MR imaging of the excised human brainstem: a correlative neuroanatomic study.

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MR Imaging of the Excised Human Brainstem: A Correlative Neuroanatomic Study

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The purpose of this study was to examine an excised human brainstem with high-resolution MR imaging. The MR images were correlated with myelin-stained histologic specimens and standard anatomic descriptions. Structures visualized included nuclei and/or fibers of all the cranial nerves, with the exception of the trochlear nerve. The topography of the brainstem is discussed. Major tracts such as the corticospinal, spinothalamic, spinocerebellar, medial and lateral lemniscus, and other ascending and descending tracts and intrinsic brainstem nuclei such as the olivary complex, pontine nuclei, red nucleus, and inferior and superior colliculi were identified. Functional neuroanatomy of the brainstem is reviewed.

This neuroanatomic description and review of the complex MR anatomy of the brainstem should assist in the delineation of brainstem structures on MR imaging.

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Although MR imaging has been widely accepted as the most valuable imaging technique for the investigation of diseases of the brainstem, only a few of the major nuclei and fiber tracts have been demonstrated during clinical studies. Flannigan et al. [1] used a 0.35-T MR unit for clinical studies and compared the major nuclei and fiber tracts demonstrated by this method with normal anatomic frozen sections. Hirsch et al. [2] also studied brainstem anatomy in cadaver specimens, demonstrating excellent anatomic deatil.

In a previous study, Solsberg et al. [3] demonstrated that the anatomic detail shown by MR studies of the excised human spinal cord is considerably superior to that shown in clinical studies. The purpose of this study was to examine an excised human brainstem by a technique similar to that which has been used for the spinal cord and to correlate the MR images with corresponding histologic sections and with standard anatomic descriptions [4–6].

Materials and Methods

During a postmortem examination, the brain of a 34-year-old man with no history of neurologic disease was excised. The caudal edge of the specimen corresponded to the inferior margin of the foramen magnum. The specimen was placed in a 10% formalin solution for fixation. When fixation was complete (at 7 days) the rostral brainstem was separated from the diencephalic structures by sharp dissection. The cerebellar hemispheres and vermis were almost completely removed, leaving a thin rim of cerebellar tissue attached to the brainstem. The brainstem was then placed in a plastic graduated cylinder for imaging.

A General Electric CSI (Fremont, CA) 2-T MR imaging unit and a 56- by 51-cm slotted tube resonator coil [7] were used for imaging. After tuning and shimming, a sagittal image was acquired and the positions of the rostral and caudal edges of the specimen were noted. By using a multislice spin-echo imaging sequence, transverse images with 1-mm slice thickness were obtained perpendicular to the longitudinal axis of the brainstem at 3-mm intervals. The position of each MR image was referenced to the caudal and rostral ends of the specimen. TR/TE/excitations were 800/40/8.

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Key to Numbers Used in Figures

1 cerebellum (tonsil)
2 small vascular markings
3 dorsal median fissure
4 ventral median fissure
5 ventral gray horn
6 central gray matter
7 spinal trigeminal nucleus
8 fasciculus gracilis
9 fasciculus cuneatus
10 trigeminal spinal tract
11 lateral corticospinal tract
12 ventral spinothalamic tract region
13 ventral spinocerebellar tract region
14 lateral spinothalamic tract region
15 bundle of crossing corticospinal fibers
16 nucleus gracilis
17 nucleus cuneatus
18 rostral end of pyramidal decussation
19 cerebellum (hemisphere)
20 pyramid and corticospinal tract
21 hypoglossal nucleus
22 medial accessory olivary nucleus
23 reticular formation
24 internal arcuate fibers
25 decussation of medial lemniscus
26 posterior spinocerebellar tract
27 cerebellum (vermis)
28 open part of fourth ventricle
29 dorsal nucleus of vagus nerve
30 nucleus solitarius
31 medial vestibular nucleus
32 inferior vestibular nucleus region
33 inferior olivary nucleus
34 position of nucleus ambiguus
35 medial longitudinal fasciculus
36 region of tectospinal tract
37 medial lemniscus region
38 pia mater
39 fourth ventricle
40 lateral recess of fourth ventricle
41 choroid plexus
42 vertebral artery
43 dorsal accessory olivary nucleus
44 medial accessory olivary nucleus
45 central tegmental tract
46 inferior cerebellar peduncle (restiform body)
47 lateral spinothalamic tract and ventral spinocerebellar tract region
48 rootlets of vagus nerve
49 cerebellum (nodulus)
50 dorsal cochlear nucleus
51 ventral cochlear nucleus
52 vestibulocochlear nerve, cochlear part
53 glossopharyngeal nerve
54 inferior cerebellar peduncle
55 superior vestibular nucleus
56 glossopharyngeal nerve nucleus
57 middle cerebellar peduncle
58 cerebellum (lingula)
59 colliculus of facial nerve
60 abducens nucleus
61 facial nerve nucleus region
62 fibers of facial nerve
63 facial nerve
64 superior cerebellar peduncle
65 corticospinal fibers
66 anterior medullary velum
67 trigeminal complex (motor and sensory nuclei)
68 pontine nuclei
69 mesencephalic nucleus and tract of trigeminal nerve
70 decussation of trapezoid body
71 pontocerebellar fibers
72 trigeminal nerve
73 lateral lemniscus and lateral spinothalamic tracts
74 corticopontine fibers
75 cerebral aqueduct
76 crus cerebri
77 periaqueductal gray matter
78 inferior colliculus
79 medial geniculate nucleus
80 trochlear nucleus region
81 substantia nigra
82 brachium of inferior colliculus
83 decussation of superior cerebellar peduncles
84 oculomotor nerve
85 strionigral and pallidotegmental fibers
86 posteromedial striate artery
87 superior colliculus
88 brachium of superior colliculus
89 oculomotor nucleus region
90 rostral lip of pons
91 hippocampal gyrus
92 posterior commissure
93 red nucleus
94 oculomotor fibers
95 posterior cerebral artery
96 optic tract

The specimen was then prepared for light microscopy by embedding paraffin and cutting 5-μm-thick sections. Care was taken to orient the sections in the same plane as the MR images. Sections were retained at the levels corresponding to the MR images by referencing each microtome slice to the caudal and rostral ends of the specimen. The sections were then stained with a hematoxylin and eosin/Luxol fast blue stain to demonstrate cellular, collagen, and myelin distributions.

The MR images and histology were correlated and compared with anatomic references. Only structures or regions seen on both MR and light microscopy images are labeled on the figures. Numbers given parenthetically in the text of this article refer to labeled anatomy on corresponding figures.

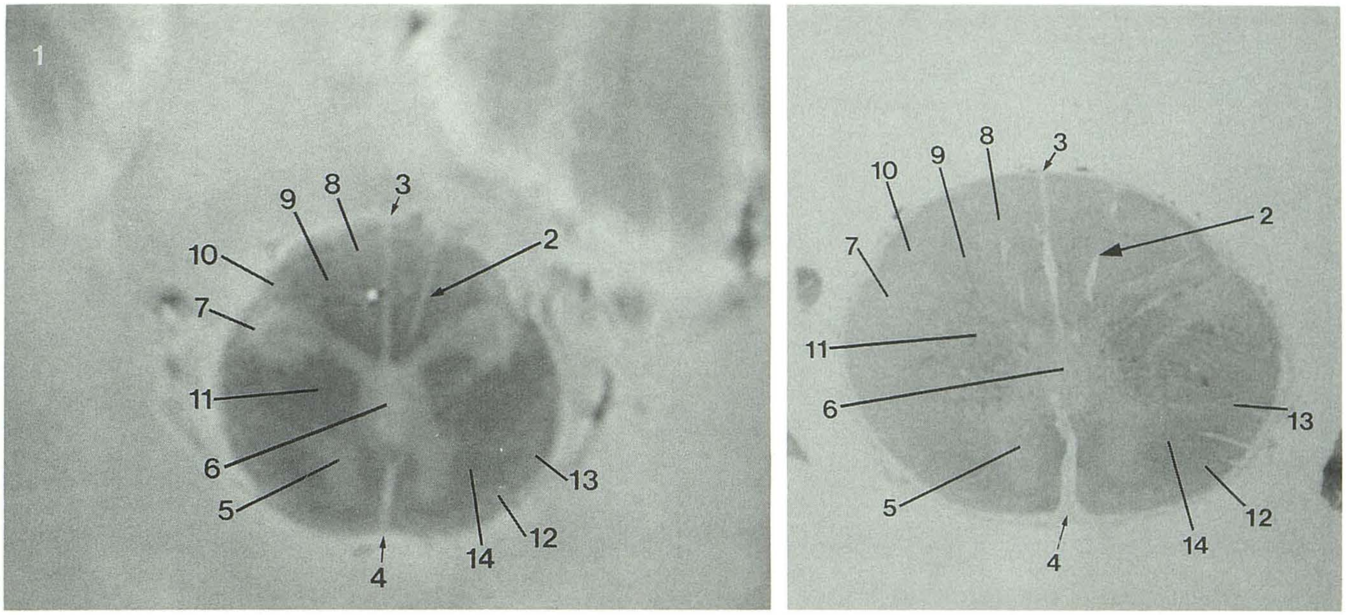
Results

Uppermost End of Cervical Spinal Cord (Fig. 1)

The dorsal (3) and ventral (4) median fissures are well seen. The cerebellar tonsils (1) lie dorsal to the medulla.

The spinal trigeminal nucleus (7) is seen on MR as an area of relatively high intensity in the region of the dorsal gray horn. This is the spinal extension of the trigeminal nucleus, which is also shown on the photomicrograph.

The gray matter is divided at this level into the central gray matter (6) and the ventral (5) and dorsal gray horn.



A B

Fig. 1.—Uppermost end of cervical spinal cord.
***A*, MR image.**
***B*, Light microscopy image.**

The fasciculus gracilis (8) and fasciculus cuneatus (9) form the posterior funiculus. These afferent tracts carry joint, position, and light touch sensation. The difference in intensity between these structures shown previously in the spinal cord [3] was not seen in the brainstem. A small vessel (2) is seen in the dorsal intermediate sulcus and coursing between the fasciculi.

The trigeminal spinal tract (10) is lateral to the fasciculus cuneatus. The lateral corticospinal tract (11) occupies a more ventromedial position. The lateral (14) and ventral (12) spinothalamic tracts and the ventral spinocerebellar tract (13) are not visualized; however, their locations are indicated.

Pyramidal Decussation (Fig. 2)

The spinal trigeminal tract (10) and nucleus (7) are again seen. The trigeminal spinal nucleus appears as a crescentic band of high intensity on MR, although this nucleus is not seen on the histologic preparation.

The ventral gray horn (5) is now separated from the central gray matter (6) by decussation of the corticospinal fibers (15) that traverse posteriorly to form the lateral corticospinal tract.

Rostral End of Pyramidal Decussation (Fig. 3)

The ventral gray horns (5) are now lateral to the pyramidal decussation (18).

The fibers of the fasciculus gracilis (8) have almost all terminated in the nucleus gracilis (16). Although the fasciculus cuneatus (9) is still evident, many of the fibers are replaced by the nucleus cuneatus (17), which is better demonstrated on the MR image.

The ventral spinothalamic (12) and ventral spinocerebellar (13) tracts are now seen as areas of higher intensity than the adjacent white matter. These are not seen as separate structures on the light microscopy image.

Region of Hypoglossal Nucleus and Decussation of Medial Lemniscus (Fig. 4)

The cerebellar hemispheres (19) are seen straddling the medulla posteriorly. The position of the hypoglossal nucleus is noted (21).

The fasciculus gracilis is no longer present because all of its fibers have terminated in the nucleus gracilis (16). The nucleus cuneatus (17) is more prominent, but the fasciculus cuneatus (9) is still evident.

The fibers from the nuclei gracilis and cuneatus arch around the central gray matter as the internal arcuate fibers (24) and then cross the midline to form the medial lemniscus (25).

Lateral to the internal arcuate fibers is the reticular formation (23), which extends along the whole brainstem.

The posterior spinocerebellar tract (26) now occupies a position superficial to the fasciculus cuneatus.

Caudal Part of Fourth Ventricle at Level of Obex (Fig. 5)

In this slice the inferior vermis (27) of the cerebellum forms the roof of the caudal part of the fourth ventricle (28). The pia mater (38) is also well seen on both the MR and histologic images.

The hypoglossal nuclei (21) are in a paramedian position deep to the obex and are better seen in the histology preparation.

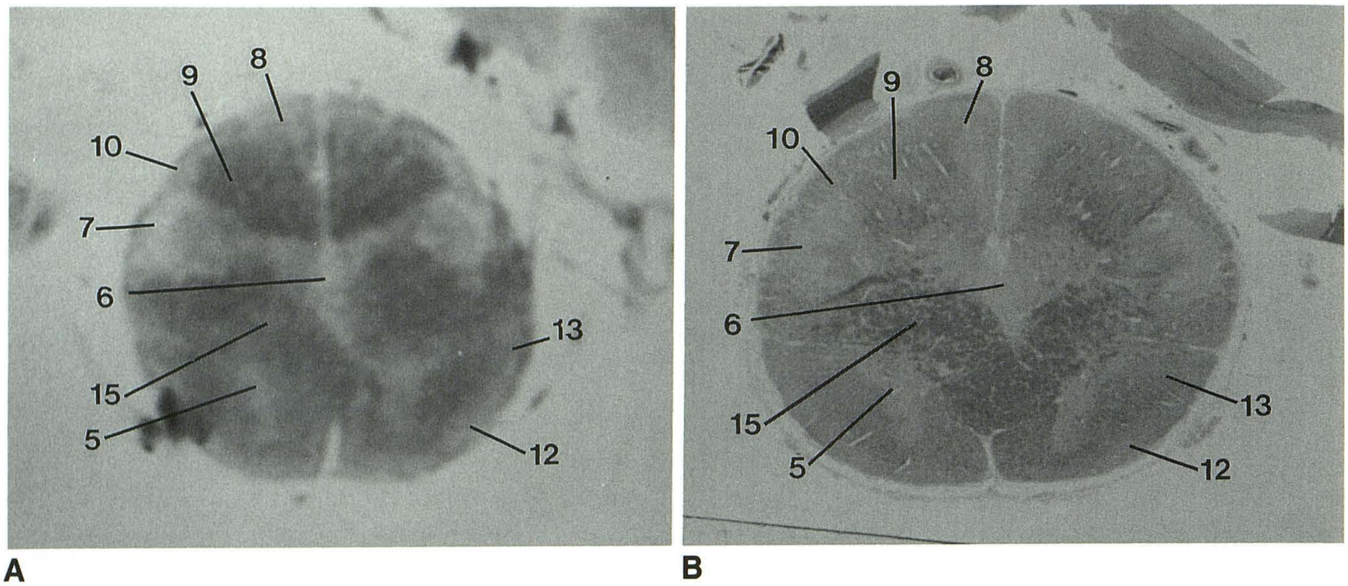


Fig. 2.—Pyramidal decussation.
***A*, MR image.**
***B*, Light microscopy image.**

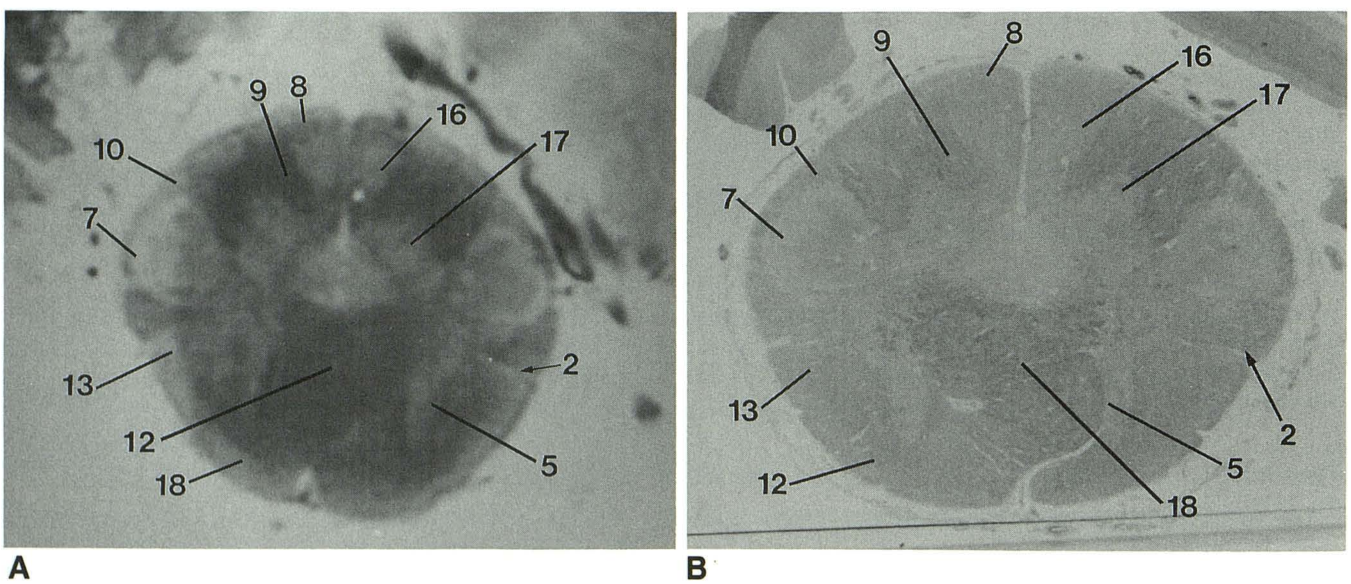


Fig. 3.—Rostral end of pyramidal decussation.
***A*, MR image.**
***B*, Light microscopy image.**

Lateral to the dorsal nucleus of the vagus nerve (visceral motor) is the nucleus solitarius (30), which contains the central neurons of the afferent fibers from the carotid body (glossopharyngeal nerve) and the sensory part of the vagus nerve. This nucleus appears as an area of dark Nissl staining in the histology specimen. A corresponding area of decreased signal intensity is seen on MR.

The medial vestibular nucleus (31) occupies a position in the lateral wall of the obex. This nucleus is well demonstrated on both images. The region of the inferior vestibular nucleus (32) is lateral to the medial vestibular nucleus. The nucleus ambiguus (ventral motor nucleus of the vagus) is not demonstrated, but its location (34) is indicated.

The olive is a protuberance seen on the anterolateral aspect of the medulla. This contains the inferior olivary nucleus (33) and other components of the olivary complex. The olivary complex is a "relay station" in the extrapyramidal system.

The medial longitudinal fasciculus (35) appears as an area of low signal just anterior to the region of the hypoglossal nuclei on MR. This fasciculus contains ascending and descending fibers of the synergistic oculocephalic centers, which control eye and head movement coordination. There is also

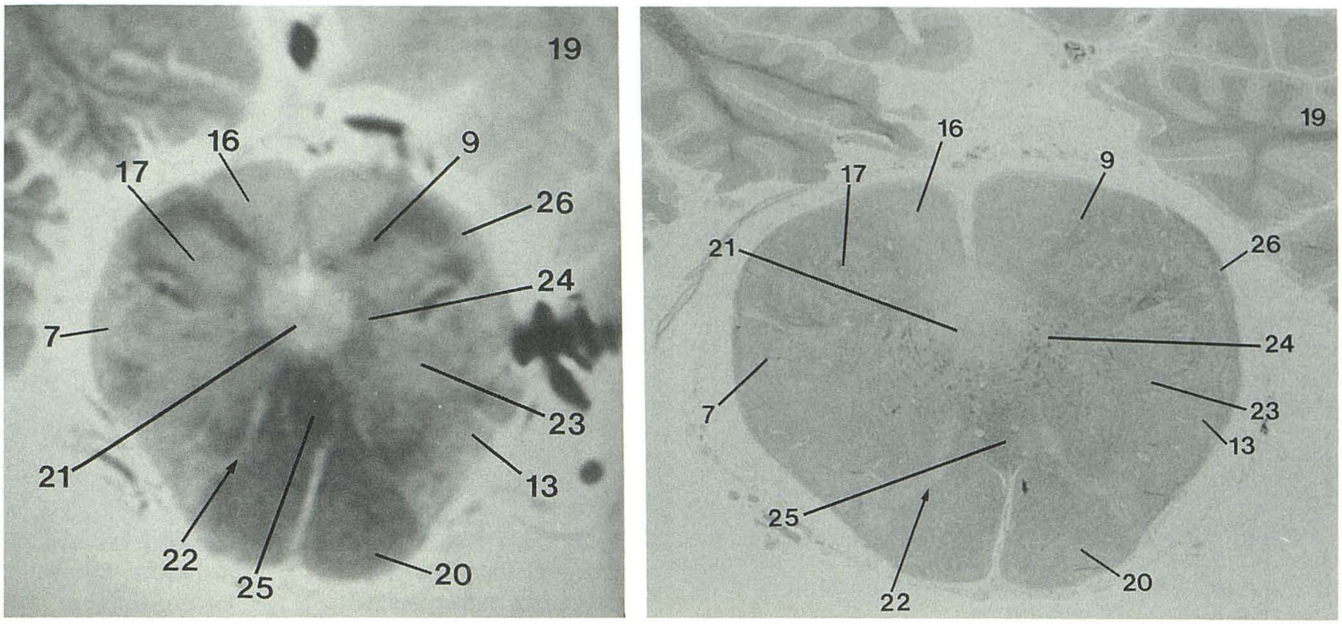


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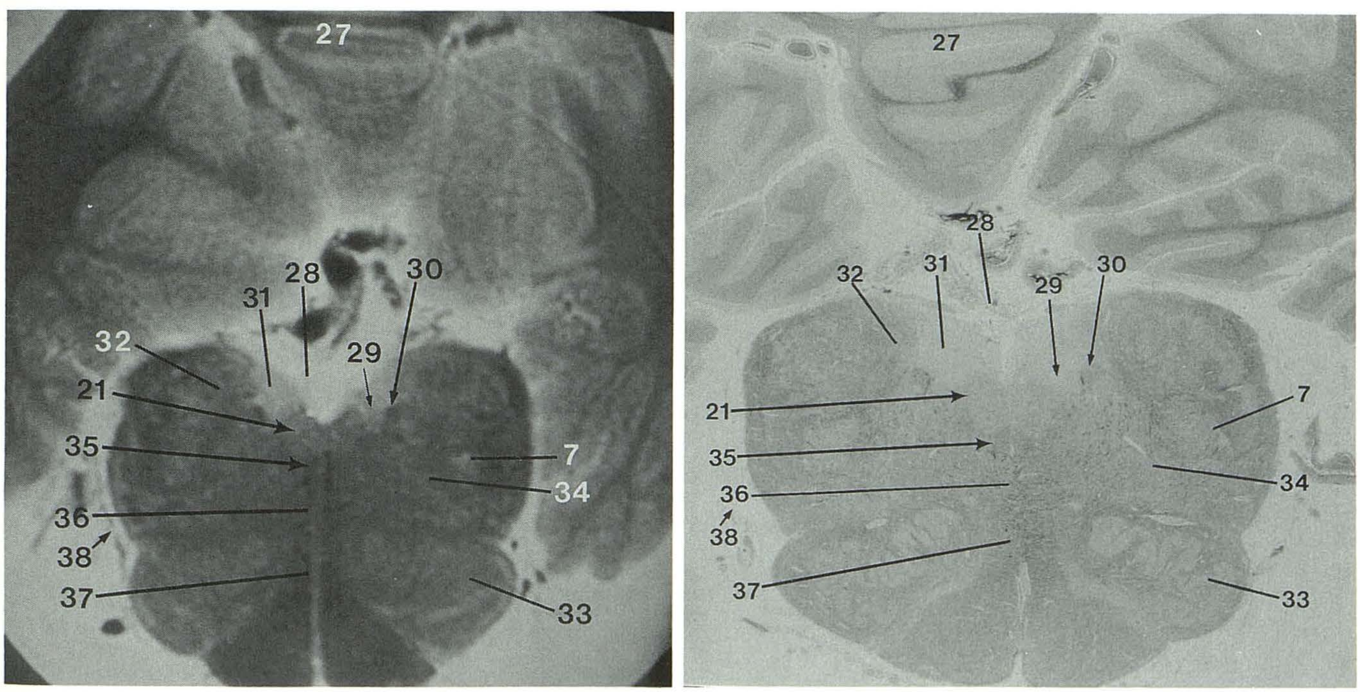
Fig. 4.—Region of hypoglossal nucleus and decussation of medial lemniscus.
***A*, MR image.**
***B*, Light microscopy image.**



A B

Fig. 5.—Caudal part of fourth ventricle.
***A*, MR image.**
***B*, Light microscopy image.**

dark Nissl staining in this area on the corresponding photomicrograph.

The regions of the tectospinal tract (36) and medial lemniscus (37) are denoted. The more anteriorly placed tectospinal tract and medial lemniscus are not visualized. The role of the tectospinal tract is not well understood; however, it is thought to control turning of the head in response to light. The medial lemniscus contains fibers from the nuclei fasciculus and cuneatus and from the ventral spinothalamic tract. This is, therefore, an afferent pathway for joint, position, and light touch sensation.

Midsection of Medulla (Fig. 6)

The fourth ventricle (39) contains the choroid plexus (41), which extends into the lateral recess (40). The vertebral arteries normally course along the anterolateral surfaces of the medulla. The artery is seen more laterally (42) because of preparation artifact.

The medial (44) and dorsal (43) accessory olivary nuclei are further components of the olivary complex. These are well defined on both the MR and light microscopy images.

This level shows the positions of the nuclei of the cranial nerves (VIII, IX, X, and XII) below the floor of the fourth ventricle. The hypoglossal nucleus (21) is now seen in the medial aspect of the floor of the fourth ventricle. The dorsal motor nucleus of the vagus nerve (29), the nucleus solitarius (30), and the vestibular complex (31, 32) are seen in more lateral positions.

The central tegmental tract (45) occupies a position between the dorsal accessory and the inferior olivary nuclei. This is a major tract in the extrapyramidal system.

The fibers of the posterior spinocerebellar tract ascend into the cerebellum via the inferior cerebellar peduncle (restiform body) (46). The inferior cerebellar peduncle is seen as an area of low signal intensity on all MR images. It is located in the most posterolateral portion of the medulla.

Rostral Portion of Medulla (Fig. 7)

The nodulus (49) of cerebellum is seen invaginating the roof of the fourth ventricle at this level. The choroid plexus (41) is again demonstrated.

The previously described nuclei of the cranial nerves are again seen. Along the posterior aspect of the inferior cerebellar peduncle (54) lies the dorsal cochlear nucleus (50).

The cochlear part of the vestibulocochlear nerve (52) is seen entering the ventral cochlear nucleus (51) anterolateral to the inferior cerebellar peduncle. Just medial to the cochlear part of the vestibulocochlear nerve is the glossopharyngeal nerve (53). These structures are better demonstrated on the light microscopy image.

Junction of Medulla and Pons (Fig. 8)

The paramedian small vessels (2) are identified on both MR and light microscopy images.

The nucleus of the glossopharyngeal nerve (56) now is seen in the medial part of the floor of the fourth ventricle. The medial vestibular (31) and the superior vestibular (55) nuclei lie more laterally.

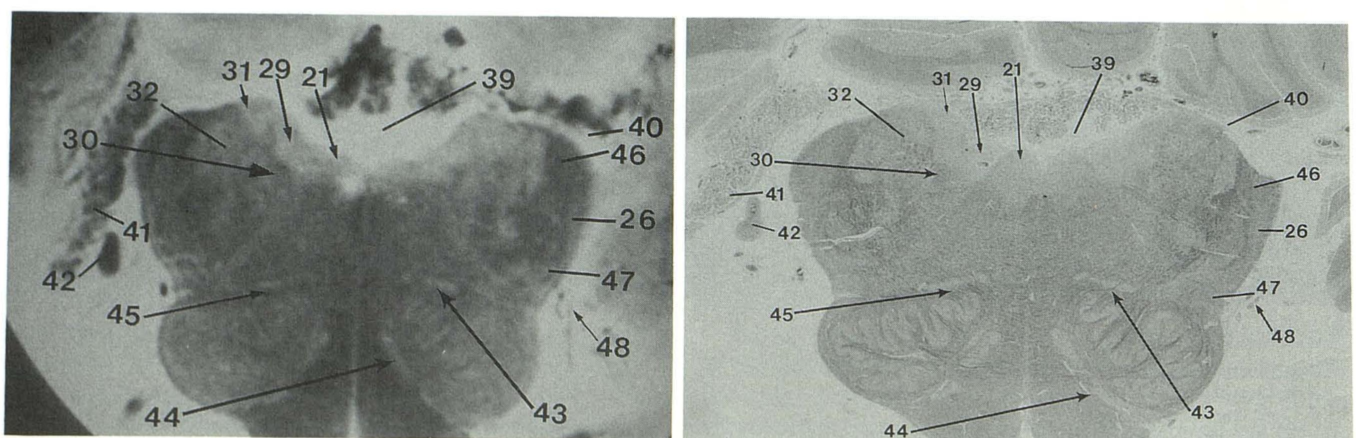
The cochlear part of the vestibulocochlear nerve (52) and the ventral cochlear nucleus (51) are again visualized on both the MR and light microscopy images. However, the nerve is not demonstrated as well on the light microscopy section because of a cutting artifact.

The middle cerebellar peduncle (57) is now visible lateral to the inferior cerebellar peduncle. The fibers of the inferior cerebellar peduncle are seen coursing posteriorly into the cerebellum on the light microscopy preparation.

Level of Facial Colliculus in the Pons (Fig. 9)

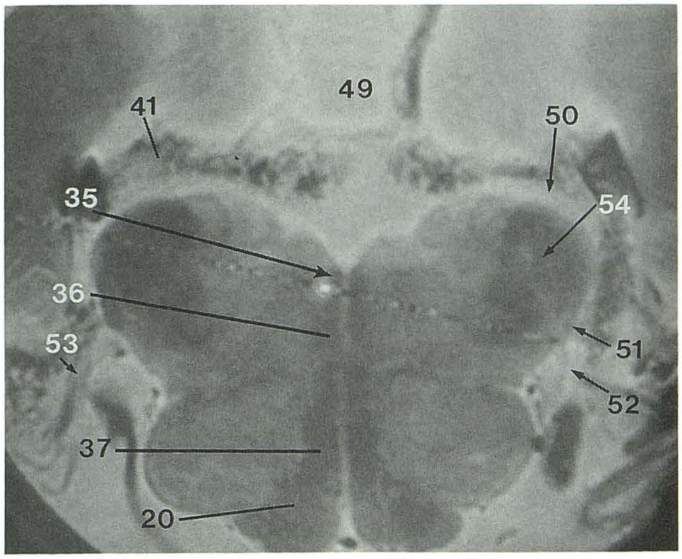
The superior vestibular nucleus (55) lies along the anterolateral wall of the fourth ventricle. These bilateral structures are demonstrated on both the MR and light microscopy sections.

Although the nucleus of the facial nerve is not seen, its location is noted (61). The ascending fibers of the facial nerve course over the abducens nucleus (60), forming a prominence in the floor of the fourth ventricle. This prominence is the facial colliculus (59). The ascending fibers are not seen; however, the descending fibers (62) are clearly demonstrated as



A B

Fig. 6.—Midsection of medulla.
***A*, MR image.**
***B*, Light microscopy image.**



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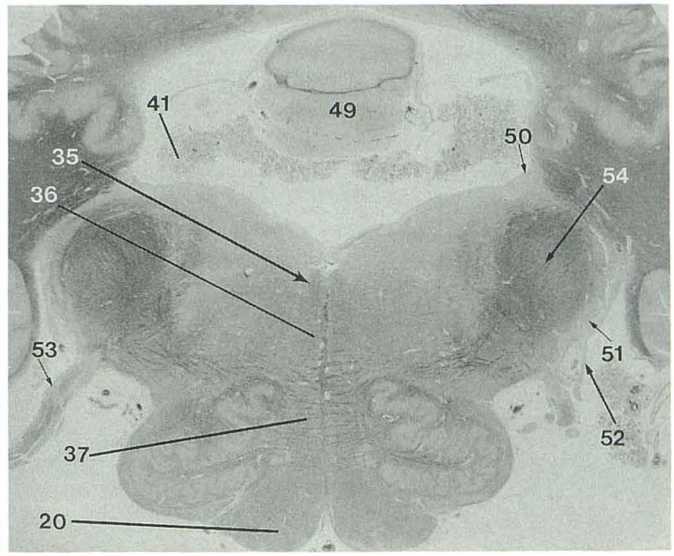
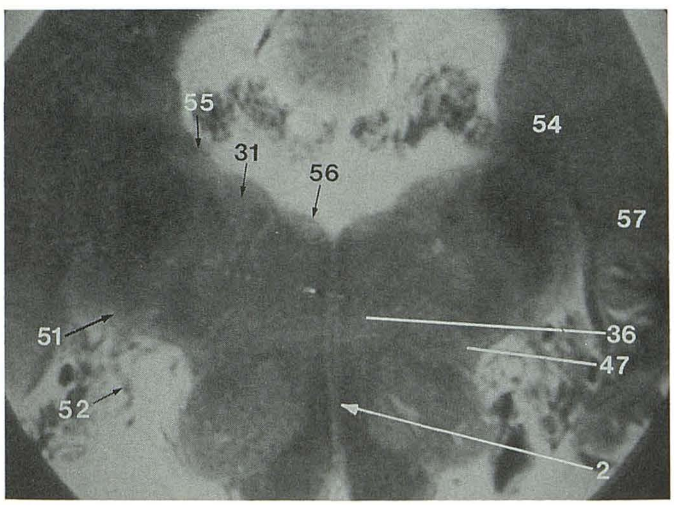


B

Fig. 7.—Rostral portion of medulla.
***A*, MR image.**
***B*, Light microscopy image.**



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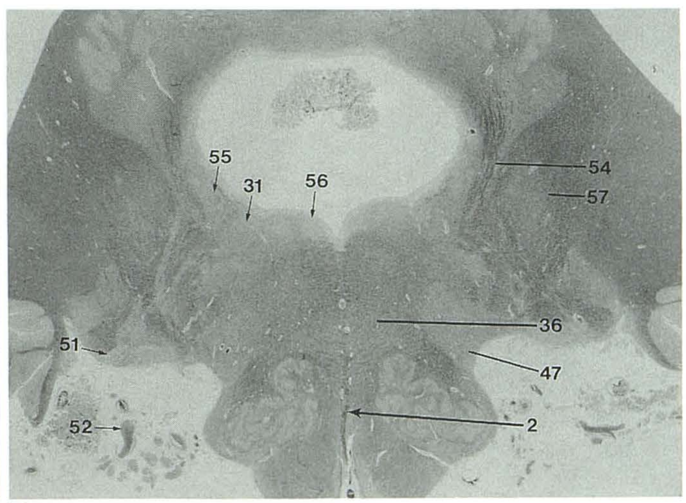


B

Fig. 8.—Junction of medulla and pons.
***A*, MR image.**
***B*, Light microscopy image.**

they continue on this parabolic route to form the facial nerve (63).

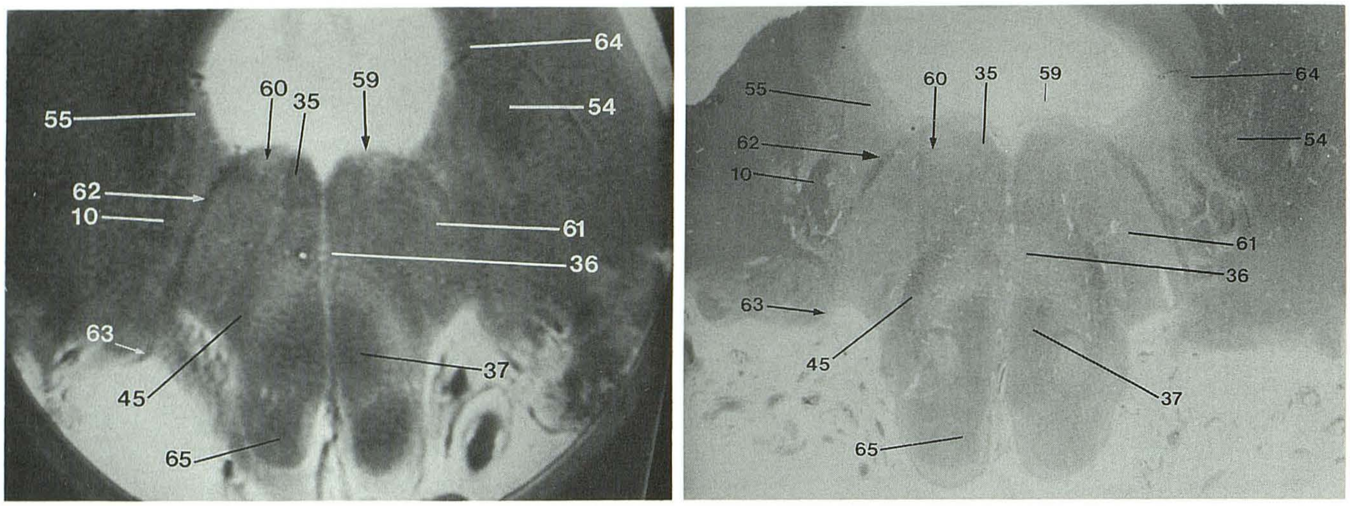
The medial longitudinal fasciculus (35), region of the tectospinal tract (36), and region of the medial lemniscus (37) are again demonstrated. The position of these white-matter tracts is unchanged from the previous descriptions. However, the central tegmental tract (45) now occupies a more lateral position than in the medulla oblongata. This tract is better seen in the histology preparation.

The superior cerebellar peduncle (64) is seen on the MR image as a dark band lateral to the fourth ventricle. The position is confirmed on the light microscopy image.

Section Through Midpons (Fig. 10)

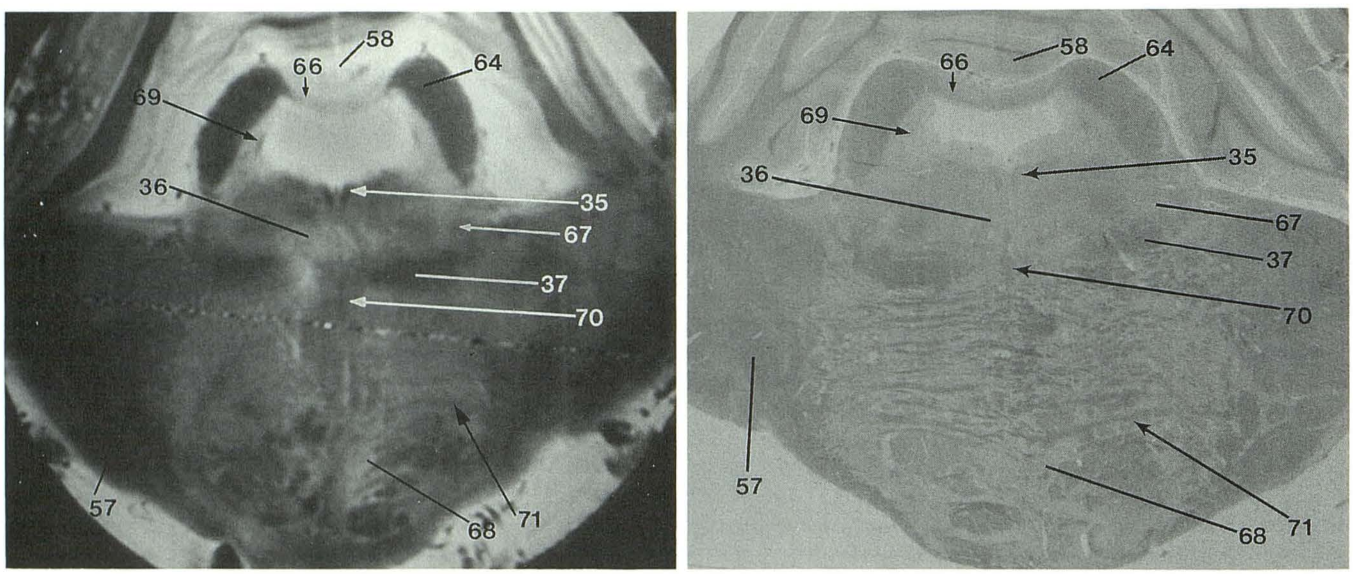
The lingula (58) of the cerebellar vermis lies on the anterior medullary velum (66), forming the roof of the fourth ventricle at this level. The MR anatomy of the vermis has been described previously by Courchesne et al. [8] and Press et al. [9].

The trigeminal complex (67) is not identified clearly. This complex is formed by the sensory and motor trigeminal nuclei. However, some trigeminal fibers extend posteriorly from the trigeminal complex as the mesencephalic nucleus and tract (69), which is better demonstrated on MR.



A B

Fig. 9.—Level of facial colliculus in pons.
***A*, MR image.**
***B*, Light microscopy image.**



A B

Fig. 10.—Section through midpons.
***A*, MR image.**
***B*, Light microscopy image.**

The pontine nuclei (68) are seen as bright areas surrounding the dark corticospinal tract fibers (65) on MR (Fig. 9); the locations of these structures are confirmed on the light microscopy image. The pontine nuclei are part of the extrapyramidal system.

The pontocerebellar fibers (71) are efferent tracts from the pons that travel posteriorly to ascend through the middle cerebellar peduncle (57) to the cerebellum. These fibers are seen as horizontal dark striations.

The superior cerebellar peduncle (64) is well demonstrated on MR as a dark band lateral to the fourth ventricle. This structure carries fibers of the ventral spinocerebellar and extrapyramidal tracts and of the vestibulospinal system. These structures are important in the control of posture, equilibrium, the head, and oculocephalic reflexes.

The medial lemniscus (37) is seen on MR as a broad low-intensity band in the posterior part of the pons as it continues on its rostral course to the thalamus.

Section Through Rostral Pons and Rostral Part of Fourth Ventricle (Fig. 11)

The trigeminal nerve (72) is seen anterolateral to the middle cerebellar peduncle (57) at this level.

The lateral lemniscus (73) lies posterolateral to the medial lemniscus (37). The lateral lemniscus carries ascending fibers from the cochlear nuclei.

Section at Junction of Pons and Mesencephalon (Fig. 12)

The superior cerebellar peduncle (64) has now entered the pons and is seen in a more anteromedial position than in the midpons. The corticospinal (65), corticopontine (74), and pontocerebellar (71) tracts are again identified at this level. In this section, the lateral lemniscus (73) is more conspicuous as it courses rostrally to reach the inferior colliculus.

Section at Level of Inferior Colliculi (Fig. 13)

The crus cerebri (76) represent the fiber projections of the corticospinal tracts. The interpeduncular fossa is an arachnoid cistern between the crus cerebri. The oculomotor nerve (84) is seen in the roof of the interpeduncular fossa. These structures are well demonstrated on the light microscopy and MR images.

The nucleus of the trochlear nerve is not well delineated; however, its location (80) is denoted.

A bright rim is seen between the periaqueductal gray matter (77) and the cerebral aqueduct (75). This probably represents

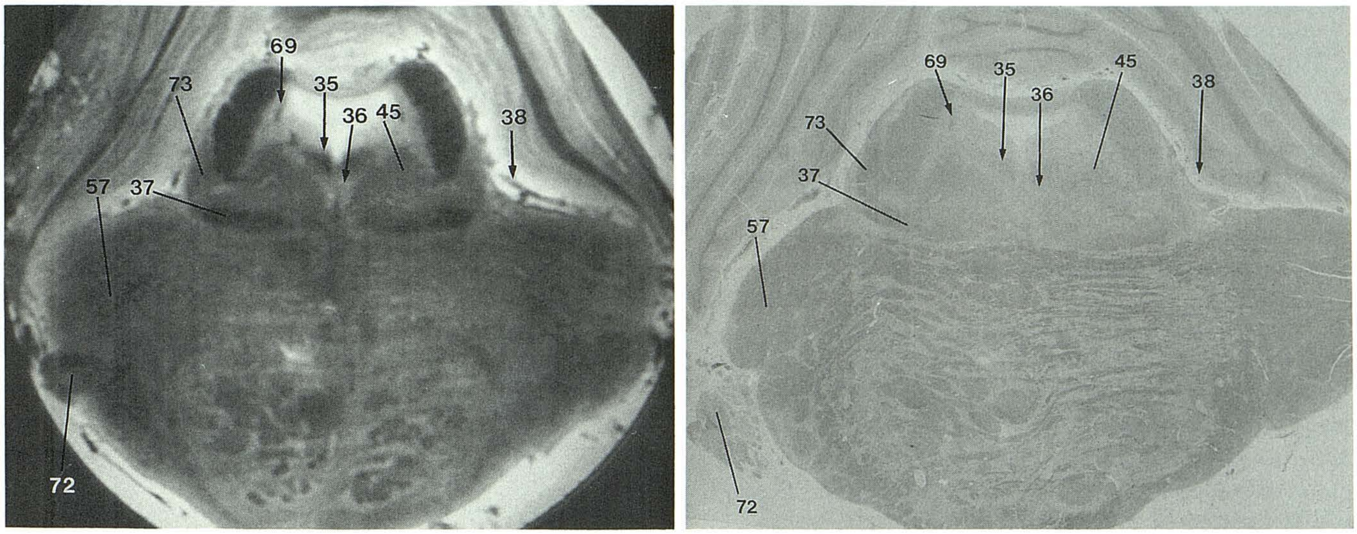


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Fig. 11.—Section through rostral pons and rostral part of fourth ventricle.
***A*, MR image.**
***B*, Light microscopy image.**

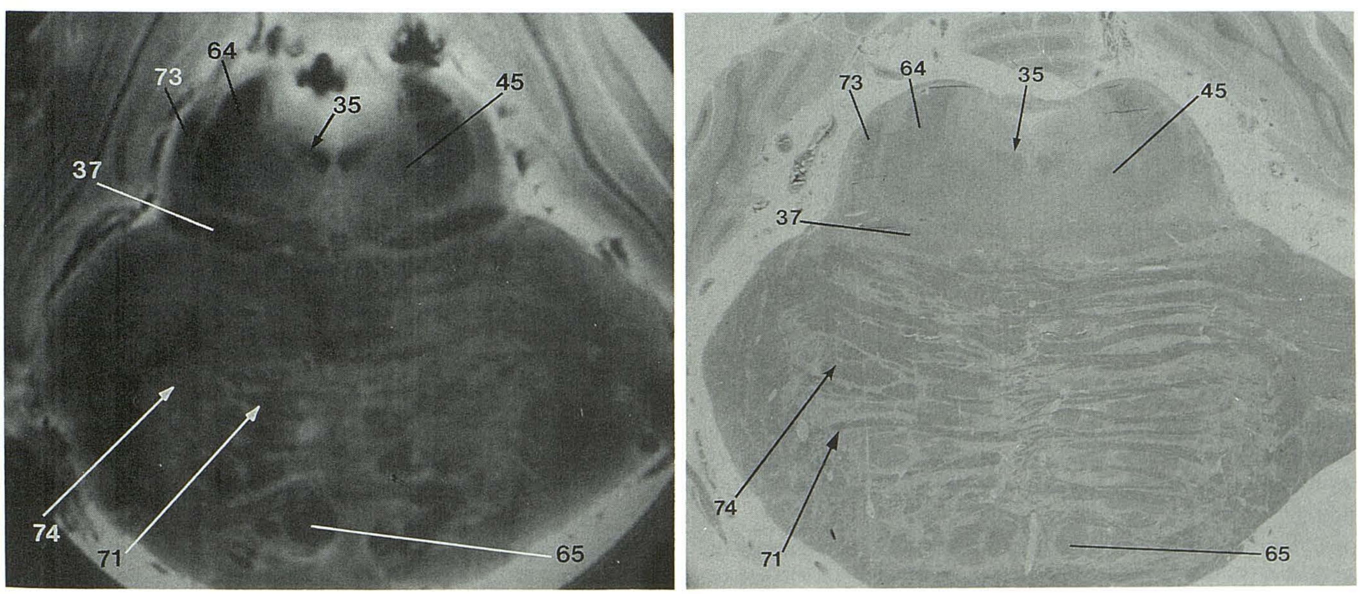

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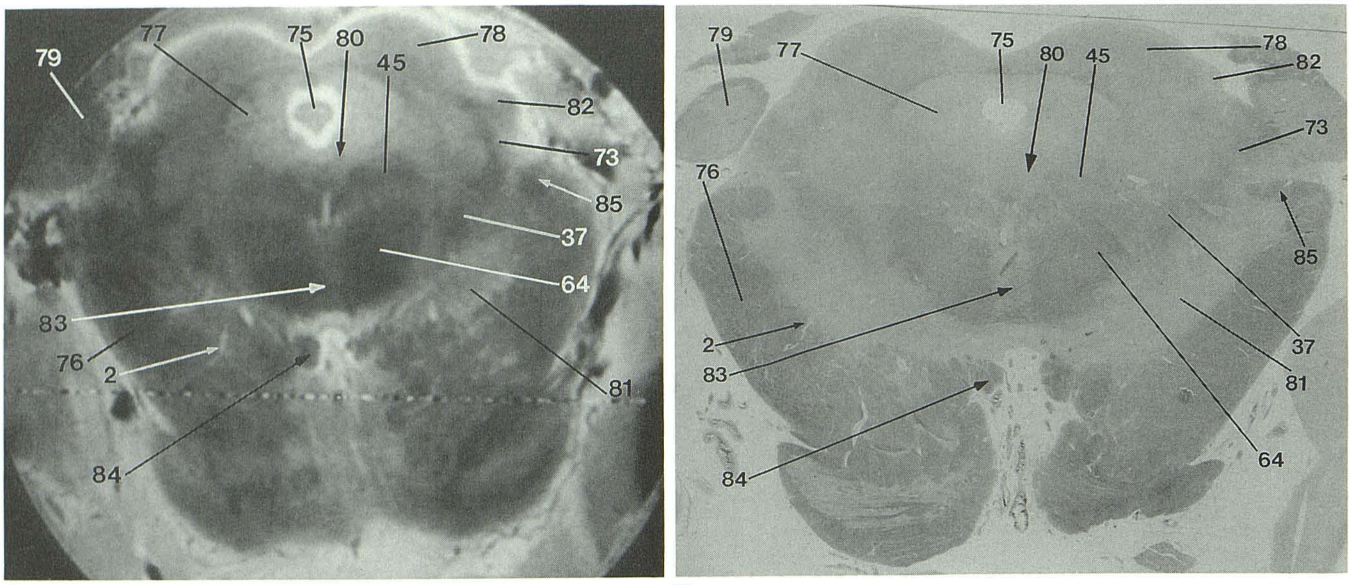
Fig. 12.—Section at junction of pons and mesencephalon.
***A*, MR image.**
***B*, Light microscopy image.**



A B

Fig. 13.—Section at level of inferior colliculi.
***A*, MR image.**
***B*, Light microscopy image.**

an edge magnetic susceptibility artifact. The lateral lemniscus (73) enters the inferior colliculus (78). The inferior colliculus lies posterolateral to the aqueduct in the tectum. The brachium of the inferior colliculus (82) is the connection between the inferior colliculus and the medial geniculate nucleus (79). The inferior colliculus and its projections function in the auditory pathways.

At this level, the superior cerebellar peduncles (64) join in the middle of the mesencephalon, forming the decussation of the cerebellar peduncles (83).

The substantia nigra (81) represents the anatomic division between the crus cerebri (tegmentum) and the more posteriorly placed structures (tectum). The substantia nigra is seen as a broad band of relatively bright signal on MR. The substantia nigra and its connections are important structures in the extrapyramidal system.

The pallidotegmental and strionigral fibers (85) are seen as round low-intensity areas in the posterolateral portion of the substantia nigra.

Section at Level of Superior Colliculi (Fig. 14)

The rostral lip of the pons (90) lies on the anterior surface of the mesencephalon at this level. A posteromedial striate artery (86) is seen entering the interpeduncular fossa. The oculomotor nucleus is not seen; however, its location (89) is noted.

The superior colliculus (87) and the brachium of the superior colliculus (88) are seen in the tectum at this level. These structures function in the visual pathways receiving afferents from the optic tracts and with efferent outflow primarily to the occipital cortex.

Level of Mesencephalic/Diencephalic Junction (Fig. 15)

The hippocampal gyrus (91) of the temporal lobe lies anterolateral to the crus cerebri (76) separated by the transverse fissure. The posterior cerebral artery (95) lies in the transverse fissure. The optic tract (96) is also demonstrated in this region.

The red nucleus (93) is a major structure in the extrapyramidal system. This structure is important in posture and coordination. The paired red nuclei lie on either side of the midline anterior to the reticular formation (23) and posterior to the substantia nigra (81).

The posterior commissure (92) forms the most posterior portion of the tectum at this level. The axial plane through the posterior commissure represents the mesencephalic/diencephalic junction or the end of the brainstem neuroanatomically. The pineal gland is seen only on MR because of a cutting artifact.

Discussion

MR images have been used to show the cranial nerves and nuclei in the brainstem. Brainstem topography and gray- and white-matter structures are demonstrated.

The MR contrast between gray and white matter in formalin-fixed specimens is different from that observed in vivo. This may be attributed to the relatively short T1 relaxation time of formalin relative to water and, also, to shrinkage of the specimen due to fixation.

While the conspicuity of structures seen with these in vitro techniques is beyond the capabilities of current clinical examinations, this study should serve as a neuroanatomic description and review of the complex MR anatomy of the human brainstem.

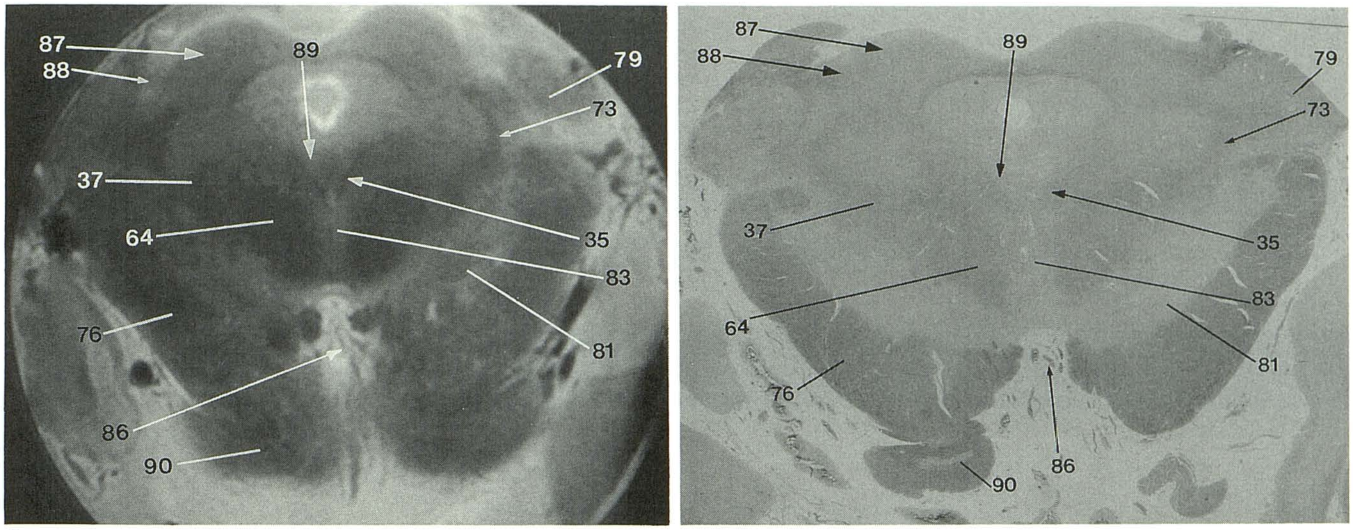


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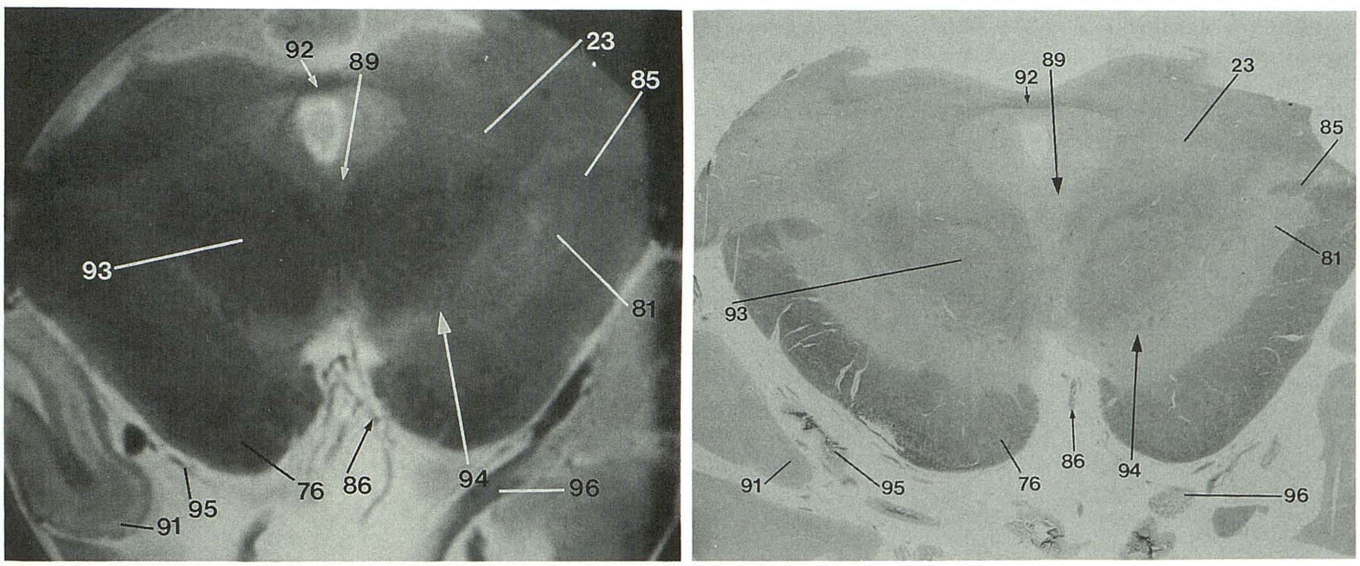
Fig. 14.—Section at level of superior colliculi.
***A*, MR image.**
***B*, Light microscopy image.**



A B

Fig. 15.—Level of mesencephalic/diencephalic junction.
***A*, MR image.**
***B*, Light microscopy image.**

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