Lesions ventral to the brain stem in the region of the petrous apex and clivus consist of meningiomas, neurilemomas, cholesteatomas, and aneurysms of the verteobasilar system. Approaches to these lesions include the retromastoid paracerebellar, frontotemporal transsylvian, posterior subtemporal,\textsuperscript{22} combined supra- and infratentorial\textsuperscript{1,10,11,15,21} translabyrinthine,\textsuperscript{4} and transcochlear\textsuperscript{6} techniques. Difficulties experienced by the surgeon when using these approaches for deep-seated lesions ventral to the brain stem arise from the great depth of the working area, the necessity for brain retraction or even resection, the interposition of cranial nerves between the surgeon and lesion, and (in some cases) obligatory loss of hearing.

Because of these difficulties, certain other approaches that are used primarily for extradural pathology ventral to the brain stem have been extended for the management of intradural lesions.\textsuperscript{2,6,16} The present report describes a study involving human cadaver dissection to define the application of the subtemporal preauricular infratemporal approach\textsuperscript{17} to intradural lesions ventral to the brain stem. This approach has been used to treat five patients: two with meningiomas, one with a meningioma and a verteobasilar aneurysm, one with a chordoma, and one with a chondrosarcoma in the region of the clivus and petrous apex. Although chordomas and chondrosarcomas are extradural neoplasms, the two patients included in this report had the bulk of the tumor in the intradural space. This approach has specific advantages over existing approaches to this area: it provides direct access to the region ventral to the brain stem and caudal to the trigeminal root and is useful for the management of both intradural neoplastic and vascular lesions.

Materials and Methods

Ten fixed human head specimens from cadavers were divided into 20 sides for study. For dissection, the heads were mounted on a three-point headrest, and standard macro- and microsurgical techniques were used. Microscopic as well as gross color photographs were taken. After dissection of each specimen, the brain was removed and the base of the skull was examined from the inside to confirm the identification of structures that had been visualized during the operative approach.
FIG. 1. Schematic diagram showing the right petrous internal carotid artery (ICA) unroofed and its relationship to the third division of the trigeminal nerve (V3) and eustachian tube. Note the clival bone medial to the artery.

FIG. 2. Dissection of the right middle cranial fossa viewed from intracranially (midline is to the reader’s left and the nose is upward). Part of the dural covering of the base has been removed to show the trigeminal root (V), the mandibular nerve exiting the foramen ovale (V3), the middle meningeal artery entering through the foramen spinosum (a), the horizontal petrous internal carotid artery partly devoid of bone cover (b), and the greater superficial petrosal nerve (c) coursing over the artery. Part of the petrous bone has been drilled to show the internal auditory canal (IAC), the geniculate ganglion (d), the superior semicircular canal (g) under the arcuate eminence, the cochlea (e), and the eustachian tube (f). Ret = retractor.

and to establish their relationship to structures that had not been seen during the approach.

Surgical Procedure

For this approach, a frontotemporal craniotomy and neck dissection to control the internal and external carotid arteries is carried out as described in previous publications. The zygomatic arch and lateral rim of the orbit is also removed. The petrous internal carotid artery (ICA) is completely exposed up to its point of entry into the cavernous sinus (Fig. 1). Bone between the artery and the third division of the trigeminal nerve (V3) as well as in front of V3 is removed, and the vessel is elevated from the groove and rotated laterally. Because of the location of the cochlea and geniculate ganglion of the facial nerve, bone removal is avoided posterior to the genu of the petrous ICA (Fig. 2). The petrous temporal and clival bone, which is exposed medial to the displaced ICA, is drilled away by working medial to the ICA and also between it and V3, thus exposing the clival dura (Fig. 3). While drilling the bone medial to the petrous ICA, it is important to remember the relationship of the jugular bulb, hypoglossal canal, and the pars nervosa of the jugular foramen. The vein lies immediately posterolateral to the artery at the skull base, while the nerves are located between the two and just medial to the vein. The base of the styloid process,
Preauricular infratemporal approach

FIG. 3. Dissection of the left side (the nose is to the left). Dura covering the temporal (Temp) lobe, mandibular nerve (a), and the petrous internal carotid artery (b) has been rotated laterally to expose the clival dura (f) after removal of the clival bone. Note the relationship of the cut stump of the facial nerve (d), the jugular foramen with the cranial nerves (c), and the internal jugular vein (e).

which can be palpated, lies adjacent and lateral to the jugular bulb (Fig. 4). Since, in this approach, instead of the mandible being dislocated inferiorly the mandibular condyle is resected, postoperative facial paralysis due to stretch is rare. However, the surgeon must take precautions to protect the facial nerve.

Exposure of the Petrous Apex and Clivus

The bone comprising the petrous apex and clivus is soft and cancellous except in the region of the hypoglossal canal, jugular foramen, and foramen magnum, where it becomes hard and cortical in nature. The field of exposure narrows down as one descends to the level of the hypoglossal foramen because the jugular bulb and foramen, which are located immediately lateral to the ventral margin of the foramen magnum, somewhat obstruct the view. The clival dura has two layers: the outer periosteal layer and the inner visceral layer. The outer periosteal layer is quite adherent to the bone and there is a prominent venous plexus between the two layers, including the inferior petrosal sinus. The dural window, exposed by drilling the clival bone, measures 2 to 2.5 cm in its anteroposterior diameter and 3 to 3.5 cm in its vertical diameter, and extends medially to Dorello's canal, laterally to the internal auditory meatus, superiorly to Meckel's cave, and inferiorly to the hypoglossal foramen (Fig. 5).

Intradural Structures Exposed

Figure 6 illustrates the intradural structures exposed in this approach. They are described more fully below as visualized in the cadaver specimens dissected in this study.

Brain Stem. Areas 8 to 15 mm wide of the ventral surface of the pons rostral to the pontomedullary junction were seen during exposure, including the midline groove and the ipsilateral surface of the basis pontis as far as the origin of the facial nerve laterally and the trigeminal nerve superiorly. The opposite surface of the pons was visible up to the origin of the contralateral abducens nerve. Through the dural opening, 8 to 15 mm of the ventral surface of the medulla caudal to the pontomedullary junction was visible. This included the medullary pyramids bilaterally, the origin of the ipsilateral hypoglossal rootlets, and part of the inferior olive on the same side.

Cranial Nerves. The inferior surface of the ipsilateral trigeminal root from the pons to Meckel's cave could be seen at the upper extreme of the dural opening.
FIG. 5. Inside view of the posterior cranial base showing the dural opening in the petroclival region achieved by the approach described here. Note the relationship of this opening with the fifth to 12th cranial nerves (indicated by Roman numerals).

FIG. 6. Diagram showing the intradural clival structures visualized through the subtemporal preauricular infratemporal approach through the right side. Numbers in parentheses indicate the number of specimens in which the particular structure was seen. S = same side, O = opposite side. AICA = anterior inferior cerebellar artery; ICA = internal carotid artery; V-B = vertebrobasilar; PICA = posterior inferior cerebellar artery. Roman numerals denote cranial nerves.

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Arteries. The vertebral arteries were visible after they had crossed the hypoglossal roots. A shorter length of the opposite vertebral artery was exposed than of the ipsilateral vertebral artery, being directly proportional to the distance between the medulla and the clivus. The vertebrobasilar junction was seen in all except two specimens (Figs. 7 right and 9), where it was located caudal to the opening and was clearly on the other side of the midline. In two of the specimens, the tributary (Fig. 7 left). The ipsilateral abducens nerve, from its origin to its entry into Dorello's canal, lay in the middle of the intradural exposure (Fig. 7). The origin of the contralateral abducens nerve was also seen, but its exit from the posterior fossa was not exposed.

The ipsilateral hypoglossal rootlets were seen at the inferior extent of the dural opening. When the ipsilateral vertebral artery was ectatic, the hypoglossal roots were draped over the vessel and elevated to a variable degree (Fig. 8). The opposite hypoglossal nerve could be seen exiting the dura, but its origin at the brain stem was hidden behind the intervening medulla. In two of our specimens the hypoglossal nerve exited through two foramina instead of one.
Preauricular infratemporal approach

of the anterior spinal artery arising from the vertebral artery was exposed. The basilar artery was visible up to the mid-clival area, along with perforating branches to the brain stem.

The origin of the ipsilateral anterior inferior cerebellar artery (AICA) was seen in all specimens unless it was higher than the superior limit of the exposure (Figs. 7 left and 9). However, the basilar artery had to be rotated to visualize the origin of the opposite AICA. As the AICA travels laterally after its origin, it can be located anterior or posterior to the abducens nerve. The origin of the posterior inferior cerebellar artery was seen only if it was the dominant vessel of the posterior fossa and it arose more rostrally (Fig. 9).

Clinical Application of Approach

Table 1 summarizes the use of this approach in five patients with lesions in the clivus and petrous apex region. Two of the patients (Cases 1 and 2) are described below to illustrate the use of this approach and its benefits.

Case 1

This 53-year-old woman was evaluated for a history of headaches and diplopia.

Examination. With the exception of a partial third nerve palsy, the neurological examination was normal.

FIG. 7. Dissection of the right side (the nose is to the right and vertex is upwards). Left: The following intradural structures are visualized: the pons, medulla (M), pontomedullary junction (J), trigeminal root (5), abducens nerve (6), and branches (a) of the anterior inferior cerebellar artery (AICA). Right: The structures visible after the clival dura is opened include: the pons, abducens nerve (6), basilar artery (B), left (Vr) and right (Vl) vertebral arteries, and right AICA origin (A).

FIG. 8. Dissection of the right side (the nose is to the right) with the temporal lobe retracted upward (RET) and the petrous internal carotid artery (ICA) displaced anteriorly showing the following intradural structures: medulla (m), anterior inferior cerebellar artery (a), posterior inferior cerebellar artery (b), and the right hypoglossal rootlets (h) draped over the right vertebral artery (v).

FIG. 9. Dissection of the right side (the nose is to the right), showing the intradural combined supra- and infratentorial exposure. The tentorium (Tent) has been divided to show the superior cerebellar artery (a), trigeminal root (V), pons (p), abducens nerve (6), right anterior inferior cerebellar artery (d) and posterior inferior cerebellar artery (c), basilar artery (ba), and right (Vr) and left (Vl) vertebral arteries. The right petrous internal carotid artery (ICA) has been displaced anteriorly to show the remaining clival bone (CL).
TABLE 1

Clinical summary of five patients undergoing the approach described*

<table>
<thead>
<tr>
<th>Case No.</th>
<th>Age (yrs), Sex</th>
<th>Diagnosis of Lesions</th>
<th>Location of Lesions</th>
<th>Operation</th>
<th>Time Between Ops</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>53, F</td>
<td>meningioma, ACoA aneurysm, VB junction aneurysm</td>
<td>rt CS, petrous apex, clivus</td>
<td>1: frontotemporal, orbitozygomatic approach 2: subtemporal preauricular infratemporal approach</td>
<td>2 wks</td>
<td>residual tumor caudal to V root removed at Op 2, VB junction aneurysm visualized &amp; clipped at Op 2</td>
</tr>
<tr>
<td>2</td>
<td>34, M</td>
<td>meningioma</td>
<td>rt middle fossa, CS, petrous apex, clivus</td>
<td>1: frontotemporal, orbitozygomatic approach 2: subtemporal preauricular infratemporal approach</td>
<td>5 days</td>
<td>extension of tumor on clivus from V root to IAC removed at Op 2, CSF leakage from eustachian tube &amp; communicative hydrocephalus treated by VP shunt &amp; reexploration with resection of eustachian tube</td>
</tr>
<tr>
<td>3</td>
<td>54, F</td>
<td>meningioma</td>
<td>mid-clivus down to C1-2, both sides of midline</td>
<td>1: retromastoid craniectomy 2: suboccipital craniectomy &amp; C-1 laminectomy 3: rt subtemporal preauricular infratemporal approach</td>
<td>8 wks</td>
<td>after Ops 1 &amp; 2 tumor remained ventral to brain stem that could not be visualized; most remaining tumor ventral to brain stem removed at Op 3, except for a small residue at ventral lip of foramen magnum</td>
</tr>
<tr>
<td>4</td>
<td>32, M</td>
<td>Grade I chondrosarcoma</td>
<td>lt petrous apex, clivus</td>
<td>1: frontotemporal, orbitozygomatic approach 2: subtemporal preauricular infratemporal approach</td>
<td>6 mos</td>
<td>tumor remaining in mid-clivus buried in lower pons after Op 1; Op 2 delayed because of pulmonary embolism requiring anticoagulation; at Op 2 lower pole of tumor was identified but planes between tumor &amp; brain stem were obscured</td>
</tr>
<tr>
<td>5</td>
<td>29, F</td>
<td>chordoma</td>
<td>midline, upper &amp; middle clivus</td>
<td>1: frontotemporal, zygomatic osteotomy &amp; preauricular infratemporal approach 2: subtemporal preauricular infratemporal approach</td>
<td>4 wks</td>
<td>at Op 1 entire upper &amp; mid-clivus exposed &amp; intradural portion of tumor removed by working above &amp; below V root; at Op 2 extradural portion of tumor infiltrating clival bone removed</td>
</tr>
</tbody>
</table>

* Abbreviations: ACoA = anterior communicating artery; VB = vertebrobasilar; CS = cavernous sinus; IAC = internal auditory canal; CSF = cerebrospinal fluid. Roman numerals denote cranial nerves.

Computerized tomography (CT) and magnetic resonance (MR) imaging revealed that she had a tumor in the right petroclival region extending into the cavernous sinus and sella turcica, and caudally down to the verteobasilar junction (Fig. 10 left). Arteriography showed that the right ICA had been occluded by the tumor and that she had an anterior communicating artery (ACoA) and a vertebrobasilar junction aneurysm (Fig. 11 left). Embolization of the external carotid artery blood supply to the tumor was performed before a direct approach was attempted.

**First Operation.** The meningioma was approached by a frontotemporal craniotomy and removal of the orbital rim and zygomatic arch. The ACoA aneurysm was clipped, and the tumor was removed from the cavernous sinus, superior clivus, and sella turcica. Despite resection of the anterior 2 cm of the temporal lobe and division of the tentorium, the caudal extension of the tumor along the clivus and the verteobasilar junction aneurysm could not be visualized. Because of the duration of the procedure, removal of the remaining tumor was deferred for a second operation.

**Second Operation.** Two weeks after the first procedure, the previous craniotomy was reopened and the mandibular condyle excised. The right ICA (which had been obliterated by the tumor) was removed from its point of entry into the petrous bone up to its entry into the cavernous sinus, and the clivus was drilled off medially, while staying anterior to the internal auditory canal. The dura inferior to the trigeminal root was opened, revealing the entire caudal extent of the tumor.

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**Fig. 10.** Computerized tomography scans in Case 1. **Left:** Preoperative scan showing a meningioma in the right petrous apex, cavernous sinus, and clivus. The **arrowhead** indicates the portion of tumor extending down the clivus and the arrow shows the relationship to the basilar artery. **Right:** Postoperative scan showing the site of the bone window (arrows) in the petrous apex and clivus used to remove the caudal portion of the tumor and to clip the verteobasilar aneurysm.
Preauricular infratemporal approach

The sixth nerve, which was found to pass through the tumor, was dissected free and the tumor in the clivus was removed. The vertebrobasilar junction was now visible and appeared to harbor a thin-walled aneurysm in a fenestrated basilar artery. This aneurysm was clipped (Fig. 11 right). The subtemporal dura was opened and the remaining tumor above the level of the fifth nerve, in the posterior portion of the cavernous sinus, was removed. The clival dural opening was closed by packing with fat.

Postoperative Course. Postoperative CT scans showed that the tumor had been completely removed (Fig. 10 right). The patient had a third and sixth nerve palsy on the right side. There was no cerebrospinal fluid (CSF) leak. Her hearing was diminished due to occlusion of the eustachian tube, a condition which was corrected with a tympanostomy.

Case 2

This 34-year-old man presented with a long-standing history of seizures and the recent onset of right-sided numbness of the face.

Examination. He had diminished sensation in the trigeminal distribution and an absent corneal reflex on the right side with clouding of the right cornea. A CT scan had shown that the meningioma (diagnosed from a previous biopsy) in the middle fossa extended from the orbital apex anteriorly to the mid-clivus posteriorly (Fig. 12 upper left).

First Operation. A frontotemporal craniotomy was performed with removal of the orbital rim and zygomatic arch. The majority of the intradural tumor was

FIG. 11. Right vertebral arteriograms in Case 1. Left: Preoperative view showing the vertebrobasilar aneurysm (asterisk) and the opposite vertebral artery (arrowhead). Right: Postoperative view showing the clips (arrow) on the vertebrobasilar aneurysm.

FIG. 12. Computerized tomography scans in Case 2. Upper Left: Preoperative scan showing a meningioma in the middle fossa, petrous apex, and clivus. Upper Right: Scan after the first operation showing residual tumor (arrowheads) in the clivus at the level of and medial to the internal auditory canal (IAC). Lower: Site of the bone window in the clivus to remove the residual tumor seen in the scan shown upper right. Note the relationship of the window to the cochlea (c) and the IAC (a).
removed along with the trigeminal root and ganglion, which had been infiltrated by the tumor. Postoperative CT scans showed residual tumor in the clivus and infratemporal fossa (Fig. 12 upper right).

Second Operation. Five days after the first operation, using the same approach, the mandibular condyle was excised and the petrous ICA completely unroofed. The geniculate ganglion was noted to be devoid of bone cover. The petrous ICA was displaced and the clivus was drilled. Epidural bleeding from the clival dura was controlled with Surgicel packing and the dura was opened to reveal the caudal portion of the tumor. The tumor was removed along with the petroclival dura. The anterior surface of the seventh and eighth cranial nerves was seen as they entered the internal auditory canal; the mid-basilar artery including the origin of the AICA was also visualized. Some of the fascicles of the sixth nerve which had been injured were sutured. The extradural portion of the tumor, which had extended through the foramen ovale, was also removed and the area was reconstructed with fascia lata and a temporalis muscle rotation flap.

Postoperative Course. A CT scan revealed a gross total removal of the tumor (Fig. 12 lower). The patient had a palsy of the right fourth through sixth nerves and paresis of the third nerve. Ten days after the second operation, a CSF leak developed through the eustachian tube, due to communicating hydrocephalus. This was treated with reclosure of the eustachian tube and placement of a ventriculoperitoneal shunt.

Discussion
The main difficulty encountered by the surgeon during surgical management of the intradural lesions ventral to the brain stem is related to access to and depth of the working area. The subtemporal preauricular infratemporal route approaches the ventral posterior fossa structures from an anterolateral direction and circumvents some of the problems of other approaches to this area. The approach involves extensive bone removal in the base of the skull but spares the important areas of the petrous temporal bone. Thoracic knowledge of the anatomy of this region from the surgeon’s perspective is essential to realize maximum benefit from the exposure. Since the surgeon essentially approaches the brain stem from anterolaterally, the cranial nerves do not pose an obstacle. An extrapharyngeal path of exposure reduces risks of infection, and brain retraction is virtually avoided.

Advantages of This Approach
The main benefit of the subtemporal preauricular infratemporal approach is in its ability to provide a direct access to the area ventral to the brain stem, from the trigeminal root down to the hypoglossal foramina, without any brain retraction. Frequently, however, tumors extend above and below the trigeminal root, in which case it is easy to combine this approach with a frontotemporal craniotomy. It was found that when the temporal lobe was elevated intradurally, and the tentorium was divided posteriorly to the entry point of the trochlear nerve and laterally over the trigeminal root including the superior petrosal sinus, additional exposure of the ventral aspect of the upper brain stem was obtained. This included the posterior clinoid process and the third and fourth cranial nerves. Hence, combining the two approaches provided exposure of the entire ventral aspect of the brain stem (Fig. 9).

In summary, the benefits of the approach include: 1) preservation of the hearing apparatus; 2) minimal manipulation of the extracranial portion of the facial nerve; 3) exposure of the area directly ventral to the brain stem without the need for brain retraction; 4) exposure and control of the ipsilateral petrous ICA (this feature is useful when dealing with tumors that extend both intra- and extradurally to involve this segment of the ICA); 5) avoidance of the necessity to traverse septic spaces; 6) allowance of several options for reconstruction; 7) The ease by which this approach can be combined with an intradural subtemporal exposure and (by dividing the tentorium and the superior petrosal sinus) the ability to provide a wide exposure of the entire clivus above and below the trigeminal root almost down to the foramen magnum.

Disadvantages of This Approach
The disadvantages of this approach result from: 1) excision of the mandibular condyle (this can cause the patient to suffer from trismus, malocclusion, and arthritis in the opposite temporomandibular joint); 2) division of the eustachian tube leading to a temporary reduction in conductive hearing (this is reversible with a tympanostomy); and 3) division of the chorda tympani nerve at the petrotympanic fissure.

Other Approaches
The conventional posterolateral approaches to the area ventral to the brain stem necessitate working between cranial nerves, thus increasing the risk of injuring them. Even then, the structures in the midline and beyond are seldom seen unless the brain stem is displaced by tumor. Moreover, by these approaches the blood supply to the tumors is obliterated toward the end of the procedure rather than at the beginning. Other alternative approaches to intradural clival lesions are divided into anterior (transoral and transcervical) and lateral (translabyrinthine, transcoclear, transtemoral, and transpetrous). Limitations of the transoral route include: a long narrow path of exposure; lateral restriction by the hypoglossal foramina, occipital condyles, jugular foramina, and the petrous ICA; and transgression of the pharynx with its potential for serious infection and CSF fistula formation with limited options for reconstruction of the surgical defect. Extension of the tumors above the mid-clivus or laterally into the petrous region is not accessible via the transoral approach.
Preauricular infratemporal approach

The transcervical approach to the ventral brain stem, as initially described by Stevenson, et al.,19 and Mullan, et al.,13 provides an exposure similar to the transoral operation but avoids traversing the pharynx.20 The disadvantage of this route includes the depth and oblique angle of the approach path, which may allow the arch of the atlas to obscure the view.3 Again, superior and lateral extensions of tumors cannot be removed.

The transcochlear, transtemporal, and transpetrous approaches are the lateral approaches that have been used to gain access to lesions ventral to the brain stem.6,7,9,16 The transtemporal and transcochlear approaches involve destruction of the petrous bone and displacement of the facial nerve from the fallopian canal with concomitant facial paralysis (albeit temporary) and hearing loss, while the transpetrous approach employs a very limited opening in the petrous apex and requires significant temporal lobe retraction. Although the translabyrinthine approach has been used to remove cerebellopontine angle meningiomas,4 restricted exposure and obligatory loss of hearing has probably limited its use.

Analysis of Cases

In the five cases in which we have used the subtemporal preauricular infratemporal approach (Table 1), the tumor extended rostral and caudal to the trigeminal root, reaching to both sides of the midline. Attempts to visualize the lower pole of the tumor through the supratentorial exposure even with division of the tentorium required excessive temporal lobe retraction. Since all five patients had intact auditory function, the subtemporal preauricular infratemporal approach was supplemented with the conventional subtemporal exposure which provided adequate access inferior to the trigeminal root. Total tumor removal was not possible in two patients (Cases 3 and 4). One of these (Case 4) had a low-grade chondrosarcoma. In this patient, there was a 6-month delay between the first subtemporal operation and the second attempt to remove tumor ventral to the brain stem while he received anticoagulation therapy for pulmonary thromboembolism in the interim period. This delay allowed excessive scarring and obliteration of the planes of dissection between the brain stem and the tumor. Thus, although the caudal part of the tumor was visible, it could not be removed. The other patient (Case 3) had a clival meningioma and was the first patient to be treated with this approach. We were not as aggressive with bone removal in her case as in later patients and hence the full potential of the approach could not be realized; a small fragment of residual tumor was left.

Conclusions

We have shown that the subtemporal preauricular infratemporal approach provides direct visualization of structures ventral to the brain stem and caudal to the trigeminal root from an anterolateral direction. There is no brain retraction involved and the cranial nerves do not obstruct access to the lesion. Pharyngeal contamination is not a problem and several options for reconstruction are available. When further rostral access is required, a conventional subtemporal exposure along with division of the tentorium can conveniently complement the approach.

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