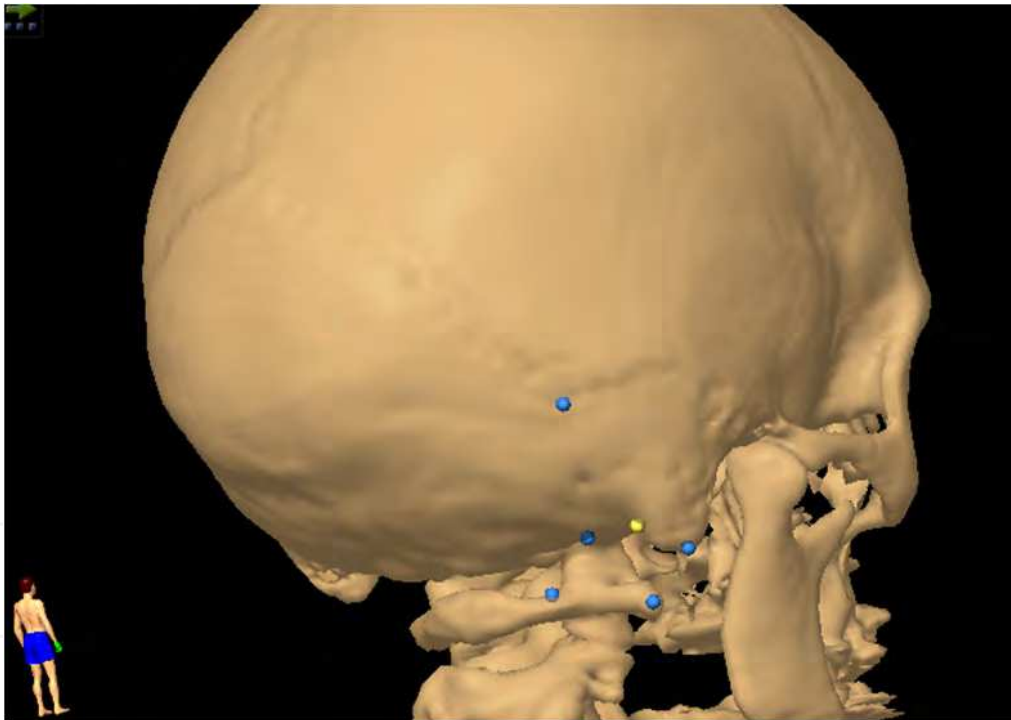


Fig. 9. Anatomical landmarks for intraoperative registration – lateral craniocervical approach



Fig. 10. Anatomical landmarks for intraoperative registration – suboccipital midline approach

For most surgeries, an accuracy flaw around 2-4 mm can be accepted, specially for large target areas. The target registration error may vary according to the utilized navigation system, but data imaging and its correlation with the landmarks during registration consist decisive factors to neuronavigation success. Nonetheless, the surgeon should be familiar with the limitations and potential sources of error in all steps involved neuronavigation before intraoperative tracking.

Some possible errors for accuracy flaw involves shifting. First, the reference star, which should be well-attached to the head fixer to avoid any kind of deslocation; second, patient's head deslocation in the Mayfield clamp; and, finally, brain-shift, which isn't accidental and can be, on most cases, a predictable event.

Brain-shifting may be avoided with new image data (ultrasound, CT or MRI) acquisition intraoperatively, when available. However, the distortion in meningioma surgery usually is minimal and avoidable in most cases, specially when the navigation focus lies on a well-centered minimal invasive craniotomy. In skull base meningioma surgery, this distortion still avoidable due to the extensive bone work.

5. Intra-operative tracking based on tumor location

Meningioma surgery may involve different challenges for the surgeon, according to its size, location, relationship and adherence with brain and neurovascular structures. It may vary from a simple small frontal convexity meningioma resection to a large petroclival tumor surgery involving cranial nerves and compressing brainstem from posterior to middle fossa.

Discuss the neuronavigation utility for meningioma surgery must be focused based on tumor location. According to each case, there are ways to optimize its usage beyond the misunderstood 'find the tumor' concept.

5.1 Convexity meningiomas

For most neurosurgical centers, convexity meningiomas probably is the standard for neuronavigation usage in meningioma surgery due to its urgency in place the craniotomy in the right place.

Contrast enhanced images are the preferred modality for both CT scan and MRI , since the objective is 'see' the lesion. During surgical planning, a surgical trajectory should be defined determining the size and location for craniotomy. The 3D reconstruction allows an optimal view and avoids mistakes. For image-to-patient registration, surface matching may be an useful method for tumors anterior to coronal suture, but adhesive fiducials to the scalp still the safest choice.

After skin incision, the image-guided craniotomy should be at least a 2cm larger than the maximum diameter of tumor's dural base. It will provide an better area to tumor removal and duroplasty (figure 8).

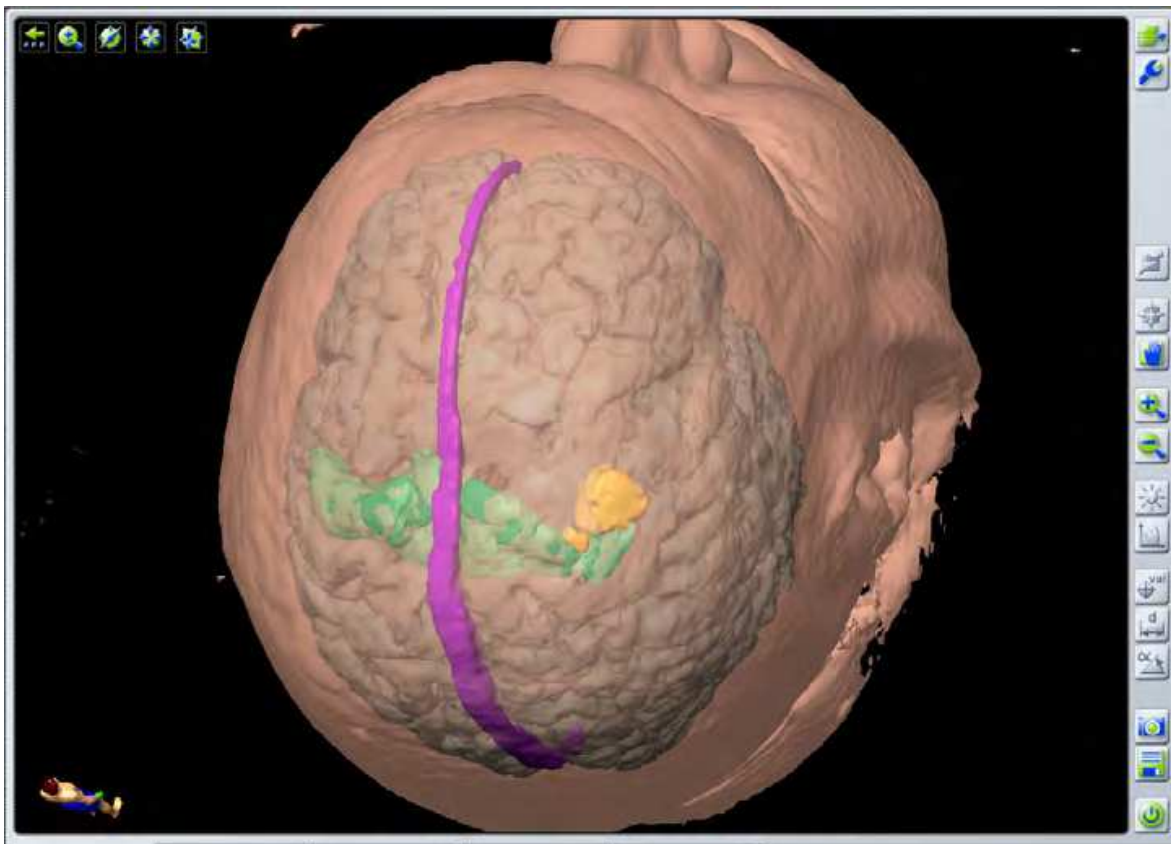


Fig. 11. Convexity meningioma on Workstation: tumor (yellow), superior sagittal sinus (purple) and motor cortex (green)

Brain-shifting usually is a minor treat for neuronavigation in these cases because the optimal place for craniotomy is determined before. Still, the tumor lies attached to dural tail and bone. Venous anatomy, specially those underlying the dura, may be understood with neuronavigation, providing an adequate dural opening avoiding accidental bleeding.

5.2 Parasagittal and falcine meningiomas

Although the craniotomy for parasagittal/falcine meningiomas can be planned considering only tumor relationship with the superior sagittal sinus, neuronavigation is important to display underlying venous anatomy and the midline. The use of MRI provides the necessary data for planning, where the relevant structures can be marked (figure 12). Vascular studies should always be available for additional information and, eventually, data fusion.

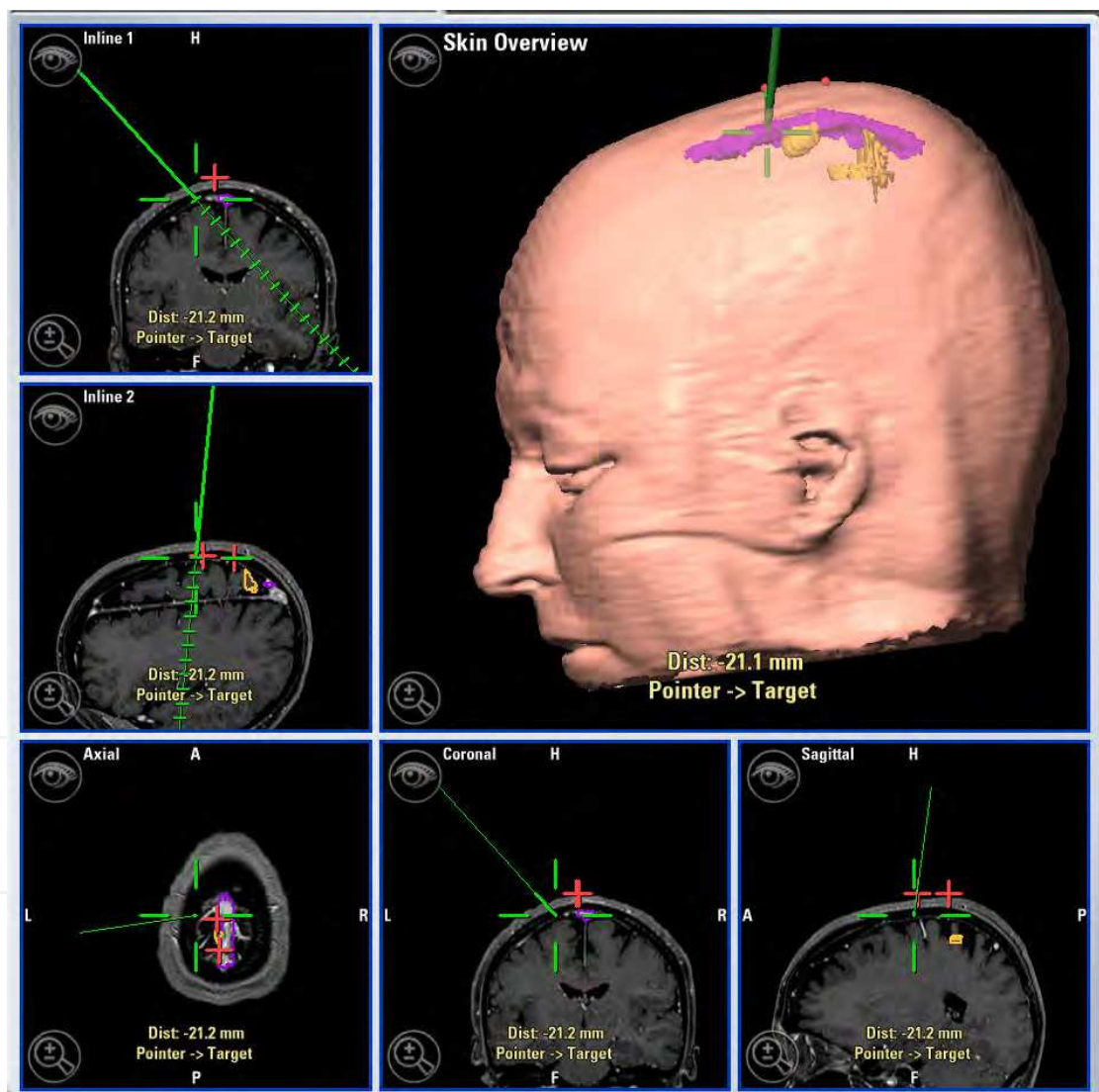


Fig. 12. Parasagittal meningioma navigation during craniotomy placement

The method of registration is similar to convexity meningiomas, where fiducials are the preferred and surface matching reliable only for lesions in the anterior 1/3 of the superior sagittal sinus and falx.

For falxine tumor, the neuronavigation should provide a safe surgical corridor between draining veins and midline. The brain-shifting is still a rare problem, as these tumors are tethered to fixed structures such as superior sagittal sinus and falx. Once more, draining veins and major arterial branches can be predicted with neuronavigation assistance. For large tumors, functional MRI may promote a better understanding of the distorted cerebral eloquent anatomy to avoid post-operative deficits.

5.3 Tentorial meningiomas

For tentorial meningiomas surgery, the neuronavigation should provide important information in the understanding of venous anatomy. Although the approach, both supra and infratentorial, doesn't depend on neuronavigation, the exact midline localization provided by the system aids to deal with the dural sinuses. The transverse sinuses location should be located either, avoiding a major bleeding risk during craniotomy (figure 13).

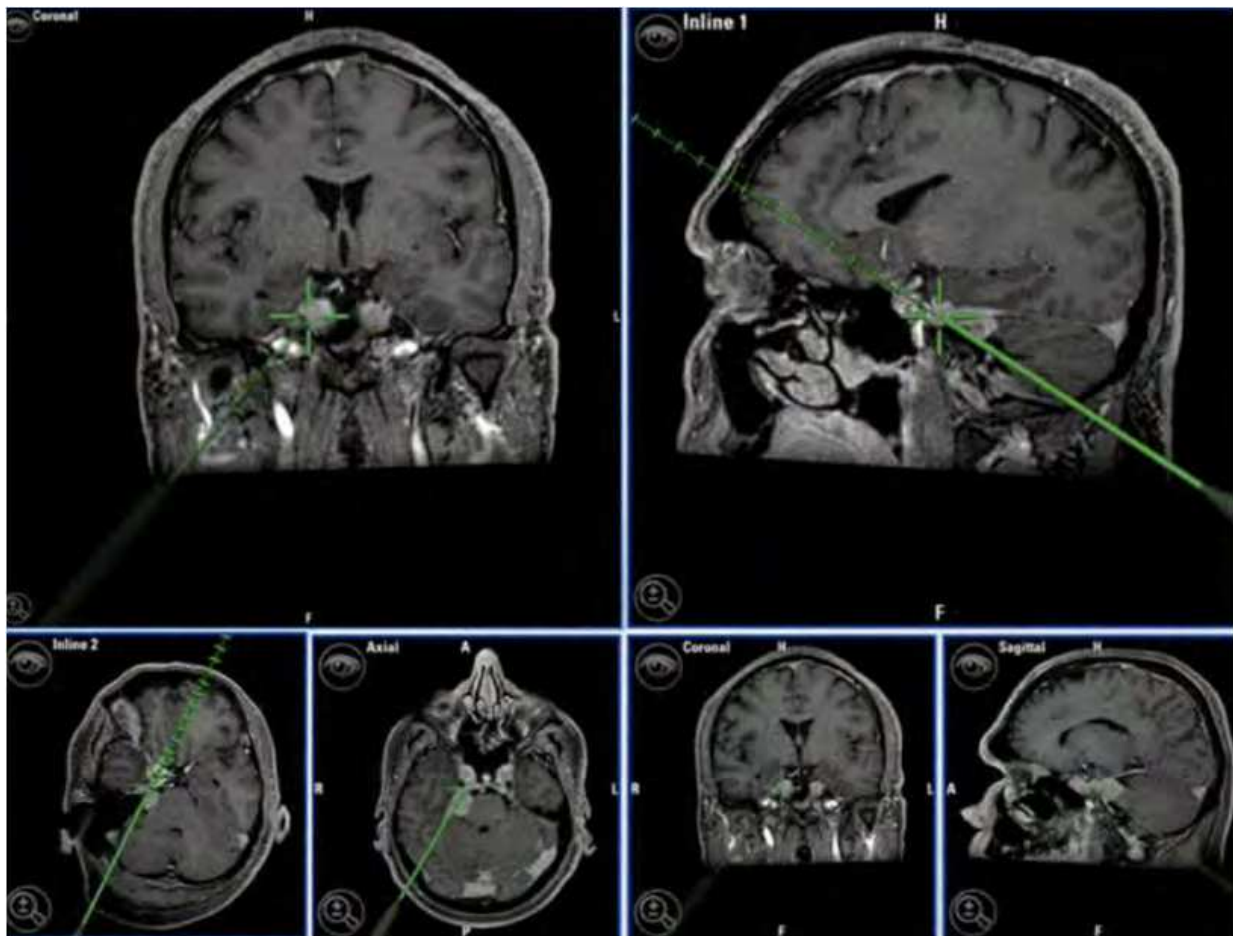


Fig. 13. Tentorial meningioma navigation

Fiducial markers are the best choice for registration, and they should be placed near the area of interest and dural sinuses.

Location of the vein of Labbe can be identified with navigation to avoid damage during dural opening, for supratentorial lesions. Also, distorted deep venous drainage can be identified when the surgeon is working near the midline.

5.4 Olfactory groove and suprasellar meningiomas

For skull base navigation, CT/MRI fusion should always be considered. There will be a special reliability in neuronavigation, since the surgeon will aim bone and fixed structures. In anterior fossa meningiomas surgery, neuronavigation isn't necessary for craniotomy, as they usually demand a frontolateral approach.

Surface matching can be a reliable method for registration in anterior fossa meningioma surgery. During surgery, the neuronavigation can be used before dural opening to frontal sinus identification, and after in order to determine tumor relationship with midline, olfactory groove, optic nerves and internal carotid arteries. The relevant anatomy may be marked in surgical planning. Also, the neuronavigation should aid to show the position during tumor debulking, specially when approaching posterior structures such as infundibulum.

5.5 Sphenoid wing and cavernous sinus meningiomas

Sphenoid wing and cavernous sinus meningiomas can be accessed using a pterional approach and its variants without the need for neuronavigation. However, it can provide valuable intraoperative information during tumor debulking as the location of vascular structures distorted by the tumor. The mesial structures, including cavernous sinus, can be identified without accuracy loss due to brain-shifting, as these structures remain attached to skull base.

Fiducial markers and surface matching are good choices for registration, as well, anatomical landmarks, especially if mixing skin landmarks (before skin incision) and bone landmarks (after skin incision) such as key hole and zygomatic arch.

Neurophysiologic monitoring is always a valuable tool to help predict cranial nerves location and, with neuronavigation support for spatial orientation, reduces post-operative deficits.

5.6 Petroclival and jugular forame meningiomas

The neuronavigation usage for posterior fossa tumors can be divided in an extra-dural application, specially during the craniotomy, helping determine dural sinuses location, and an intra-dural application, aiding tumor debulking and avoiding inadvertent neurovascular damage. CT/MRI fusion is essential for neuronavigation in these cases.

The registration technique may vary to fiducial markers and, according to the approach, anatomical landmarks. There is a special challenge for posterior fossa registration due to distortion and accuracy loss and it may be avoided with registration hints. For a retrosigmoid craniotomy, skin anatomical landmarks can provide a reliable registration. For craniocervical lateral approaches and suboccipital midline approaches, there will be enough bone anatomical landmarks (such as inion, foramen magnum borders, atlas arch, digastric incisure, mastoid tip) to use for registration, with the advantage of more proximity from the area of interest and, consequently, a minor target registration error (figure 14). Although faster than fiducial markers, anatomical landmarks registration demands more familiarity and experience with the method than other methods of registration.

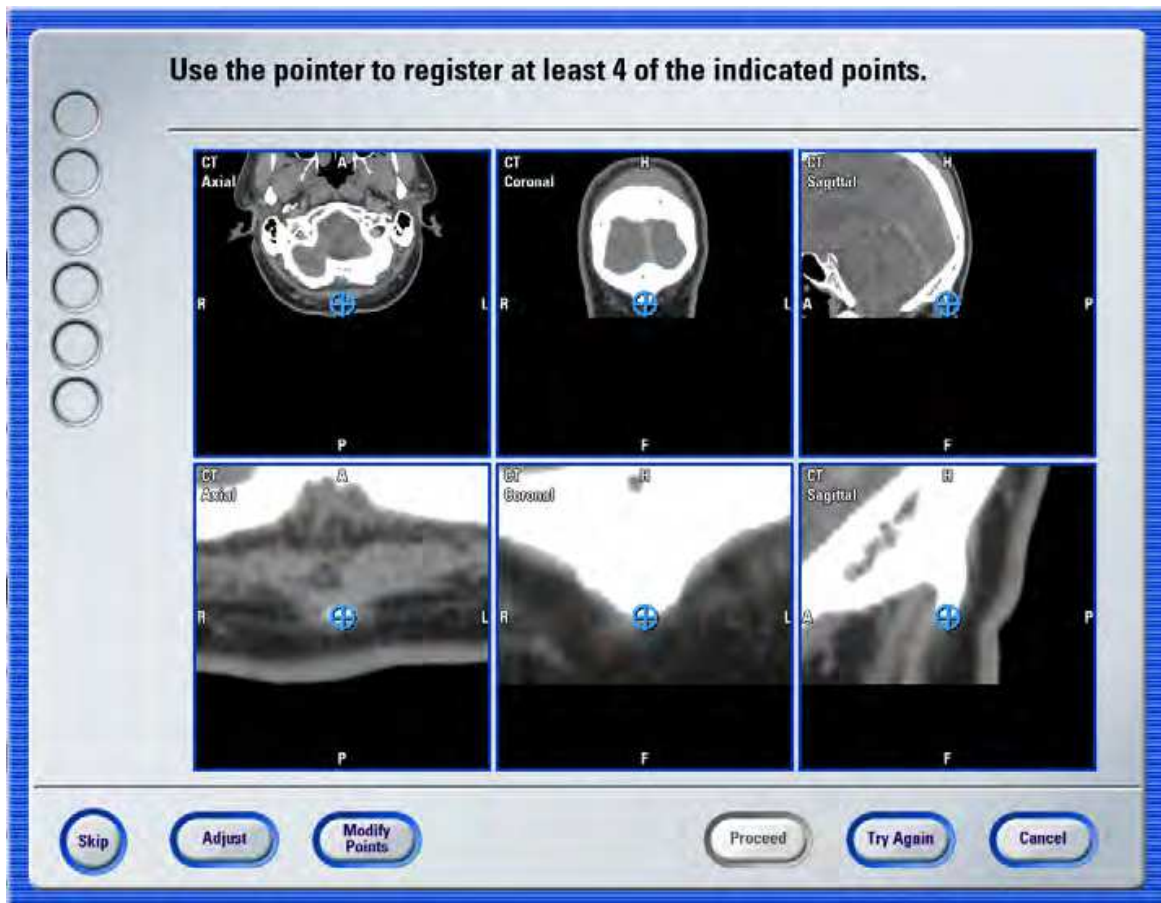


Fig. 14. Intra-operative registration with anatomical landmarks on bone anatomy (Inion)

The transverse and sigmoid sinuses should be marked in surgical planning to optimal positioning of lateral craniotomies (figure 15). In midline approaches, the torcula as well the transverse sinuses are marked delimiting the supratentorial from infratentorial dura. The intradural usage of neuronavigation may be susceptible to accuracy error if the registration wasn't skillfully performed. Tumor limits and foramina can be identified with neuronavigation support. Although cranial nerves are hard to mark in the surgical planning, vessels position can be predicted using to same tool. It is specially important in determine the location of basilar and vertebral arteries, hidden by the tumor. Still, the neuronavigation is a reliable tool for surgeon's orientation through midline when debulking large tumors with brainstem displacement.

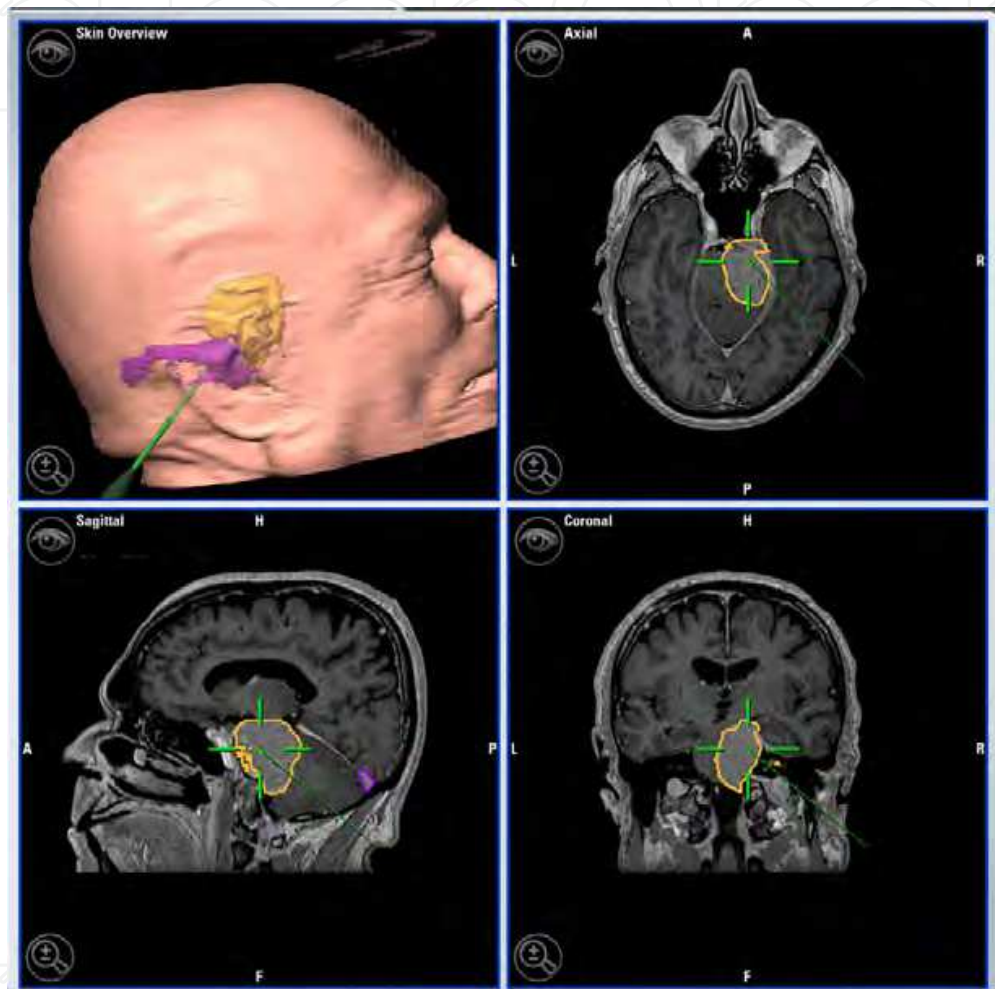


Fig. 15. Navigation for a petroclival meningioma: tumor (yellow) and transverse-sigmoid sinuses (purple)

In case of craniocervical approaches, the neuronavigation can aid to identify the relevant anatomy of the neck dissection, such as carotid and vertebral arteries (figure 16).

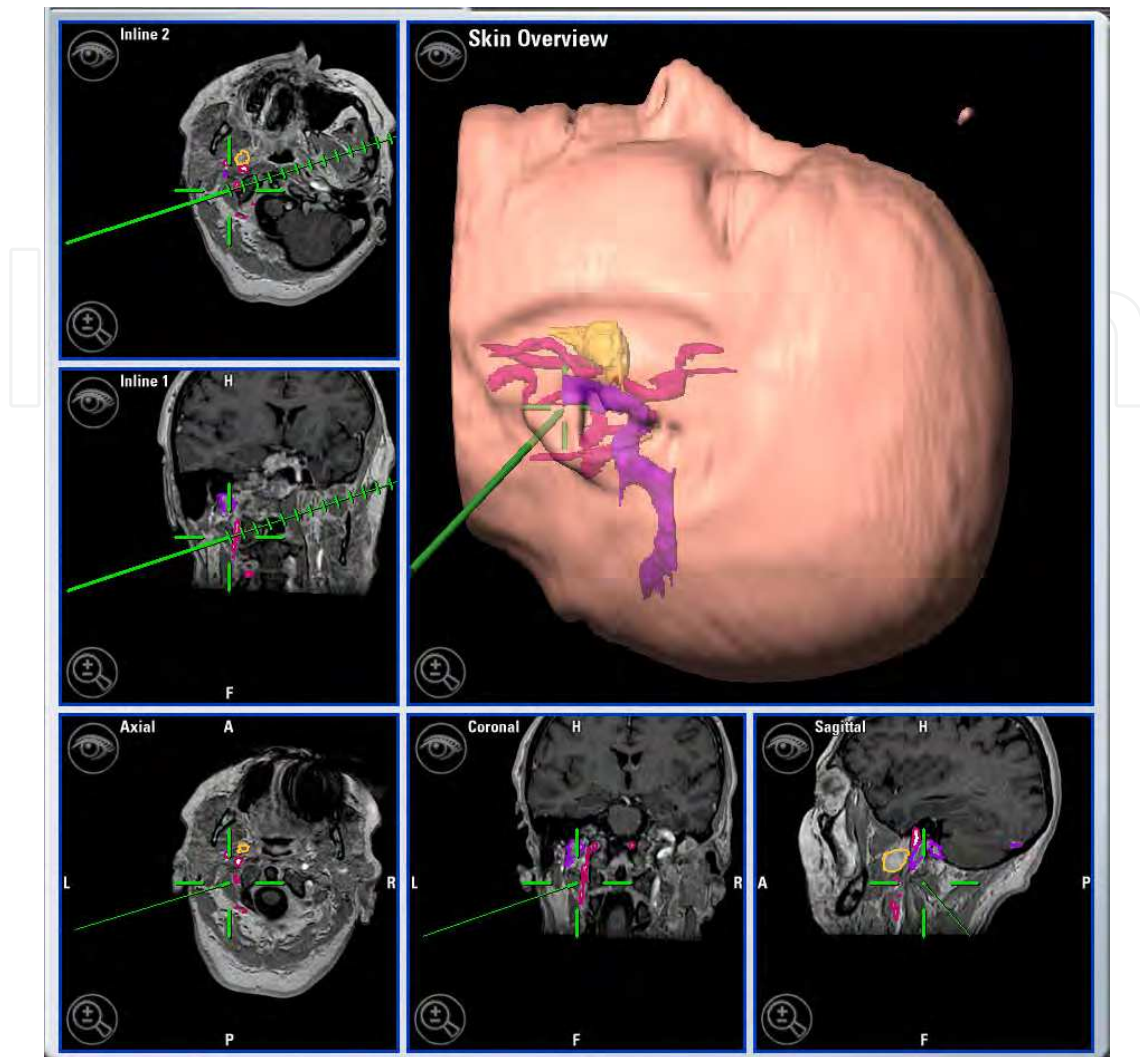


Fig. 16. Navigation for a jugular forame meningioma: tumor (yellow), transverse-sigmoid sinuses and jugular bulb (purple) and posterior arterial circulation (red)

6. Final considerations: Future applications of image-guided surgery for intracranial meningiomas

Image guided surgical technology plays a significant role in contemporary neurosurgery that doesn't exclude the neurosurgeon's anatomy knowledge and personal experience. It is a tool designed to aggregate more information to the surgery, specially with the preoperative planning. It also provides continuous new possibilities and perspectives for surgical treatments, as neuroimaging is improving through the years. The main goal for neuronavigation in meningioma surgery stands in optimal craniotomies, less dural sinuses damage and safer tumor removal. The method don't aims to turn the surgery 'easier', but 'safer', and in reliable ways.

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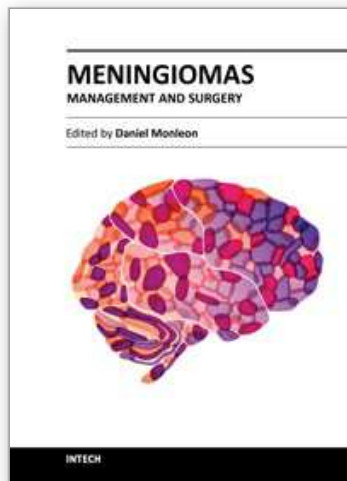
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This book is aimed at neurosurgeons with an interest in updating their knowledge on the latest state of meningiomas surgery and management. The book is focused at performing a portrait of that what is state of the art in management of meningiomas. All the chapters have been developed with high quality and including the most modern approaches for the different aspects they deal with. The book concentrates on those problems that, although perhaps less common in the day to day routine of the average neurosurgeon, when present pose a special challenge. This is neither a "how to" book nor a book about meningioma biology. It presents some of the most relevant aspects in the latest developments for meningioma surgery and management in a clear and professional manner.

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