

Original Article

A virtual reality model of the clivus and surgical simulation via transoral or transnasal route

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Abstract: Background: Neurosurgery in areas with restricted space and complicated anatomy can be greatly aided by the virtual reality (VR) technique. The clivus represents one of such challenging surgical areas, but its VR has not been established. The present study aimed to document a VR model of clival anatomy that may be useful in clival surgery. Methods: High resolution CT angiography and MRI were used. The study included a total of 20 patients who did not have any obvious abnormalities detected in the oral, nasal, and clival areas. The images were fused with a Dextroscope. Results: In the VR model, the key structures such as the clival bone, basilar artery, brainstem, pituitary gland, and paranasal sinuses were clearly observed. The morphology of the clivus and its spatial relationships with the neighboring structures were also illustrated. Visualization of the clival model can be made flexible from various planes, angles, or orientations. In addition, surgical access to the clivus via the transoral route or transnasal route was simulated in detail. Conclusion: The simulation of the VR model offers a straightforward, three-dimensional, interactive understanding of the size and shape of the clivus, and its relationships with the surrounding blood vessels and bones. It also demonstrates simulated operational procedures such as opening the surgical window, measuring the exposure distance and angles, and determining the critical boundaries in relation to key structures such as the brainstem and arteries. Digitalized VR modeling appears to be helpful for understanding the anatomy of the clivus and its surgical approaches.

Keywords: Clivus, digitalized anatomical model, transnasal, transoral, surgical simulation

Background

Neurosurgery in areas with restricted space and complicated anatomy tends to be associated with higher morbidity. Preoperative planning and surgical practice are the key to obtaining better surgical outcomes. In the old days when only cadavers were available, the surgeons were left with very limited chances to optimize or improve the surgical skills. However, the advent of virtual reality (VR) opened up possibilities for aiding surgical access to challenging sites [1-4]. VR represents an innovative paradigm in surgical simulation [1, 5]. It enables the anatomical environment to be recreated in a virtual space without the requirement of physical models. VR aids in surgical planning and preoperative evaluation, and has contributed to reforming surgical paradigms. The documentation of VR aided neurosurgery is a very important step to solidify the neurosurgical education and planning.

The clivus is a rather challenging surgical site due to very restricted surgical space and being surrounded by several vital structures [6]. The development of clival surgery guided by VR would be an essential addition to neurosurgery education and training [7]. The clival VR model would enable simulation of the surgical operation and provide preoperative measurement of the anatomical structures. It also represents unlimited training opportunities for new surgeons who wish to become very skillful in managing the area.

Surgical approaches to the clivus are either via the transnasal route or transoral route in order to deal with clival pathologies including mucous cyst, chordoma, chondrosarcoma, craniopharyngioma, meningioma, and pituitary adenoma [6, 8-10]. The clivus is located in the midline area of the skull base. It is part of the cranium, formed by the basilar part of the occipital bone and the corpus ossis sphenoidalis. The clivus

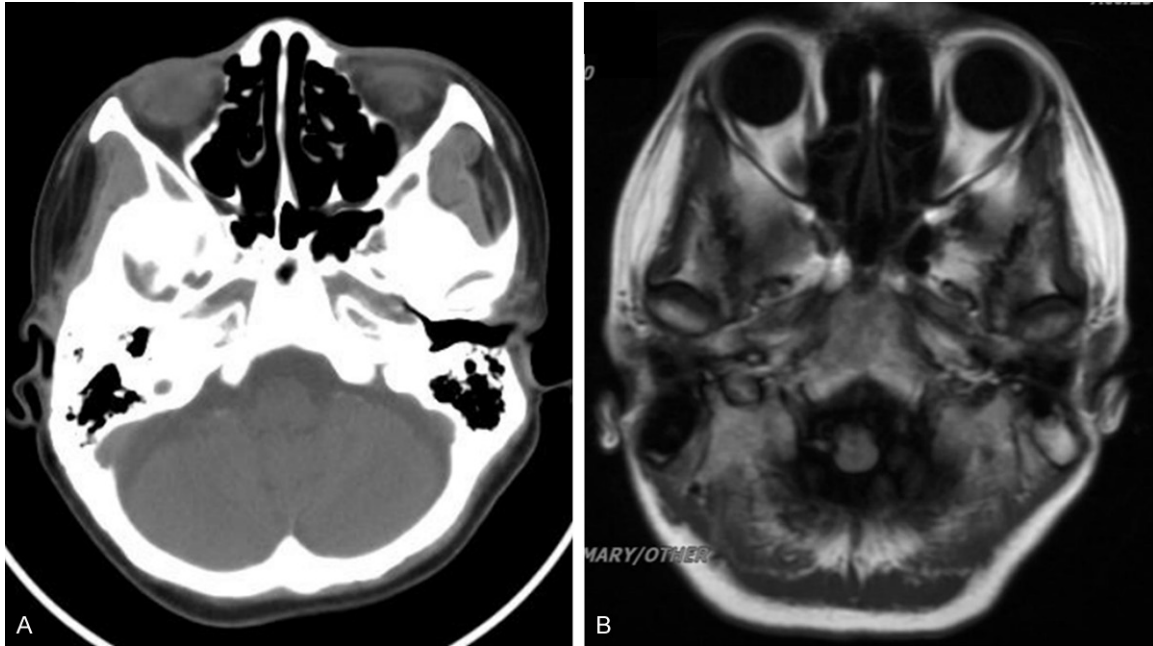


Figure 1. Raw clival images from (A) CTA and (B) MRI.

sits between the anterior foramen magnum of the occipital bone and the posterior clinoid process, and slopes obliquely backward at an angle of approximately 45 degrees. The dorsal part of the clivus is the dorsum sellae, and it is bordered ventrally by the anterior foramen magnum of the occipital bone. Lateral to the clivus is the foramen lacerum, petrooccipital fissure, jugular foramen, and internal aperture of the hypoglossal canal. The clivus is positioned in a very central site of the skull base, and it is near several vital structures including the brainstem, internal carotid artery, fifth, sixth, and seventh cranial nerves, cavernous sinus, hypophysis, and hypothalamus. The surrounding important structures allow only very limited surgical exposure of the clivus.

The goal of the present study is to document a VR model of clival anatomy that may be useful in clival surgery [3]. In addition, measurements between key landmarks would be taken to better define the local anatomy, the coverage, and the orientation for safe bony removal during surgery. To this end, the present study took advantage of high resolution medical imaging to simulate the clival anatomical environment and then create a clival VR model with the digitalized information available [11, 12]. Moreover, we aimed to simulate in detail the surgical access to the clivus via the transoral or transnasal route. The clival VR model may serve as a

guide in preoperative education/evaluation and surgical planning during the management of clival pathologies.

Materials and methods

Subjects

This study was approved by the Institutional Review Board of Fuzhou General Hospital, Fujian Medical University. All patients included in this report were admitted to Fuzhou General Hospital between May 2010 and January 2012 and were diagnosed with spontaneous subarachnoid hemorrhage, but did not have pathologies identified in the skull base. These patients underwent brain CT and MRI [13]. The study included 20 patients, 12 males and 8 females. Patient age ranged from 25 to 70 years. CT angiography (CTA) confirmed that these patients had cerebral anterior circulation aneurysms, and all underwent the clipping surgery successfully. On CT scans, no obvious abnormalities were found in the oral, nasal, or clival areas. Consent to allow use of the imaging data was obtained from the participating patients.

Image acquisition

Computed tomography angiography was performed using a 64-slice spiral CT scanner (Discovery Ultra, GE). The rotator time was 0.5 s/rotation with 120 kVp and 200 mAs, the slice

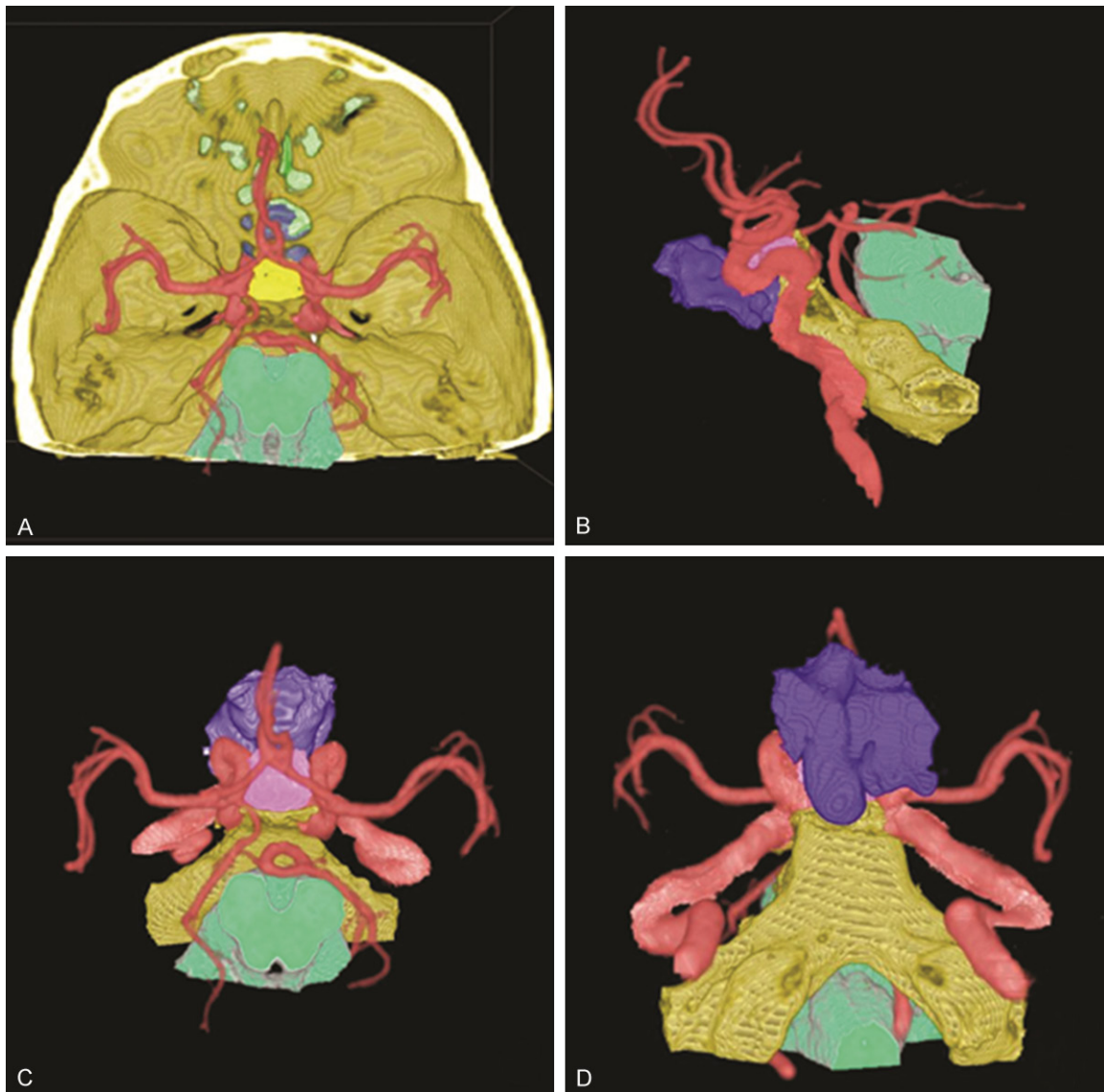


Figure 2. VR model established from CTA and MRI. A. An overview of the digitalized clival VR model. The cranial bone is in amber; the basilar artery in red, the brainstem in green, the sphenoidal sinuses in blue, the pituitary gland in yellow, and the ethmoid sinus in spring green; B. A side view of the clivus and its spatial relationships with the surrounding structures. The clival bone is in amber, the brainstem in green, the basilar artery in red, the pituitary gland in purple, and the sphenoidal sinuses in blue; C. A top down view; D. A bottom up view.

thickness was 0.625 mm, the slice interval was 0.625 mm, the field of view was 240 mm×240 mm, and the matrix size was 512×512. The contrast media, iohexol (Omnipaque), was injected at the dose of 2 ml/kg via the cubital vein with an infusion rate of 3.5 ml/s. Magnetic resonance imaging was performed using a 3.0 T MRI scanner (Trio Tim, SIE Company) with MPRAGE (magnetization prepared rapid acquisition gradient echo) sequence with coverage of the head region in the coronal plane. The slice thickness was 1.0 mm with no interval,

the field of view was 250 mm×250 mm, and the matrix size was 512×512. T1-weighted imaging used a repetition time (TR) of 1900 ms and an echo time (TE) of 2.52 ms. T2-weighted imaging used a TR of 3200 ms and TE of 403 ms. All the image sequence data were stored on a CD-ROM in DICOM format.

Co-registration of MR and CT datasets

The CTA and MRI datasets were co-registered using a 3-D workstation with a Dextroscope (Volume Interactions/Bracco, Singapore) [14,

Table 1. Measurement between the anterior nasal spine and the clivus

	$\bar{x} \pm s$
Distance between the anterior nasal spine and the sellar floor (mm)	78.8 $\pm$ 3.1
The angle formed by the nasal base and the line connecting the anterior nasal spine and the sellar floor (°)	31.7 $\pm$ 0.9
Distance between the anterior nasal spine and the dorsum sellae (mm)	83.6 $\pm$ 4.3
The angle formed by the nasal base and the line connecting the anterior nasal spine and the dorsum sellae (°)	33.0 $\pm$ 1.8
Distance between the anterior nasal spine and the clival recess (mm)	81.7 $\pm$ 5.9
The angle formed by the nasal base and the line connecting the anterior nasal spine and the clival recess (°)	31.6 $\pm$ 2.3

15]. This is a system that enables integration of tomographic images from CT and MRI into true 3-D volumetric objects that can be viewed stereoscopically. Skin fiducials visible in both data sets were specified as landmarks. The co-registration was performed with least-squares error minimization. Both manual and automatic adjustment was made to ensure the accuracy of the co-registered 3-D model with the image contrast and coverage optimized. CTA mainly re-established the cranium and blood vessels while MRI reconstructed the soft tissues including the pituitary gland and the brainstem. Important anatomical structures such as the sphenoidal sinus, intracranial arteries, pituitary gland, brainstem, etc. were labeled in the VR model with digitalized information available (**Figures 1** and **2**).

Visualization and simulation

In the co-registered clival VR system, various functions were available for detailed exploration and visualization. The shape, size, and orientation of the structures can be studied readily while measurement and marking can be made easily. Simulation of the conventional transnasal and transoral routes to the clivus was also demonstrated. The simulation included the procedures involved in opening the clival bone window, viewing from different angles, and measuring the safety width of the window. The images were stored with the data collected. Statistical analysis using SSPS 13.0 software was performed to obtain the descriptive statistics in **Tables 1** and **2**.

Results

Overview of the clival VR model

The raw images of the clival region from CTA and MRI are shown in **Figure 1**. After image fusion, the clival VR model was established

using a Dextroscope. As demonstrated in **Figure 2**, the position of the key structures such as the clival bone, basilar artery, brainstem, pituitary gland, and paranasal sinuses were clearly observed. The morphology of the structure and its spatial relationship to the neighboring structures were also illustrated. Visualization of the clival model can be made flexible from various planes, angles, or orientations. The raw states can be recovered without any limits.

Measurement in the clival model

The clival VR model indicates that on the mid-sagittal section, the full length of the clivus is 30.6-51.2 mm, with the average length being 41.7 $\pm$ 2.9 mm. Frontal to the superior clivus is the hypophyseal fossa and the sphenoidal sinuses. Frontal to the inferior clivus is attachment of the soft tissue of the posterior pharyngeal wall. Lateral to the clivus is the cavernous sinus and the petrous part of the temporal bone with the internal carotid artery, abducens nerve, and trigeminal nerve passing through. The distances were measured between the anterior nasal spine and the structures around the clivus, and are summarized in **Table 1**.

The distribution of the sphenoidal sinuses varies among individuals. In some individuals, the sphenoidal sinuses extend as far as adjacent to the dorsum, to the pterygoid plate and the greater wing of the sphenoid bone, and even to the basilar part of the occipital bone. The posterior and inferior walls of the sphenoidal sinuses are anatomically interconnected with the clivus; the posterior wall directly constitutes a part of the superior clivus while the inferior wall is linked with it. The carotid artery ascends perpendicularly to the cranium and then becomes the internal carotid artery. The artery then turns medioanteriorly, proceeds horizontally, passes through the foramen lacerum, turns upwards after the passage, and then enters the cavern-

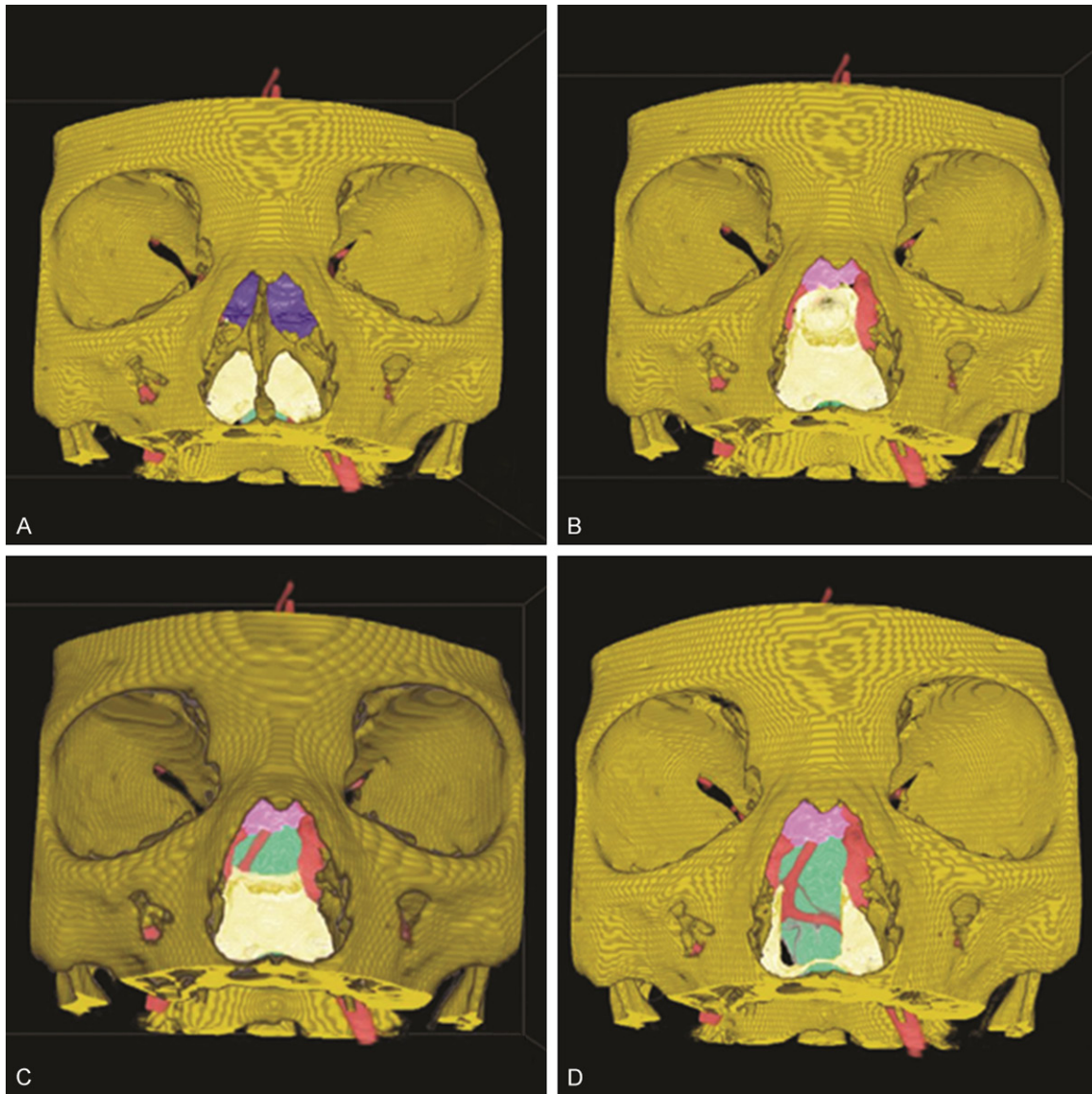


Figure 3. Surgical simulation via the transnasal route to the clivus. A. In the transnasal surgery, the middle and inferior nasal concha are removed with the nasal septum preserved. The anterior wall and the opening of the sphenoidal sinuses are preserved; B. The pituitary gland and the internal carotid are exposed after the removal of the anterior, lateral wall of the sphenoid sinus and the bone of the sellar floor; C. The brainstem and basilar arteries behind the clivus are exposed after the further removal of the inferior wall of the sphenoid and the posterior bone; D. The coverage of the opened window for the clival surgery is shown after the further removal of the inferior clival bone. The cranium is in amber, the clival bone in yellow, the sphenoidal sinuses in blue, the pituitary gland in purple, the brainstem in spring green, the internal carotid and the basilar arteries in red.

ous sinus. This study shows that the shortest distance between the bilateral internal carotid arteries is 18.8 ± 1.9 mm, and the two arteries at the level of the sellar floor have a distance of 19.5 ± 1.0 mm. Beside the anterior clivus is the foramen lacerum, an irregular aperture formed between the posterior clinoid process and the petrous apex with the opening tilting medioanteriorly. The length of the foramen lacerum is

approximately 1 cm. It is bordered anteriorly by the corpus ossis sphenoidalis, inferior pterygoid process, and the greater wing of the sphenoid bone. Posterior and lateral is the apex partis petrosae of the temporal bone, and medial is the basilar part of the occipital bone. The internal carotid arteries and the accompanying sympathetic nerves enter the cranium via the upper part of the foramen (Figure 2).

Table 2. Measurement of the structures surrounding the hypoglossal canal

Distance	$\bar{X} \pm s$ (mm)
The length of the hypoglossal canal	7.7 $\pm$ 0.8
The distance between the midpoint of the clival inferior rim to the line connecting the bilateral hypoglossal canals	4.5 $\pm$ 1.6
The distance between the midpoint of the clival inferior rim to the left hypoglossal canal	16.7 $\pm$ 2.1
The distance between the midpoint of the clival inferior rim to the right hypoglossal canal	17.6 $\pm$ 1.0
Inner diameter of the hypoglossal canal	24.9 $\pm$ 1.3
Outer diameter of the hypoglossal canal	32.1 $\pm$ 1.9

Surgical simulation via the transnasal route to the clivus

Transnasal surgery to the clivus is often performed through unilateral nose with a wider nasal meatus. The opening of the sphenoidal sinuses is located in between the superior nasal concha and the nasal septum, which serves as an ideal landmark for anatomical reference. During the operation, the anterior spina ossis sphenoidalis may be preserved as the landmark of the midline. Alternatively, the midline can be defined by the sellar floor or clival recess. In the VR model, after opening the sphenoidal sinuses, a virtual drill is used to remove the anterior wall of the sphenoid sinus. While extending the drilling laterally in the anterior wall, bone removal should be restricted within the medioinferior side of the pterygoid canal. It is also observed that the cavernous part of the internal carotid artery causes a bulge in the lateral wall of the sphenoid sinus. To visualize the structures adjacent to the clivus, drilling is done from the midline area of the clival bone so that the internal carotid arteries are exposed in the midline region. The arteries define the lateral boundaries for removal of the clival bone. Drilling of the inferior wall of the sphenoid is then done so that the exposure extends to the middle and inferior parts of the clival bone. To remain restricted within the lateral boundaries, drilling in the bone area should proceed very slowly. In the VR system, each area is assigned a specific color. When the surgeon makes an error during drilling, an immediate change in the color(s) around the surgical area will be recognized. For example, if the color red, which represents blood vessels, appears in the middle of the bone where drilling is occurring, the surgeon will notice the color change to red immediately. Note that in some cases the clival bone is very thin (**Figure 3**). The measurements indicate that the average shortest distance between the bilateral boundaries is 18.0 $\pm$ 1.8 mm. Right above the opened window is the pituitary gland, which prevents the

visualization of the dorsum sellae and the posterior clinoid process. These two structures define the superior boundary of the exposure. The inferior border of the opened window is the inferior rim of the clivus. The average distance between the superior and inferior borders is 40.7 $\pm$ 1.6 mm.

Surgical simulation via the transoral route to the clivus

After the occipital joint of the atlas is exposed, the virtual drill is used to remove the clival bone from the midline area of the inferior clivus. The drilling begins from the inferior rim of the clivus and then moves upward toward the vertical line formed by the bilateral hypoglossal canals. The measurements which define the boundaries for the surgical window are shown in **Table 2**. Careful drilling is necessary while removing the lateral bone. Caution should be taken to avoid injuries to the hypoglossal nerve.

To expand the exposure upward, a part of the hard palate and the posterior bone of the nasal septum need to be removed. The inferior and anterior walls of the sphenoid sinus are drilled to expose the superior part of the clivus. Drilling should be done closely along the midline and gradually move laterally to prevent ruptures of the internal carotid arteries on the sides. In addition, the drilling needs to be horizontally restricted within the two internal carotid arteries to avoid injuries to the inferior petrosal sinus of the petrous oblique fissure. The resultant opened window exposes the entire clivus. When visualized from the oral region to the skull base, the brainstem and basilar arteries are readily observed in the cranium, as shown in **Figure 4**.

The simulation indicates that a safe area opened for transoral surgery can be defined as follows. The upper boundary is the sellar floor and the lower boundary is the inferior rim of the clivus. The average distance is 40.7 $\pm$ 1.6 mm. When drilling the clival bone toward the lateral

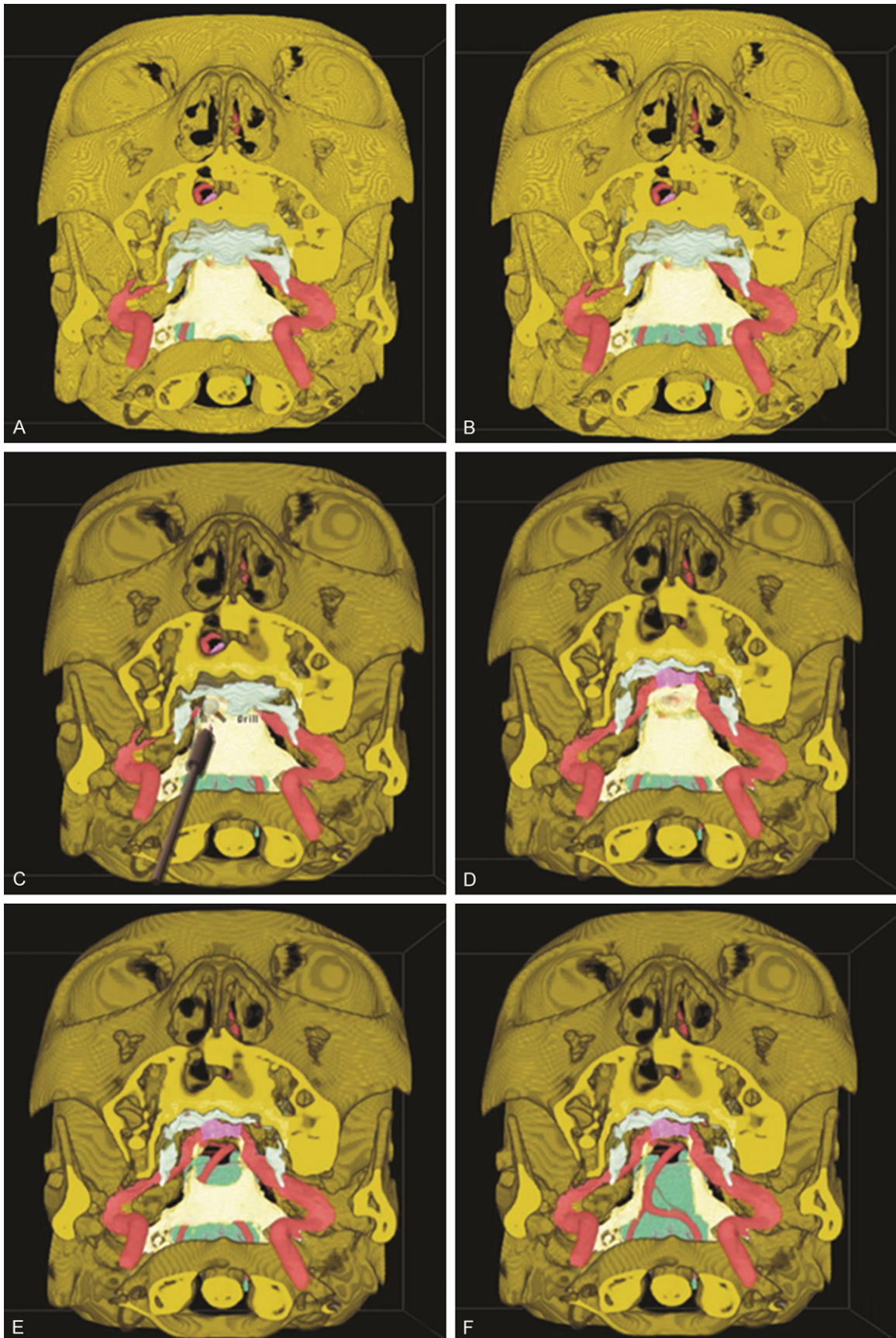


Figure 4. Surgical stimulation via the transoral route to the clivus. A. At the inferior clivus, the virtual drill is used to remove the clival bone within the internal foramen of the hypoglossal canal; B. Removal of the clival bone between the bilateral hypoglossal canals exposes the anterior brainstem and the vertebral artery. Caution should be taken to avoid damage to the structures of the hypoglossal canal; C. Superior clivus exposed after removal of a bony part of the hard palate; D. The sphenoid exposed after the removal of the inferior and anterior walls; E. The pituitary gland and internal carotid arteries besides the clivus exposed after the removal of the sellar floor, the lateral wall of the sphenoid, and the posterior bone; F. The entire clival bone exposed in the opened window. The brainstem and basilar arteries behind the clivus were also observed.

sides at the level between the sellar floor and the hypoglossal canals, the working area should be restricted within the two internal carotid arteries. The average distance is 18.0 ± 1.8 mm. When drilling toward the lateral sides at the level between the hypoglossal canals and the inferior clivus, the area should be limited within the internal foramen of hypoglossal canal. The average width of the window at the level is 24.9 ± 1.3 mm.

Discussion

The clival VR model: the technique and the features

The clivus is surrounded in very close proximity by vital structures which make the anatomy in the clival area complicated. High quality images are required to establish the clival VR model in order to achieve visualization and surgical simulation. In this study we describe a VR model that we created to represent the anatomical environment of the clival area and allow surgical simulation. Dual imaging modalities (i.e., CTA and MRI) helped identify the various structures with different contrasts and signal intensities so that the revealed anatomy is more complete. CT was able to demonstrate the bone in great detail, and some parts of the bone were color coded. The blood vessels visualized with CTA had round lumens and less variability in diameter. MRI T1WI showed the brainstem and pituitary gland with the boundary clearly defined. The VR model has considerable advantages compared to conventional dissection of corpses and 2-D cross-sectional images, because its use is unlimited and it provides more information on three-dimensional spaces. And even more importantly, the model can be customized for individual patients and tailored according to the pathological condition for preoperative surgery.

In the surgical procedures, the window space opened for the clival operation is very critical. The window should be kept within the lateral boundaries defined by the bilateral carotid arteries and the hypoglossal canals on an indi-

vidual basis. The average lateral spacing is 9 mm from the midline when drilling in the superior and middle clivus. But the width can be narrower in some individuals according to the measurements from the VR model of the distances between the bilateral boundaries for the posterior vertical part of the internal carotid arteries and the vertical part at the sellar floor. Caution needs to be taken to identify the critical anatomical landmarks and only drill the bone of the clivus. The average distance between the internal foramen of the hypoglossal canals is 24 mm. When drilling at the inferior clivus, the exposure should be kept strictly within the borders so as to keep the hypoglossal nerves intact.

The reconstruction methods

Surface rendering and volume rendering are two commonly used methods for reconstruction of anatomical structures from medical imaging [16-18]. Surface rendering is a fast approach for reconstructing the intracranial blood vessels identified by CTA. It is efficient in reconstruction, and has minimal hardware and software requirements. However, it results in edges that are not as clean as those obtained with volume rendering. In addition, it does not contain information from the underlying tissues, and thus it is not feasible for clinical diagnosis, preoperative evaluation, and surgery simulation. VR is based upon the method of volume rendering, which allows the accurate representation of the anatomical structures, detailed visualization of the three spatial dimensions, and identification of the spatial relationships of an anatomical area in relation to common landmarks. However, the computational loading of volume rendering is very exhaustive and requires much higher hardware standards.

Comparison of the transnasal and transoral routes

Surgical operation in the clivus takes the anterior course regardless of the transnasal or transoral route being taken. Understanding the

anatomy and experiences with surgery is necessary. To avoid damage to the surrounding structures, it is critical to determine the midline. The VR model indicates that the bony nasal septum and the vomer are located in the midline. These structures can be used as a reference point. In the sphenoid sinus, the midline can be determined by the sellar floor and the clival recess. If the protuberance of the internal carotid artery can be localized during the surgery, the gap between the bilateral protuberances also helps to define the midline. The surgical space of the transoral route is relatively larger than the transnasal space. The pharyngeal tubercle is also found along the midline when the inferior clivus is exposed during the surgery. Access via the transoral route is relatively efficient with better viewing of the entire clivus.

The value of the clival VR model in surgical guidance

The simulation of the VR model offers a straightforward, three-dimensional, and interactive understanding of the size and shape of the clivus, and its relationships with the surrounding blood vessels and bones. It also demonstrates simulated operational procedures such as opening the surgical window, measuring the exposure distance and angles, and determining the critical boundaries in relation to key structures such as the brainstem and arteries. The information is very useful for planning minimally invasive neurosurgery [3, 19-21]. The VR model helps to identify suitable landmarks and spacing with respect to the clival pathology so as to minimize the affected areas and maximize the resection of the lesion. It is envisioned that digitalized VR modeling will be helpful for understanding the anatomy of the clivus and its surgical approaches by offering immediate results and unlimited practice at the preoperative stage. VR significantly saves cost and time in training neurosurgeons, and thus is increasingly being recognized as a future mainstream procedure for preoperative planning and practice [22-25].

Limitations

There are inevitable differences between the clival VR model and reality in clinical surgery. The removed and relocated tissues during surgery cannot be demonstrated in the model. The lack of tactile sense and proprioception is also a disadvantage of VR simulation surgery.

Additionally, the model is unable to reveal the dura, soft tissues and some cranial nerves, which affects the representation value and thus its applicability for surgical guidance. Also, the three-dimensional measurements might be slightly different from those in real surgery, which is another shortcoming. Finally, in the present study, the model was established from the unaffected clivus of patients. Patients with a pathological clivus may be needed for refining the VR model.

Conclusions

The complicated anatomy of the clival region makes clival surgery arduous. Traditional surgical planning and research is often based upon the dissection of corpses and 2-D cross-sectional images. Three-dimensional information may be conceptualized in experienced surgeons, but is inaccessible to novices. The 3-D clival model enables preoperative planning and stereography, which are very useful for inexperienced surgeons. In contrast to the intra-operative neuronavigational system for guiding the surgeon during the surgery, our VR model is for preparing the surgeon at the preoperative stage. The measurements derived from our VR model are comparable to those of previous observations, which directly support the validity of our method. The measurements can be taken flexibly within the 3-D space beginning and ending at any point. The flexible viewing and exploration will help the surgeon to gain a VR impression and may bring about the déjà vu phenomenon when the surgeon performs the real surgery. The model is more objective and thus is more likely to be accepted as standard. The VR model may be considered as an aid to conventional surgical routines [26].

Disclosure of conflict of interest

None.

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