

# Application of Keyhole Microneurosurgery in China

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**Key words:** China; Keyhole Surgery; Microneurosurgery

## INTRODUCTION

Microneurosurgery made its debut in the early 1960s. It became popular in the medical field and became a primary operation method in neurosurgery since it improved the efficacy of neurosurgery with a less surgery-related injury. Over the past five decades, the accumulation of experience of microsurgery, improvement of microsurgery techniques, refined micro-instruments, and advanced preoperative diagnostic imaging allowed the evolution of microneurosurgery techniques and further reduced surgery-related trauma. The advanced development has made it possible for a neurosurgeon to treat more sophisticated lesions with smaller craniotomy. Keyhole neurosurgery, the combination of modern microsurgical techniques, preoperative imaging, neuroendoscopy, and modern minimally invasive surgery concept, is one of the

techniques representing the medical advancement from microneurosurgery to minimally invasive neurosurgery.

The concept of keyhole microsurgery was introduced in 1971 by Wilson, who advocated using microsurgical techniques to refine conventional microsurgery approach.

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Access this article online

Quick Response Code:



Website:  
www.cmj.org

DOI:  
10.4103/0366-6999.211884

**Received:** 28-03-2017 **Edited by:** Li-Min Chen

**How to cite this article:** Chen LG, Chen SD, Huang GF, Huang Y, Kang DZ, Lan Q, Li G, Li XG, Liu ZX, Qi ST, Tian XH, Wang GL, Wang S, Wang XY, Wang YF, Wang YJ, You C, Yu YB, Yue SY, Zhang D, Zhang JM, Zhang JN, Zhang JT, Zhang SZ, Zhang X, Zhang YZ, Zhao JZ, Zhao WG, Zhao YL, Zhou DB, Zhou LF; on behalf of the Keyhole Microneurosurgery Consensus Group of Chinese Neurosurgical Society. Application of Keyhole Microneurosurgery in China. Chin Med J 2017;130:1987-94.

However, the concept did not accept until 20 years later, for the small anatomic window he advocated was just for saving operation time rather than authentic keyhole concept in contemporary neurosurgery: operating with a minimum of trauma while achieving maximal surgical efficiency. In 1991, Fukushima *et al.* first reported their surgery on anterior communicating aneurysm clipping through the interhemispheric keyhole approach with a 3 cm-diameter craniotomy.<sup>[1]</sup> In 1999, Perneczky's monograph on keyhole microsurgery<sup>[2]</sup> was published, which marked the maturity of this technique.

Keyhole neurosurgery is a new minimally invasive microsurgery based on precise microneurosurgical techniques. With anatomic and pathological structures and "keyhole effect", this method is precisely designed to minimize anatomic window for an ideal exposure of lesions that reduces unnecessary intracranial structural exposure or destruction. The "keyhole" is small but crucial, with keyhole bone window as its figurative summary. Choosing the right size and location of the craniotomy is based on the operation needs in accordance with the principle of "large enough for treating the lesion while minimizes approach-related trauma." With current techniques, bone windows within 3 cm in diameter are sufficient for the operation of microsurgery for most of the deep lesions. In general, a 4-cm incision and a cranial bone window about 2.5 cm in diameter are used in the surgery.

The minimal exposure and minimal invasive operation of the keyhole microsurgery have clear benefits for patients, including less intraoperative injury, less postoperative infection risk, less surgery-related complication, shorter hospitalization time, less cost of treatment, and optimal cosmetic outcome, which improves patient's acceptance of the surgery. In addition, surgeons can spend more time and pay more attention to the treatment of lesions, thus improving the operation quality; it can reduce the workload of nurses as well.

To standardize and promote the keyhole microsurgery in neurosurgery, the Chinese Neurosurgical Society has organized relevant experts and scholars to compile "Consensus on the Application of Keyhole Microneurosurgery in China" from November 2015, and the final draft was approved in December 2016. This is intended to improve neurosurgeons' knowledge of keyhole microsurgery technology, to standardize the operations, and thus to promote the enormous development of minimally invasive neurosurgery in China.

The levels of recommendations for keyhole approaches are classified as following standards: Level I – evidence obtained from meta-analysis or systematic review of randomized controlled trials; Level II – evidence obtained from at least one randomized controlled trial; Level III – evidence obtained from well-designed control studies, case-control studies, and cohort studies; Level IV – evidence obtained from multiple time series designs with or without the intervention; Level V – opinions of respected authorities,

based on clinical experience, descriptive studies, or reports of expert committees.

## PREOPERATIVE PREPARATION OF KEYHOLE MICROSURGERY

Keyhole microsurgery is based on advanced development of microsurgical techniques, which requires surgeons to have adept operation skills and rich clinical experience. Sophisticatedly designed surgical instruments are also needed.

### Accurate preoperative planning for keyhole microsurgery approach

Meticulous preoperative planning is crucial to a successful keyhole microsurgery. Every step, from skin incision to cranium closing, should be taken into consideration. Patient's lesions and anatomic structure are important basis for selecting an appropriate keyhole approach. If the surgery is complicated, alternative approaches should be considered for unplanned events.

The dissection practice for the application of keyhole microsurgery approach can improve surgeon's adaptation of microsurgery instruments, familiarity of the intracranial anatomy, and exposure zone in different keyhole approaches, and improve the confidence of the surgeons in keyhole microsurgery. Therefore, it can be used as a basic training before the clinical application.

### Surgical instruments

#### Microscope

A high-quality surgical microscope is essential for a successful keyhole microsurgery. As the bone window is narrow, it is necessary to constantly adjust the microscope angle to change the projection area to make efficient illumination. As a result, a surgical microscope with electromagnetic lock adjustment function can better satisfy the requirements.

#### Refined microsurgery instruments

A gun-type rod-shaped instrument can effectively increase the visual space in the operation, so as to avoid the microscope field from being shadowed by the fingers of the surgeons or the instrument itself. For a more successful keyhole microsurgery, rod-shaped or narrow-wing micro-scissors, dissectors, or aneurysm clip holder should be used when possible. Among them, the cutting-head tip of the micro-scissors will be slightly curved. Many of the existing tumor removal equipment, such as ultrasound aspirator, radio frequency (RF) knife, and laser knife, all have rod-shaped or pointy head handle, are convenient for the resection of tumor through the keyhole approach.

#### Power system

In the operation, a 3-mm diameter hole is created in the skull, and a bone window with 2.0–2.5 cm diameter is formed by taking out the bone flap. After the surgery, the small bone flap is placed back to its original position and fixed. If necessary,

the inner plate of the bone window edge can be grinded out to expand the field of vision. A micro-grinding drill measured to be 8–10 cm long and 0.3 cm in distal diameter is more suitable for the removal of the anterior and posterior clinoid processes, opening the back of the internal auditory canal and other deep bone removal operations through the keyhole approach.

#### **Automatic retractor**

As the keyhole microsurgery has small operational space, and almost only one surgeon is performing the surgery, an automatic retractor is also one of the necessary surgical instruments as it does not affect the field of view, and it can fix the exposure zone under the surgical field of vision without the help of an assistant. Retractors fixed by bedside support arm work best, so the flexible retractor is easy to adjust and control, and retractors that fix to the skull should be avoided.

#### **Neuroendoscope**

The development and improvement of a neuroendoscope provides favorable conditions to the keyhole microsurgery, which can improve the poor field of vision during operation.<sup>[3-7]</sup> Neuroendoscope with a diameter of 2–4 mm can provide a bright, detailed image of deep lesions, and the near to the lesion, the better and clearer the image magnification will be. Angular endoscope can also show blind spots which are difficult to be identified by the microscope, reducing the traction and injury to normal tissues, and improving the surgical outcome.

#### **Head holder**

A head holder can provide a suitable head position to reduce intraoperative traction of brain tissue.

#### **Operating bed**

An electrically powered operating bed is very useful for adjusting the head and body positions of the patient for observations at different directions under the microscope during operation, and it also helps the surgeons to maintain a comfortable body posture.

#### **Other instruments**

Other instruments such as two brain spatulas, two aspirator tubes, bipolar forceps, or clip holder can be simultaneously used during the operation through keyhole approach. If necessary, a neuroendoscope can be used for observation and operation.

### **Preparation and sterilization of the operation area**

The skin incision in keyhole surgery is generally about 4 cm, so hair is not necessary for shaving off before operation. The shaving area may be 1 cm around the incision or comb the hair to two sides and make an incision in the hairline. To prepare for the operation, first wash and clean the hair, and use iodophor to clean the surgical area, followed by routine sterilization. A sterile drape may be applied to the operation area to isolate the surrounding hair. Mark the incision line with a sterile marker for identification.

## **COMMON KEYHOLE MICROSURGERY APPROACHES**

### **Supraorbital keyhole approach**

This approach is recommended at Level III<sup>[8-11]</sup> and IV<sup>[12,13]</sup>.

#### **Head position**

Lay the patient in a supine position. Use Mayfield head holder to fix the patient's head. Rotate the head about 10°–60° to the contralateral side depending on the site and size of the lesion. If ipsilateral mesial temporal lobe region and the middle cerebral artery M1 and M2 segments need to be exposed, rotate the head only about 10°–20°; for the suprasellar and rear sella lesions, rotate the head about 20°–40°; for the anterior skull base midline lesions such as olfactory sulcus meningioma, rotate the head about 40°–60°. Lean the head back for about 10°–15°, so that the frontal lobe goes backward because of gravity and leaves the anterior skull base to reduce intraoperative traction; slightly bending the head sideward about 5°–15° to the contralateral side is helpful for the contralateral approach surgery, and it also offers the surgeon a more comfortable operation direction.

#### **Incision**

Make an eyebrow incision which starts internally from the outer edge of the supraorbital foramen and ends externally at the outer edge of the eyebrow. Pay attention to protect the supraorbital nerve, and there is no need to shave eyebrows. Use plaster application to close eyelid fissure. Use iodophor to clean the eyebrows by the operation area and sterilize it in routine manner. Then, use sterile gauze to cover the eyebrows and surrounding area, followed by fixation of surgical drape and coverage with the surgical towels in the routine manner. Incise the skin, retract with an eyelid retractor, and separate the subcutaneous and frontal fascia with monopolar electrotome. Cut the temporalis fascia along the superior temporal line for 2 cm. The frontal periosteum is incised in a semicircle shape from the superior temporal line, and then stripped and flipped. The base is located in the superior orbital rim. Bluntly separate the temporalis muscle, push it to 1.0–1.5 cm behind the superior temporal line, and fix the tissue with suture to expose the operation area.

#### **Craniotomy**

Mill out a bone hole about 3 mm in diameter behind the frontal bone zygomatic process (keyhole position). The bone hole should be posterior to the temporal line, and the location should not be too low to avoid milling through the orbital wall. Use the milling cutter along the hole's orbital roof toward the back to take a bone flap about 2.0 cm × 2.5 cm, and try to avoid opening the frontal sinus. If the frontal sinus is opened, it should be tightly repaired. It can be sealed with gelatin sponge or bone wax or reinforced with glue if needed. Grind out the inner plate of supraorbital bone window edge to gain greater visual space. Some bone ridge protrusion in the anterior skull base can be removed through the space outside dura mater. Cut off a piece of flap-shaped dura under the microscope and with the base at the orbital rim. Use a brain spatula to lightly lift up the frontal lobe base to constantly

absorb cerebrospinal fluid (CSF), so as to decrease the brain pressure; further explore the skull base to expose and open chiasmatic cistern, carotid artery cistern to further release CSF, resulting in the collapse of the brain tissue which will incline and leave the skull base under the action of its own gravity, which provides an effective operative space.

### **Cranium closure**

Dura should be tightly sutured and drainage tube is not needed. Use skull lock or connector to fix the bone flap. Suture periosteum and myofascial layer by layer, use of metal cosmetic suture with continuous intradermal stitches, can greatly reduce surgical scars.

### **Exposure zones**

The supraorbital keyhole approach effectively exposes the frontal lobe base, anterior clinoid process, canalis opticus, olfactory sulcus, olfactory tract, optic nerve, optic chiasm, oculomotor nerve, anterior communicating artery, anterior cerebral artery A1 segment, pituitary stalk, diaphragma sellae, dorsum sellae, posterior clinoid process, basilar artery apex, posterior cerebral artery P1 segment, superior cerebellar artery proximal, front upper pontine and interpeduncular cistern, anteromedial temporal lobe, internal carotid, middle cerebral artery (M1, M2 segment, and part of M3 segment), anterior choroidal artery, posterior communicating artery; and contralateral carotid artery medial surface, anterior cerebral artery A1 and A2 proximal, middle cerebral artery M1 and M2 proximal.

### **Pterional keyhole approach**

This approach is recommended at Level III<sup>[14]</sup> and IV.<sup>[15,16]</sup>

#### **Head position**

Slightly lean the patient's head back, so that the frontal lobe inclines and leaves the orbital roof by gravity; rotate the head about 30°–60° to the contralateral side based on actual need: a greater rotation angle to the contralateral side is needed when the lesion is closer to the frontal end. Slightly bend the head about 15° to the contralateral side, to compensate for the upward inclination angle along the middle skull base.

#### **Craniotomy**

About 2 cm outside the keyhole, around the pterion, make an anterior hairline incision about 4–5 cm long. Incise the skin, subcutaneous tissue, and temporal fascia, separate the flap, and retract it with a hook. Incise the temporal muscle along the direction of the muscle fibers through pterion and expand it with the mastoid expander after separation. An osseous depression can be seen in the exposed central skull bone, which is the mark of the sphenoid ridge on the surface of the skull. Drill a bone hole about 3 mm in diameter on the bottom of the sphenoid ridge, and from this location, mill out a bone flap about 2.5 cm in diameter, and remove 1/2–2/3 of the lateral sphenoid ridge, if necessary, the edge can reach the lateral side of the supraorbital fissure. Centering on the sphenoid ridge, cut open the dura flap and retract it forward to expose the Sylvian fissure. Usually, the frontal and temporal lobes are exposed 1:1, and this ratio may be adjusted according to surgery needs by moving up or down

of the incision location, thus the location of the burr hole and the exposure area of the frontal and temporal lobes. For treating anterior communicating artery aneurysms, the Sylvian fissure are usually located at the lateral 1/3 of the bone window, 2/3 of the brain tissue exposed under the bone window is the frontal lobe, and the other 1/3 is the temporal lobe. The Sylvian fissure can be opened to reduce the tension between the frontal and the temporal lobe. For treating middle cerebral artery aneurysms or lateral posterior communicating artery aneurysms, the Sylvian fissure is usually placed in the center of the bone window, so that the temporal lobe can be slightly retracted after opening of the Sylvian fissure to fully expose field of surgery.

### **Cranium closure**

It is basically as same as that of supraorbital keyhole approach described above. The hairline incision can be sutured in the routine manner.

### **Exposure zones**

Pterional keyhole approach has the similar exposure to the blood vessels and neural structure as the standard pterional approach. It exposes (1) anterior circulation artery: ipsilateral posterior communicating artery, anterior choroidal artery, internal carotid artery, ophthalmic artery, middle cerebral artery M1 to M4 segment, anterior cerebral artery A1 and A2 proximal; contralateral cerebral anterior artery A1 and A2 proximal, middle cerebral artery M1 and M2 proximal, internal carotid artery's interior and bifurcation; (2) posterior circulation artery: basilar artery apex, superior cerebellar artery proximal, posterior cerebral artery P1 and P2a segment; (3) anterior cranial fossa, suprasellar region, parasellar, retrosella, cavernous sinus superior wall, front part of cavernous sinus lateral wall, sphenoid ridge, frontal pole, temporal pole, front end of middle cranial fossa, interpeduncular cistern, prepontine cistern, etc.

### **Subtemporal keyhole approach**

This approach is recommended at Level IV.<sup>[17]</sup>

#### **Head position**

Lie the patient in the supine position with shoulder elevated, and rotate the patient's head about 90° to the contralateral side of the lesion, and keep the zygomatic arch in the horizontal position; lean the head back about 15°, so as not to oppress the trachea; laterally bend the head 15° to the contralateral position, to compensate for the upward incline angle along the middle skull base. This head position allows the temporal lobe to incline and leave the skull base by gravity so the intraoperative tension is reduced.

#### **Craniotomy**

The skin incision is made in the front of and about 1 cm away from tragus. Starting from the superior zygomatic arch, make a vertical incision approximately 4 cm above the zygomatic arch. Incise the skin to separate the subcutaneous tissue, make sure to avoid damage to the frontal branch of facial nerve and superficial temporal artery. Make a Y-shaped temporalis fascia incision, and retract it to expose the surgical field. Longitudinally incise the temporal muscle and retract it to

both sides to expose the temporal bone squama. Drill a hole posterosuperior to the zygomatic arch base, and create a bone window about 2.0–2.5 cm in diameter with the milling cutter. Incise the dura in flap shape, and flip it to the inferotemporal. Gently lift up the temporal base, to gradually release CSF to reduce the intracranial pressure. Then, gradually go deeper to expose the edge of the tentorial incisura.

#### **Cranium closure**

It is basically as same as that of the supraorbital keyhole approach mentioned above.

#### **Exposure zones**

Lift up the bottom of the temporal to expose the lower part of the middle brain, the lateral upper part of the pons, posterior cerebral artery P2 segment and its branches, oculomotor nerve. The tentorium posterior incisura region can expose the supratentorial part of the trochlear nerve. Incise the free edge of the tentorium in the rear part of trochlear nerve and suspend it to expose the superior cerebellar artery, trochlear nerve, anterosuperior cerebellar, the lower part of the pons. Retract the margin of tentorium cerebelli between the oculomotor nerve and trochlear nerve, to expose the top of basilar artery, ipsilateral and contralateral posterior cerebral artery P1 segment. And, it can expose ipsilateral tractus opticus, internal carotid artery, posterior communicating artery, anterior choroidal artery, thalamus arteriae perforantes, posterior cerebral artery, and pituitary stalk.

### **Median suboccipital keyhole approach**

This approach is recommended at Level IV.<sup>[18]</sup>

#### **Head position**

Lie the patient in a prone position, and bend the head forward to fully extend the craniocervical junction.

#### **Craniotomy**

Make an upward suboccipital median incision that is 1 cm below the foramen magnum and approximately 4 cm long. Incise the scalp and sharply separate it along the midline, expand it with mastoid expander to expose occipital skull. Create a bone window about 2.5 cm in diameter from the trailing edges of foramen magnum, in the upward direction. Incise the dura in X shape and close the occipital sinus with cautery or suture. Open the cisterna magna, lift up the cerebellar tonsil, separate arachnoid adhesions, and expose the forth ventricle through the cerebellomedullary fissure approach.

#### **Cranium closure**

It is basically the same as that of supraorbital keyhole approach described above. Tightly suture the dura, and repair it if necessary.

#### **Exposure zones**

The suboccipital middle keyhole approach can expose the cerebellar tonsil and inferior vermis, posterior inferior cerebellar artery, the fourth ventricle, pons and medullary dorsal parts.

### **Retrosigmoid keyhole approach**

This approach is recommended at Level IV.<sup>[18-20]</sup>

#### **Head position**

The patient is laid in lateral prone posture. Rotate the patient's head about 10°–20° to the contralateral side from the lateral position, to provide a direct view angle with less retraction to the cerebellar hemisphere, and can successfully open cerebellopontine angle cistern. During the operation, based on the location of the lesion, the view angle can be adjusted by adjusting the degree of inclination (left and right) of the operating bed.

#### **Craniotomy**

Starting at the junction line of the external occipital protuberance and mastoid roots, about 1.5–2.0 cm posterior to the mastoid roots, make a vertical, downward incision about 4 cm long. Incise the scalp and muscles and expand them with the mastoid expander, then create a burr hole about 2.5 cm in diameter behind the mastoid. The top of the bone window is near the horizontal inferior margin of the transverse sinus, and its lateral edge is on the posterior edge of the sigmoid sinus. Close the mastoid air cells with bone wax if they are opened. Incise the dura mater in flap shape with its base locates at the sigmoid sinus. Retract the lower lateral cerebellum to the internal side and gradually open the cerebellum medulla lateral cistern to release CSF and to reduce intracranial pressure. Dissect cerebellopontine angle cistern and lateral cerebellar medulla cistern to expose anatomical structures.

#### **Cranium closure**

It is basically the same as that of supraorbital keyhole approach described above. Tightly suture the dura mater, and repair it if necessary.

#### **Exposure zones**

Via retrosigmoid keyhole approach, the following anatomic structures can be exposed: trigeminal nerve, facial nerve, acoustic nerve, posterior cranial nerve, lateral and anterior lateral pons, lateral cerebellar hemisphere, vertebral artery, posterior inferior cerebellar artery. For treating lesions at the posterior cranial nerve, the surgical incision and bone window position may go down accordingly.

### **Interhemispheric transcalsal keyhole approach**

This approach is recommended at Level IV.<sup>[21]</sup>

#### **Head position**

The patient is laid in the semi-sitting position with the head in the median position, forming a 45° angle with the horizontal line. After the bone flap is opened, tilt the head to the surgical side, so that the hemisphere inclines and leaves the midline, reducing the intraoperative traction.

#### **Craniotomy**

One centimeter beside the midline, make a linear incision about 4 cm long. The specific incision points are determined by the location of the lesion. Drill a cranial hole about 3 mm in diameter beside the midline, and mill out a small bone flap about 2 cm in diameter to expose the sagittal sinus edge

besides the midline. Incise the dura mater in flap shape, and flip it to the side of the midline. Carefully separates the arachnoid membrane near the sagittal sinus, without causing any damage to the large draining veins. If necessary, free up a section of the vein by separating the arachnoid on its surface and to increase the degree of displacement. Use a brain spatula to retract the lateral cerebral hemisphere, gradually go deeper, and incise the callosum longitudinally for about 2 cm to reach the lateral ventricle.

#### **Cranium closure**

It is basically the same as that of supraorbital keyhole approach mentioned above.

#### **Exposure zones**

Through interhemispheric transcallosal keyhole approach, the following anatomic structures can be exposed: the distal segment of the anterior cerebral artery, body of the lateral ventricle, third ventricle, thalamus, etc.

## **KEYHOLE MICROSURGERY TECHNIQUES**

### **Effective intracranial operating space**

Limited exposure and narrow space make it hard to operate in a microsurgery. Inappropriate brain traction will lead to more severe damage to the brain. Releasing the CSF can make larger effective intracranial operating space for keyhole surgery.

An important step in keyhole surgery is to reduce the intraoperative intracranial pressure to increase the intracranial operating space. The most effective way is to open the brain cistern to release CSF, and the brain tissue will retract on its own. For patients with high intracranial pressure, if the dehydrating agent fails to work effectively, the ventricle needs to be punctured to release CSF. For some lesions that largely occupy the intracranial space, the local brain cistern has been compressed and disappeared, so it may be difficult to release CSF during operation. To solve this problem, lumbar puncture the subarachnoid and place the shunt before the operation for intraoperative releasing of the CSF, thus reducing the intracranial pressure. Some scholars conduct conventional lumbar shunt before operation.

When keyhole surgery is performed in the skull base, it is critical to confine the surgical bone window to the skull base. For example, in the supraorbital keyhole approach, the incision is hidden in the eyebrows, and the bone window reaches the superciliary arch; in the subtemporal keyhole approach, the temporalis is separated and distracted to both sides to avoid the retraction of temporal muscle flap towards the temporal base in the conventional approach, and to prevent the surgical field from being blocked by the zygomatic arch. The keyhole approach gets rid of useless structural damages and tissue exposures to retain the effective operation space to satisfy the actual needs.

### **Bleeding control during aneurysm operation**

The steps of aneurysm clipping in keyhole surgery are the same as these of conventional microsurgeries, even

for treating ruptured aneurysms the technique would be the same. The surgeon with rich experience in correctly dealing with accidental bleeding during various surgeries under the surgical microscope can use the same methods to treat unexpected bleeding during keyhole surgery (Level II recommendation,<sup>[22]</sup> Level III recommendation,<sup>[23-26]</sup> and Level IV recommendation<sup>[27,28]</sup>).

In keyhole surgeries, effective control of the parent artery is the key to the success of aneurysm surgery, and the dissection of parent artery and aneurysm neck is particularly important. In the keyhole approach, various parts can be dissected and exposed in order, and the aneurysm neck can be dissected after effective control of the parent artery. However, rupture of aneurysm before effective control of the parent artery is still possible. When it bleeds furiously, two aspirators can be used in the surgery: the one with a larger suction head is used to aspirator the blood at the ruptured aneurysm, and the one with a smaller suction head is used to aspirator the blood in the surgical field. When the surgical field is clear, rapidly dissect and temporarily occlude the parent artery, or directly dissect the aneurysm neck and then clips it if possible. Use of cotton pads to inappropriately compress the ruptured aneurysm should be avoided as it will result in accumulative intracranial hemorrhage and cause acute brain swelling. If necessary, the aneurysm can be clipped preliminarily, and its position can be adjusted after bleeding is under control.

### **Surgical strategy for large tumors**

During keyhole surgery, due to the keyhole's amplification effect, intracranial field widens with increasing distance from the approach entrance, an ideal field of view of the deep structure can be obtained. The deeper the intracranial location, the larger field of view can be obtained through a small bone window by adjusting the angle of the microscope. This large field of view helps the surgeon operates much easily. Furthermore, all parts within the field of view can be observed in details by adjusting the angle of the microscope.

For deep brain tumors over 3 cm in diameter, there are numerous complicated nerves and vascular structures surround the lesion so that which is removed piece by piece in conventional approaches. Therefore, a bone window about 2 cm in diameter can meet the basic requirements of such surgeries without extending time of tumor removal. The cavity created after the tumor removal provides a gradually increasing surgical space, and it also allows the surrounding tumor tissues to gradually drift to the central field of view after intra-tumor decompression, leading to the complete removal of tumors (Level IV recommendation<sup>[4,29]</sup>). Use of RF knife, laser knife, and ultrasonic suction device are beneficial for the removal of large tumors and can greatly shorten the operation time.

In the subtemporal keyhole approach, after the removal of petrous bone, lesions at the posterior fossa can be treated

through the incision at the tentorium; in the retrosigmoid keyhole approach, residual tumors inside the auditory canal can be resected by removing the posterior wall of the internal auditory canal. In the supraorbital or pterional keyhole approaches, cavernous sinus tumor can be dissected by removing the anterior clinoid process or cut open the cavernous sinus along the oculomotor nerve. Combining a variety of keyhole approaches is a good way to treat huge tumors spanning the anterior and middle cranial fossa, or those spanning middle and posterior cranial fossa, avoiding the complex operation of a single approach (Level IV recommendation<sup>[30,31]</sup>). Keyhole surgery for the treatment of huge tumors can be individually designed according to the specific situation.

### Precise locating of the lesion

As the keyhole approach can reach the lesion only from one direction and the surgical approach may not be changed during operation, the precise preoperative locating of the lesion is the key to the success of the keyhole surgery. Most of the lesions are at certain intracranial anatomical locations, such as aneurysms at various parts, sella tumors, cerebello-pontine angle lesions, intraventricular lesions, and pineal region tumors. For these lesions, no additional locating is needed for the selection of an effective keyhole approach.

The neuronavigation system provides assistant to the design of individualized keyhole approach, especially for the precise positioning of small lesions in the brain parenchyma. It can also help surgeons know the progress when removing large tumors, so as to reduce unnecessary intracranial exploration.

### The appropriate treatment of surgical incision

Although the skin incision within eyebrows is relatively small in the supraorbital keyhole approach, compared to the hairline incision, it is still exposed and not suitable for patients with light eyebrows; and when subcutaneous tissue or the skin from the opposite sites of the incision fails to match well, it will easily cause defects in the appearance of the eyebrow. Coagulation should be minimized during cutting and separation to prevent postoperative tissue shrinkage. When closing up the incision, the layers should be carefully matched and should be sutured subcutaneously with noninvasive metal sutures. If necessary, tape can be used to further pull together and close the skin incision. Change dressings after surgery in a timely manner to prevent incision from errhysis and incrustation which delay healing. Because the eyebrows have loose subcutaneous tissue, it is prone to subcutaneous hydrops. If it happens, pressure bandage or puncture drainage should be used.

When the keyhole surgery is performed at the skull base, the different keyhole approaches may open the frontal sinus, mastoid air cells, petrous bone air cells, anterior clinoid process air cells, and corresponding repair at the skull base is required to prevent postoperative CSF leakage.

### Suggestions for less-experienced surgeons

Surgeons who are new to the keyhole surgery should not blindly pursue for a minimized bone window, but rather focus on understanding the concept of minimum invasion in the keyhole surgery and to have a bone window as small as possible based on their experience. Initially, a larger bone window can be made, and smaller ones can be made as the surgeons become more and more experienced. Alternatively, the surgeons can have a large incision with a small bone window. If needed, the bone window can be quickly expanded by the milling cutter and change to conventional craniotomy approach. Furthermore, surgeons can be trained in anatomic dissection to familiarize themselves with the keyhole surgery and the indications for different approaches. This is also an effective way to improve the confidence of the surgeons, and to ensure the surgery is performed safely.

In general, keyhole approach can meet the basic requirements of most neurosurgeries and can be further applied as a minimally invasive technique. It is based on the extensive experience in microsurgery, and surgeons needed to be trained in microdissection and then adapt and improve these skills. However, small craniotomies also have some restrictions. The limitations are as follows: In the keyhole approach, the space for operation is limited, and the operational orientation is essentially fixed, so it is difficult to change the orientation of surgical approach; in most cases of intraoperative aneurysm bleeding, because of the limited space for the assistant to operate, the surgeon himself will need to control bleeding and clipping of the aneurysm, which requires detailed preoperative planning. If it is expected that a multi-angle approach is needed for the surgery, craniotomy with a large bone flap is more appropriate. Patients with severe subarachnoid hemorrhage or serious disturbance of consciousness may suffer from postoperative cerebral vasospasm or intracranial hypertension, so they should be treated with craniotomy with large bone flap at the early stage, if necessary, receive decompressive craniectomy. For large tumors close to the surface of the cortex or arteriovenous malformations, the whole lesion needs to be exposed, and craniotomy with a large bone flap is a more appropriate approach. For surgeries that are known to have a difficult to relieve postoperative high intracranial pressure, craniotomy with a large bone flap is more beneficial.

The advanced development of science and technology also contributes to the development and improvement of keyhole microsurgeries. For example, in recent years, the hybrid surgical platforms<sup>[32]</sup> and simulated operation through three-dimensional printed solid brain model<sup>[33]</sup> became available, and provide strong support for the development of keyhole microsurgeries.

Accurate preoperative planning and adequate dealing with intracranial lesions are the precondition for success and safety of keyhole surgery. Due to the limited space, details are not presented here. Related publications can be read before preparation if necessary.

In conclusion, the keyhole approach can meet the basic requirements of most neurosurgeries and can be further applied as a minimally invasive technique. However, keyhole microsurgery is based on the extensive experience in microsurgery, and the surgeons needed to be trained in microdissection and then adapt and improve these skills.

### Financial support and sponsorship

Nil.

### Conflicts of interest

There are no conflicts of interest.

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