Minimally Invasive Supracondylar Transtubercular (MIST) Approach to the Lower Clivus

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Key words
- Clivus
- Endoscope-assisted surgery
- Far-lateral approach
- Jugular tubercle
- Microsurgical anatomy
- Supracondylar transtubercular approach

INTRODUCTION

The far-lateral approach (FLA), consisting of a lateral suboccipital craniotomy with removal of the C1 arch (Figures 1 and 2), has been the primary surgical approach used to access lesions involving the inferior clivus, pontomedullary junction, lateral medulla, vertebralbasilar junction (VBJ) and posterior-inferior cerebellar artery (PICA) (2, 5, 10-12, 14, 15, 21, 22, 24, 27, 28, 31). Depending on the localization of the lesion and the anatomic characteristics of the surrounding structures, the surgeon may be required to perform a vascular transposition of the vertebral artery or to further drill osseous obstacles, in order to extend the exposure of the basic FLA. The trancondylar extension involves the extradural removal of the posterior third of the occipital condyle (Figures 1 and 2). Further exposure can be achieved by removing the jugular tubercle (JT), which significantly improves access to the anterolateral brainstem and the structures located in the premedullary cisterns (Figures 1 and 2). Drawbacks to the extended FLAs include the morbidity of a large incision extending into the upper cervical spine, the exposure and manipulation of the horizontal V3 segment of the vertebral artery (VA), and operative time.

METHODS

A total of 10 cadaveric specimens (20 sides) were included in this study. The arteries and veins were infused with colored silicone. Using ×3 to ×40 magnification, the microsurgical anatomy was examined bilaterally while performing the minimally invasive supracondylar transtubercular (MIST) approach and the far-lateral supracondylar transtubercular approach. In addition, the endoscopic view through the MIST was examined in five fresh cadaveric specimens (10 sides).

RESULTS: The MIST approach provided exposure of the inferior-middle clivus, the anterolateral brainstem, and the premedullary cisterns, including the PICA-VA and vertebralbasilar junctions. The endoscope provided a clear view of cranial nerves III through XII, as well as the vertebralbasilar system. The FLST approach increased visualization of the anterolateral margin of the foramen magnum; otherwise, the surgical view is similar between the MIST and FLST approaches.

CONCLUSIONS: The MIST approach could be considered as a potential alternative to the FLST approach in the treatment of lesions involving the inferior and middle clivus, and anterolateral lower brainstem; it does not require a C1 laminectomy, significant disruption of the atlanto-occipital joint, nor extensive exposure of the extracranial VA. Moreover, the MIST approach is an ideal companion to endoscope-assisted neurosurgery.
Figure 1. (A) Far-lateral approach and its extensions. A large hockey-stick or paramedian straight skin incision, extending into the upper cervical spine, is commonly selected for the far-lateral exposure (insert). In this cadaveric dissection, the muscles forming the margins of the suboccipital triangle have been removed to show the vertebral artery and the C2 nerve exiting between the C1 and C2 laminae. The vertical part and the distal loop of the V3 segment of the vertebral artery are exposed. The horizontal segment of V3 occupies the groove of the posterior arch of the atlas and pierces the dura just medial to the condyle. Before drilling, this segment of the vertebral artery must be identified in order to prevent iatrogenic vascular injury. Classic far-lateral craniotomy (green-colored area) includes the resection of the C1 hemilamina. The transcondylar approach includes drilling of the posterior third of the occipital condyle until reaching the posterior wall of the hypoglossal canal (oblique red dotted lines). The supracondylar transtubercular extension of the approach (yellow dotted lines) involves drilling through the condylar fossa and the jugular tubercle. (B) Minimally invasive supracondylar transtubercular (MIST) approach. A small vertical or slightly S-shaped skin incision, centered approximately 2 cm medial to the mastoid process is chosen when performing the MIST approach (insert). A small lateral suboccipital craniotomy (green-colored area) is required; it includes the resection of the posterolateral rim of the foramen magnum and extends laterally until the medial edge of the sigmoid sinus. A small portion of the superior-posterior-medial edge of the occipital condyle is resected with minimal joint disruption. Next, the condylar fossa is drilled from superficial to deep in order to remove the jugular tubercle (red dotted line). (C) Lateral suboccipital craniotomy includes resection of the posterolateral rim of the occipital foramen and extends laterally until the medial border of the sigmoid sinus. Any bony impedance medial to the sigmoid sinus and occipital condyle is removed with a shaving burr. (D) Posteroinferior view of the occipital bone and foramen magnum. In the MIST approach, bony removal includes also a partial resection of the most superior-posterior-medial edge of the occipital condyle, and drilling of the condylar fossa above the condyle (red dotted line). Most of the occipital condyle is left intact. (E and F) Supracondylar and transcondylar extensions of the far-lateral approach. (E) Posteroinferior view of the occipital bone and foramen magnum. The supracondylar approach includes drilling through the condylar fossa (yellow dotted line). The condylar fossa is a depression located on the external surface of the occipital bone, behind the occipital condyle; there is often an emissary vein and associated posterior condylar canal through which the posterior condylar vein connects the vertebral artery venous plexus to the sigmoid sinus. The condylar fossa lies superficial to the jugular tubercle and lies between the jugular bulb laterally and the posterolateral portion of the foramen magnum medially. The transcondylar approach involves drilling of the posterior third of the occipital condyle. The soft cancellous bone of the condyle is removed until reaching the cortical bone that forms the condylar fossa and jugular tubercle. (F) Medial view of the occipital condyle, intracranial opening of hypoglossal canal until reaching the posterior margin of the hypoglossal canal, during the transcondylar approach (black dotted lines). The yellow dotted lines indicate the supracondylar drilling through the condylar fossa, above the occipital condyle and hypoglossal canal and extending anteriorly through the jugular tubercle. A., artery; Atl., atlanto-; Cap., capitis; Cond., condyle; Dig., digastric; For., foramen; Hypogl., hypoglossal; Jug., jugular; Lat., lateralis; M., muscle; Occip., occipital; Proc., process; Rec., rectus; Sig., sigmoid; Trans., transverse; Tub., tubercle; Vert., vertebral.
adequate flexion of the neck to open the ipsilateral craniovertebral junction. A 5-cm vertical, or slightly S-shaped, skin incision was made, centered approximately 2 cm medial to the mastoid process (Figure 1). The suboccipital muscles were dissected and separated from their attachment to the bone. A small, lateral suboccipital craniotomy was performed, including resection of the postero-lateral rim of the foramen magnum and extending laterally until the medial edge of the sigmoid sinus. Inferiorly and laterally, the craniotomy was extended with a shaving burr, over the condylar fossa and condylar canal to remove any bony impedance medial to the sigmoid sinus and occipital condyle (Figure 1). Condylar removal was limited to the upper medial posterior aspect. Access to the condyle was obtained by opening the superior-medial attachment of the joint capsule and depressing the capsule inferiorly. The capsule was >90% intact after resection (Figure 1). Bony removal included the drilling of the condylar fossa above the condyle to expose the roof of the hypoglossal canal (Figures 1 and 3). After exposing the roof of the hypoglossal canal, the extradural resection of the JT followed; the overlying dura was first separated from the cerebellum, and then the drilling was continued through the cancellous bone above the hypoglossal canal, medial to the jugular bulb, in a superoanteromedial direction approximately 45 degrees in the sagittal plane (Figure 3). The softer cancellous bone was drilled out first and then the harder cortical edges were thinned out and removed with a fine dissector. After performing the tuberculectomy, the dura was opened with a curvilinear incision extending medial to the sigmoid sinus, over the cerebellar surface, and then inferiorly and medial to the VA dural entry point, based toward the sinus and occipital condyle.

Figure 2. Intradural view of the far-lateral approach, transcondylar and supracondylar extensions. (A) The lateral suboccipital craniotomy has been performed and C1 lamina removed from the midline to the sulcus arteriosus. The dura mater has been opened and retracted laterally while the cellerellar tonsil is gently retracted upward and mediially. The glossopharyngeal, vagus, and accessory nerve arise from the posterior margin of the olive and ascend to reach the jugular foramen. The hypoglossal nerve arises along the front of the inferior olive anterior to the origin of the cranial accessory fibers as a series of rootlets that pass behind the vertebral artery as they enter the dural orifice of the hypoglossal canal. At its origin, the PICA may pass rostral or caudal to, or between, the hypoglossal rootlets. (B) The transcondylar extension of the far-lateral approach has been performed. The removal of the posterior third of the occipital condyle and lateral retraction of the dura mater provides a wider exposure of the lateral pontomedullary junction region. With a more lateral to medial and caudo-cranial view, the anterolateral portion of the foramen magnum and brainstem are visualized. At this stage, the prominence of the jugular tubercle blocks access to the basilar cisterns and lower clivus. (C) Drilling has been extended through the condylar fossa and the jugular tubercle has been removed extradurally; the dura mater has been retracted laterally into the space created by the removal of this bone. An increased visualization between the CN IX and CN X complex and CN XI is gained. Also, a greater working space is created when approaching the lower clivus. A., artery; Atl., atlanto-; CN., cranial nerve; Dent., dentate; For., foramen; Hypogl., hypoglossal; Jug., jugular; Lig., ligament; N., nerve; Occip., occipital; P.I.C.A., posterior inferior cerebellar artery; Vert., vertebral.

Adjuvative Endoscopy
In the fresh cadaveric specimens we performed the MIST approach; after an initial examination of intradural anatomical structures under the operating microscope, a rigid endoscope was introduced and guided into position. The endoscope was introduced through three different surgical corridors. The diameter of the endoscope was 2.7 mm, with an angulation of 30 degrees (Stryker; San Jose, California, USA). A three-chip digital camera (1188 HD, 5900 Optical Court, Stryker) was attached to the endoscope; illumination was provided with a xenon light source (X8000, Stryker). The video images were displayed on a video monitor (Vision Elect HD TV, Stryker) and stored with a digital capture device (SDC HD, Stryker).

RESULTS
Anatomic Considerations
The relationship of the anatomic structures must be considered when performing the extradural resection of the JT, in order to avoid neural or vascular injuries. The JT is located at the junction of the basilar and condylar portions of the occipital bone. In our cadaveric dissection, the mean distance from the posterior border of the intracranial opening of the hypoglossal canal to the apex of the JT was 14.0 ± 2 mm; the mean distance from the JT apex to the postero-medial edge of the occipital condyle was 25.9 ± 2.2 mm.

At the beginning of the tuberculectomy, drilling takes place between the intracranial openings of the hypoglossal canal and jugular foramen, at the base of the JT (Figure 3); in our specimens, the distance between these two foramens averaged 16.2 ± 1.0 mm. While drilling along the postero-medial edge of the condyle, the intracranial opening of the hypoglossal canal was located at a depth of approximately 9.8 ± 2.5 mm. The hypoglossal canal venous plexus occupied most of the canal, especially on the cephalic and posterior parts (Figure 3), providing a safe entry zone into the canal.

It is important to note that the accessory nerve, as well as rootlets of the IX and X cranial nerves, travels on the dura overlying the base of the JT (Figure 3); therefore, drilling of the tubercle should always be accompanied by sufficient irri-
Figure 3. Minimally invasive supracondylar transtubercular approach. Condylar fossa drilling, jugular tuberculectomy, and hypoglossal canal anatomy. (A) The dura has been cut parallel to the spinal accessory nerve to show its relationship with the base of the jugular tubercle. During the minimally invasive supracondylar transtubercular approach, extradural drilling is begun at the most posteromedial edge of the occipital condyle, parallel and lateral to the veins that communicate the perivertebral venous plexus and the hypoglossal canal venous plexus. The drilling is maintained medial to the posterior emissary and condylar vein and canal, between the intracranial openings of the hypoglossal and jugular foraminae (insert). (B) Upward retraction of the cerebellar tonsil allows visualization of the jugular tubercle (starred) as it projects anterior to the glossopharyngeal, vagus, and accessory nerves. When drilling the jugular tubercle, irrigation is very important to prevent thermal injury to the accessory nerve, which travels just above the overlying dura of the jugular tubercle. Also, the glossopharyngeal and vagus nerves may be injured if the dura is perforated either by the drill or the dissector. (C) The cancellous bone over the cortical bone of the hypoglossal canal has been removed. Venous extensions from the hypoglossal canal may project through the roof of the canal. The jugular tubercle is resected extradurally by continuing further drilling in an anteromedial direction. (D) The roof and posterior wall of the medial part of the hypoglossal canal have been removed and the venous plexus of the canal is encountered. Beneath this vein, the hypoglossal nerve bundles travel inside the canal divided in this specimen by a bony septum (starred). A meningeal branch of the ascending pharyngeal artery also travels inside the canal. (E) The venous plexus of the hypoglossal canal has been removed and the cancellous bone (starred) of the jugular tubercle can be seen anterior and superior to the canal. A., artery; Atl., atlanto-; Asc., ascending; Br., branch; CN., cranial nerve; Can., canal; Cond., condyle; Emiss., emissary; Ext., external; Men., meningeal; Occip., occipital; Occipitomast., occipitomastoid; Pharyn., pharyngeal; P.I.C.A., posteroinferior cerebellar artery; Plex., plexus; Post., posterior; V., vein; Vert., vertebral.
agination in order to prevent thermal injury to those nerves. The accessory nerve, as well as the glossopharyngeal and vagus, may also be injured if the dura is perforated either with the drill or with a dissector. Anterior to the JT, the anteroinferior cerebellar artery was frequently found coursing laterally away from the basilar artery, so care must be taken when drilling the anterior part of the tubercle so as to avoid injury to this vessel. When the extradural VA was found to be tortuous or accompanied by a high VBJ, the VA could be found in proximity to the inferomedial edge of the tubercle. Similarly, the lateral medullary segment of the PICA can form a lateral loop that may extend out close to the JT (25) (Figure 3). Also, if drilling at the base of the JT is extended too laterally, the jugular bulb may be disrupted and, if it is performed too anterolaterally, the inferior petrosal sinus may be injured as well.

Special care must be taken when opening the dura around the VA since the PICA or posterior spinal artery may originate or may travel close to that site (26). Once the dura is opened, the accessory nerve is the first cranial nerve to come into view (Figure 3). The rootlets of the accessory nerve arise from the postolivary sulcus and join to form a compact nerve bundle that travels close or adjacent to the dura before entering the jugular foramen. Anterior to the spinal accessory nerve, the dentate ligament is found with its two rostral extensions wrapping around the VA. The dentate ligament is paler than the neighboring nerves, extends in a sheet-like fashion from the lateral spinal cord toward the lateral dura and attaching as two fibrous strands rostrally. The strand of dentate ligament located between the spinal accessory nerve and the VA may be transected and also retracted, allowing better mobilization of the VA and improving the working space between the medulla oblongata and the VA when treating VBJ aneurysms or anterior foramen magnum tumors (3, 11, 13). The cisternal segment of the hypoglossal nerve exits from the preolivary sulcus of the medulla in the form of various rootlets (Figure 4). These project laterally across the premedullary cistern, passing usually over the vertebral artery and entering the hypoglossal canal (Figure 4). In our specimens, as well as in previous anatomic studies, the rootlets most frequently enter the hypoglossal canal in the form of two bundles (Figures 3 and 4) (1, 4). The intracranial opening of the hypoglossal canal is located just above the occipital condyle, usually in the area where the posterior and middle thirds of the condyle meet. The hypoglossal canal extends in an anterolateral direction, and exits at the level of the anterior and middle thirds of the condyle. In addition to the hypoglossal nerve, the hypoglossal canal contains a venous plexus, also named the anterior condylar vein and a meningeal branch from the ascending pharyngeal artery (Figures 3 and 4). A primitive hypoglossal artery may also traverse the canal. In our dissections, a bony septum located most frequently at the medial end, divided the hypoglossal canal in 20% of specimens (Figure 3). In another anatomic study, this septum was found in 28% of dissections (4). Each hypoglossal nerve bundle usually travels within the middle or inferior third of each canal. When a prominent meningeal artery is present, it usually travels between or on top of the bundles. When a bony septum is present, this artery will usually travel in the most posterior subcanal (1, 7).

The extradural drilling performed in the MIST approach, including the tuberculotomy, provides a posteroarterial to medial surgical view. There is increased visualization of the extradural VA, the PICA–VA junction, the VBJ and the proximal basilar artery with its perforating branches, the anteroinferior cerebellar artery and, in some cases, also the labyrinthine artery (Figure 5). With a more lateral to medial view, the anterolateral surface of the brainstem may be visualized, including the olive with the adjoining rootlets of the inferior cranial nerves. With a more superior viewing angle, the cisternal segment of the abducens nerve may be observed. With a more anterior view, the inferior and middle clivus are seen.

**Endoscope-Assisted MIST Approach**

In five fresh specimens, the adjunctive usefulness of the endoscope was assessed. Three distinct working views and trajectories were possible after performing the MIST approach (Figure 6). The removal of the JT allowed the lateral retraction of the overlying dura and provided an enlarged corridor through which the endoscope could be advanced, lateral to medial, toward the lower third of the clivus, between cranial nerve (CN) XI and the rootlets of CN IX. With an inferomedial trajectory, lateral to the medulla, below CN IX, the anterior...
DISCUSSION

Far-lateral craniotomy has been the primary surgical approach used to access lesions involving the inferior clivus, pontomedullary junction, lateral medulla, and V3 segment, as well as potential atlanto-occipital instability as a result of the disruption of the occipitocervical joint associated with wide removal of the occipital condyle (29).

The MIST approach (Figures 1 and 5) represents an alternative to the standard FLA to the lower clivus and pontomedullary region. The approach has the potential to minimize operative morbidity, without sacrificing surgical exposure, when applied to properly selected pathology. Potential advantages include a smaller skin incision, localized suboccipital craniotomy, and no removal or exposure of the C1 arch. Limited resection of the occipital condyle coupled with an extradural resection of the JT provides access to the lower clivus without the need for extensive VA exposure and manipulation and with minimal risk of occipitocervical instability.

With the traditional transcondylar extension of the FLA, a large portion of the joint capsule is removed and the condyle is drilled out anteriorly to the hypoglossal canal. This level of drilling corresponds to the resection of approximately the posterior third of the condyle (Figure 1). However, it is often difficult to precisely localize the intradural hypoglossal canal when removing the condyle via extradural drilling, and this can result in a more extensive condyle resection. Previous reports have suggested a high rate of instability with ≥50% resection of the occipital condyle (29). In the MIST approach, the majority of the capsule remains intact, with only disruption of the superior medial aspect, and drilling is confined to much less than the third of the condyle (Figure 1).

Visualization of the lower clivus is obstructed by the JT when approaching the region through the suboccipital and the far-lateral approaches (Figures 2 and 7). By removing the JT extradurally, a corridor is created above CN XI and below CN IX and CN X. The dura can be retracted into the space created by the removal of this bone, which increases visualization medially between the CN IX and CN X complexes and CN XI. In addition, the bony removal provides an enlarged surgical view and increases working space when approaching the lower clivus (Figures 2 and 5).

We compared the exposure between the extended far-lateral (Figures 1 and 2) (suboccipital craniotomy, removal of C1
arch, removal of the posterior third of the occipital condyle, and JT resection) and the MIST approaches (Figures 1 and 5, Table 1). The exposure of the lateral medulla and lower clivus were identical between the approaches. The extended far-lateral provided increased exposure of the dorsal and anterolateral foramen magnum but not of the lateral medulla and lower third of the clivus.

The usefulness of endoscopic techniques as an adjunctive tool during microsurgical approaches to the posterior fossa and cerebellopontine angle has been reported for the treatment of acoustic neuromas, intrinsic and extrinsic lesions involving the brainstem, microvascular decompression of the cranial nerves, and aneurysms of the vertebrobasilar system (8, 9, 16, 17, 23, 30). In this study, we have demonstrated that the MIST approach is an ideal companion to endoscope-assisted neurosurgery. The addition of the endoscope provided excellent visualization of the anterolateral aspect of the brainstem, CNs III through XII, the vertebral arteries bilaterally, PICA, anterior spinal artery, VB junction, and the basilar artery and its branches; in addition, the upper part of the cerebellopontine angle could be observed (Figure 6). The endoscope was introduced through three corridors: superiorly above CN X and inferolateral to the flocculus, lateral to the medulla, and inferomedial to CN IX (Figure 6).
The MIST approach requires a detailed understanding of the complex anatomy of the condylar fossa, hypoglossal canal, emissary veins, JT, and jugular bulb (Figures 1 and 3) (6, 20). Before attempting the approach, a detailed preoperative workup, including magnetic resonance imaging, magnetic resonance angiography, and computed tomographic reconstructions, should be performed in order to visualize the detailed anatomy of the osseous and neurovascular structures.

Extradural resection of the JT is challenging. The maneuver is performed through a narrow corridor with limited visualization. Aberrant or enlarged jugular bulb anatomy can limit access to the supracondylar fossa, preventing extradural JT resection. The use of intraoperative imaging guidance is strongly recommended in order to visualize the important anatomic relationships and to maintain the correct angle of drilling and define the depth of JT resection (Figure 7).

Potential applications of the MIST approach include discrete neoplastic lesions located at the pontomedullary junction. The approach can also be applied to vascular lesions of the VB junction and selective PICA–VA aneurysms. When the PICA take-off is located rostral to the hypoglossal canal, adequate exposure is possible through a MIST approach. However, when more proximal VA control is required or when the PICA origin is caudal to the hypoglossal canal, removal of the occipital condyle and likely the C1 arch will be required (19, 32).

Primary or adjunctive endoscopic neurosurgical approaches have gained widespread acceptance in neurosurgical practice (8, 9, 16, 17, 23, 30). Future applications of neuroendoscopy will likely reflect less-invasive alternatives of traditional skull base approaches. We evaluated the MIST combined with endoscopy as a potential alternative to the traditional extended FLA. Three distinct endoscopic working corridors were identified that, when combined with the microsurgical exposure gained through the MIST, provided nearly identical exposure compared to the extended far-lateral microscope-only approach. Extensive experience with basic endoscopic techniques, including introduction between neurovascular structures and working with two-dimensional visualization, is strongly recommended before applying these techniques to the MIST or any other minimally invasive operative corridors.

CONCLUSION

The MIST procedure is a minimally invasive alternative to the extended far-lateral when approaching selective pathology of the lateral medulla and lower clivus. Furthermore, the adjunctive use of the endoscope provides enhanced visualization of the vascular, neural, and bony structures, with minimal retraction of the cerebellum and cranial nerves. The MIST has the potential to minimize morbidity associated with the traditional far-lateral approach.

ACKNOWLEDGMENT

Vittorio M. Russo, Francesca Graziano, and Monica Quiroga have contributed equally to the work.

REFERENCES


