Anatomy of the brainstem: correlation of in vitro MR images with histologic sections.

W L Hirsch, S S Kemp, A J Martinez, H Curtin, R E Latchaw and G Wolf

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Anatomy of the Brainstem:
Correlation of in Vitro MR Images with Histologic Sections

William L. Hirsch[1]
Susan S. Kemp[1]
Augusto J. Martinez[2]
Hugh Curtin[1]
Richard E. Latchaw[1]
Gerald Wolf[1]

MR imaging was performed on three formaldehyde-fixed brainstem specimens that were sectioned in the axial plane and myelin stained. The histologic sections were used to identify and label the structures demonstrated on short TR/TE axial MR images. Fiber tracts and nuclei that cannot be resolved on in vivo scans were well delineated by in vitro MR. Improved gray-white differentiation may be due to much greater T1 shortening of gray matter relative to white matter after fixation. The excellent anatomic detail provided by these scans should facilitate comparison of clinical scans with histologic sections.

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MR is superior to other imaging techniques in delineating normal brainstem anatomy. However, many functionally important structures cannot be directly visualized on clinical MR studies. In practice, their location can be inferred from external or surface structures and from certain internal landmarks that can be visualized by MR. These internal landmarks seen on clinical images include the substantia nigra nuclei, inferior olivary nuclei, red nuclei, decussation of the superior cerebellar peduncles, medial lemniscus, and corticospinal tracts [1]. With formaldehyde-fixed brainstems and high-resolution surface coils, many more details of the internal architecture of the brainstem can be visualized.

Materials and Methods

The brains of three patients who died without known neurologic disease were obtained at autopsy and fixed in 10% buffered formaldehyde. The brainstem and cerebellum were removed by sectioning at the rostral midbrain. The specimens were scanned on a GE 1.5-T unit. For two of the specimens a commercial extremity coil was used. One specimen (illustrated below) was scanned in a noncommercial small-animal coil after the cerebellar hemispheres were removed. Axial short TR spin-echo images, 500/25/2 (TR/TE/excitations), were obtained, with an 8-cm field of view, 256 × 256 matrix, 3-mm slice thickness, and 0 interslice gap. Long TR sequences were also obtained; however, the short TR images were selected for evaluation because of superior anatomic detail.

After MR scanning, the specimens were sectioned in a plane similar to Reid's baseline (line from infraorbital rim to the external auditory canal). This is distinct from most published anatomic atlases, in which the plane of section is perpendicular to the longitudinal axis of the brainstem. Photomicrographs of the myelin-stained sections were labeled according to standard anatomic texts [2–6]. The images were oriented as they would be visualized on clinical scans rather than by anatomic convention. The scans were labeled from the photomicrographs of the corresponding sections.

Results

The detailed internal architecture of the brainstem was well demonstrated on fixed-specimen MR images (Figs. 1–7). Densely compacted, heavily myelinated

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[1] Department of Radiology, Presbyterian-University Hospital, DeSoto & O'Hara Sts., Pittsburgh, PA 15213. Address reprint requests to W. L. Hirsch.

[2] Division of Neuropathology, Presbyterian-University Hospital, Pittsburgh, PA 15213.

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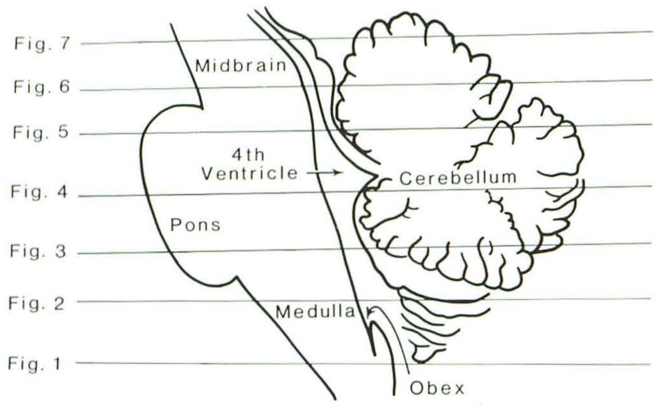

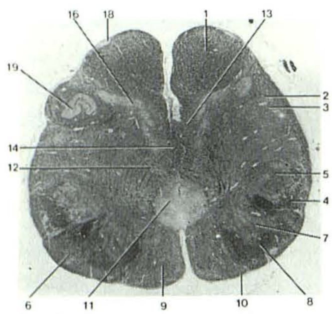

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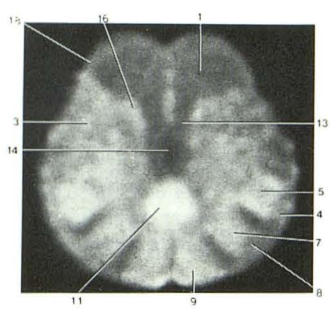


C

Fig. 1.—*A*, Location of axial sections for Figures 1–7.

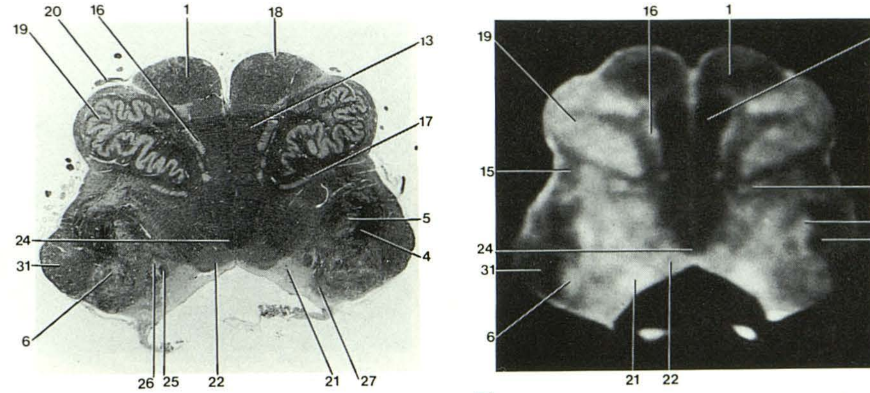
B and *C*, Stained anatomic section (*B*) and MR image (500/25) (*C*) of caudal medulla, defined inferiorly by decussation of pyramids and superiorly by pontomedullary junction. The pyramids are ventral prominences that carry densely compacted, myelinated fibers from the cortex through the cerebral peduncles to the spinal cord. The ventral lateral medulla contains the spinothalamic tracts bilaterally that carry pain, temperature, and some tactile sensations from the cord to the thalamus. These tracts are less myelinated and less compact and are not as well defined as the pyramidal tracts. The dorsal columns consist of large myelinated nerve fibers carrying mechano- and proprioceptive information from the cord to the nucleus cuneatus laterally and the nucleus gracilis medially. Second-order fibers arise in these nuclei and arc anteriorly across the midline, forming the contralateral medial lemniscus. This compact bundle of somatotopically organized fibers has a very low signal; it spirals superiorly through the brainstem terminating in the thalamus. Its configuration varies at each level, but this tract can be seen on all brainstem sections.

Key to Numbers in Figures 1–7

1 = Pyramidal (corticospinal) tract
2 = Lateral reticular nucleus
3 = Spinothalamic tract
4 = Spinal trigeminal tract
5 = Spinal trigeminal nucleus
6 = Lateral cuneate nucleus
7 = Nucleus cuneatus
8 = Fasciculus cuneatus
9 = Nucleus gracilis
10 = Fasciculus gracilis
11 = Central gray
12 = Internal arcuate fibers
13 = Medial lemniscus
14 = Decussation of medial lemniscus
15 = Spinothalamic tract
16 = Medial accessory olivary nucleus
17 = Dorsal accessory olivary nucleus
18 = Arcuate nucleus
19 = Inferior olivary nucleus
20 = Rootlet of hypoglossal nerve
21 = Dorsal motor nucleus of vagus
22 = Hypoglossal nucleus
23 = Nucleus prepositus hypoglossi
24 = Medial longitudinal fasciculus
25 = Fasciculus solitarius
26 = Nucleus solitarius
27 = Inferior vestibular nucleus
28 = Medial vestibular nucleus
29 = Lateral vestibular nucleus
30 = Fibers of the vestibulocochlear nerve
31 = Inferior cerebellar peduncle
32 = Juxtarestiform body
33 = Spinal lemniscus
34 = Lateral lemniscus
35 = Transverse pontine fibers
36 = Pontine nuclei
37 = Raphe nuclei
38 = Superior central nucleus of the raphe
39 = Central tegmental tract
40 = Facial nucleus
41 = Facial nerve fibers
42 = Middle cerebellar peduncle
43 = Superior olivary nucleus
44 = Principal sensory trigeminal nucleus
45 = Motor trigeminal nucleus
46 = Trigeminal nerve fibers
47 = Mesencephalic trigeminal nerve root
48 = Abducens nucleus
49 = Internal genu of facial nerve
50 = Dorsal raphe nucleus
51 = Superior cerebellar peduncle
52 = Decussation of superior cerebellar peduncle
53 = Pontine reticular formation
54 = Interpeduncular nucleus
55 = Rostral aspect of basis pontis
56 = Crus cerebri
57 = Substantia nigra
58 = Periaqueductal gray
59 = Inferior colliculus
60 = Brachium of inferior colliculus
61 = Trochlear nucleus
62 = Cerebral aqueduct
63 = Fibers of oculomotor nucleus
64 = Oculomotor nucleus
65 = Red nucleus

Fig. 2.—Rostral medulla.

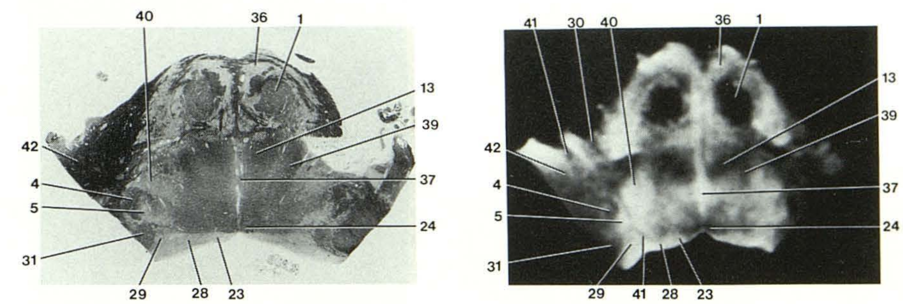
_A_ and _B_, Stained anatomic section (_A_) and MR image (TR 500/25) (_B_). In the rostral medulla, lateral to the pyramid, an eminence overlies the inferior olivary nucleus. The inferior cerebellar peduncle forms a prominence on the dorsal lateral aspect of the medulla. Dorsal to the medial lemniscus is a small but distinctive bundle of densely compacted myelinated fibers, the medial longitudinal fasciculus. This tract is visualized from the rostral medulla to the midbrain just ventral to the floor of the fourth ventricle. Its fibers are involved in vestibular function and eye movements. Several cranial nerve nuclei are seen on this slice. The hypoglossal nucleus lies in the floor of the fourth ventricle near the midline; just lateral to this is the dorsal motor nucleus of the vagus and the nucleus solitaris. Further laterally lie sensory nuclei including the inferior vestibular nucleus and the spinal trigeminal nucleus.



A **B**

Fig. 3.—Caudal pons.

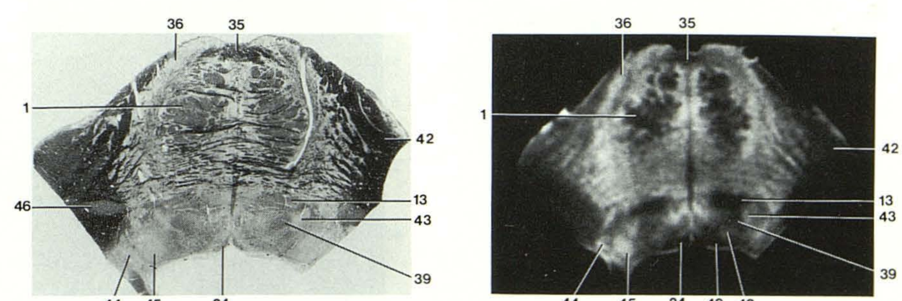
_A_ and _B_, Stained section (_A_) and MR image (500/25) (_B_). The pons extends from its junction with the medulla to the cerebral aqueduct. This slice through the caudal pons shows the longitudinally oriented pyramidal tracts surrounded by the higher-signal gray matter of the pontine nuclei. Transversely oriented fiber bundles in the ventral pons coalesce laterally to form the middle cerebellar peduncles. Several cranial nerve nuclei are visible at this level. The nucleus prepositus hypoglossi lies medially. Lateral to this in the floor of the fourth ventricle lie the medial and lateral vestibular nuclei. More ventrally in the pons lies the facial nerve nucleus and lateral to this lie the spinal trigeminal tract and nucleus.



A **B**

Fig. 4.—Mid pons.

_A_ and _B_, Stained section (_A_) and MR image (500/25) (_B_). The pyramidal tracts are becoming dispersed within the pontine nuclei. At this level the medial lemniscus appears as a low signal band just dorsal to the transverse pontine fibers. The abducens nucleus is present in a paramedian location just ventral to the floor of the fourth ventricle. This is also the level of the internal genu of the facial nerve, which courses just dorsal to the abducens nucleus. Lateral to the abducens nucleus in the floor of the fourth ventricle lie the motor and sensory nuclei of the trigeminal nerve. Between these trigeminal nuclei and the medial lemniscus lies the superior olivary nucleus.



A **B**

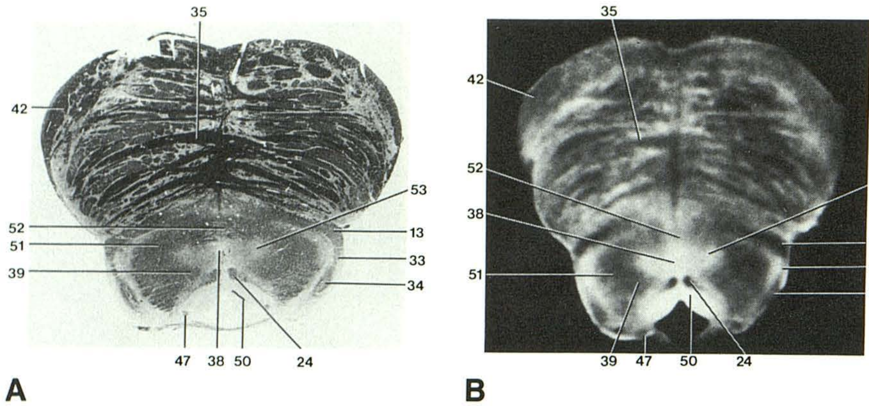


Fig. 5.—Rostral pons.

_A_ and _B_, Stained section (_A_) and MR image (500/25) (_B_). The longitudinal pyramidal (corticospinal) fibers are now thoroughly dispersed within the pontine gray matter. The superior cerebellar peduncles join the brainstem at this level just lateral to the rostral fourth ventricle. Between the peduncles lie the raphe nuclei.

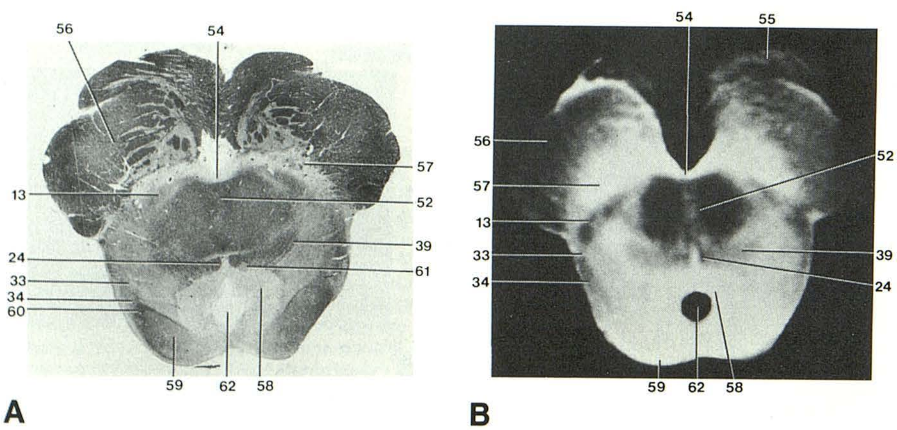


Fig. 6.—Caudal midbrain.

_A_ and _B_, Stained section (_A_) and MR image (500/25) (_B_). The cerebral peduncles comprise the midbrain ventral to the aqueduct. They consist of two parts: the dense fiber bundles of the ventral crus cerebri and the more dorsal midbrain tegmentum. However, in common usage, cerebral peduncle is synonomous with crus cerebri. The crus cerebri and tegmentum are separated by the substantia nigra, a pigmented nuclear mass. The central portion of the tegmentum consists of the decussation of the superior cerebellar peduncles. In the lateral aspect of the tegmentum lie the lateral and medial lemniscus, which carry fibers from the cochlear nuclei to the inferior colliculus. Also at this level just ventral to the periaqueductal gray matter lie the trochlear nuclei (seen on the photomicrograph only).

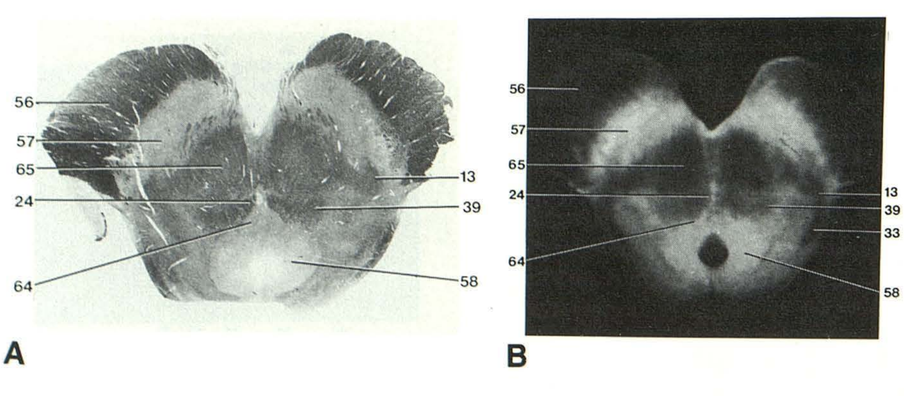


Fig. 7.—Rostral midbrain.

_A_ and _B_, Stained section (_A_) and MR image (500/25) (_B_). This section lies rostral to the decussation of the superior cerebellar peduncles. The central low-signal areas represent the red nuclei. The oculomotor nuclei are seen just ventral to the periaqueductal gray.

TABLE 1: Cranial Nerve Nuclei: Location and Function

Nerve	Type of Fibers	Nucleus of Origin or Termination	Location of Nucleus	Figure	Peripheral Sensory or Motor Ending
Oculomotor	GSE	Oculomotor nucleus	Rostral midbrain, at ventral edge of periaqueductal gray	Fig. 7	Superior rectus Medial rectus Inferior rectus Inferior oblique Levator palpebrae superioris
	GVE	Edinger-Westphal	Rostral midbrain, just rostral to oculomotor nucleus	Not visualized	Sphincter pupillae (constricts pupil) Ciliary muscle (accommodation)
Trochlear	GSE	Trochlear nucleus	Midbrain, just caudal to the oculomotor nucleus	Fig. 6 (micro only)	Superior oblique
Trigeminal	GSA	Spinal trigeminal nucleus	Pons–upper cervical cord	Figs. 1, 2, 3	Skin & deep tissues of the head, dura mater
		Principal sensory trigeminal nucleus	Dorsal pons, situated between middle & superior cerebellar peduncle	Fig. 4	Skin & deep tissues of the head, dura mater
		Mesencephalic trigeminal nucleus	Dorsal pons, just dorsal to main sensory trigeminal nucleus	Fig. 4	Mechanoreceptors of facial muscles
	SVE	Trigeminal motor nucleus	Dorsal pons just medial to main sensory trigeminal nucleus	Fig. 4	Muscles of mastication
Abducens	GSE	Abducens nucleus	Caudal pons, in the floor of the 4th ventricle	Fig. 4 (MR only)	Lateral rectus
Facial	SVE	Facial nucleus	Caudal pons, ventrolateral of pontine reticular formation	Fig. 3	Muscles of facial expression, platysma, buccinator, stapedius muscle
			Fibers of facial nerve course superiorly around the abducens nucleus ("internal genu")	Fig. 4 (MR only)	Posterior belly of digastric; stylohyoid muscle
	GVE	(Superior) salivary nucleus	Rostral medulla dorsolateral reticular formation	Not visualized	Lacrimal gland Mucous membrane of nose & mouth Submandibular & sublingual glands
	SVA	Nucleus solitarius	Rostral dorsolateral medulla, lateral to dorsal motor nucleus of vagus	Fig. 2 (micro only)	Taste from anterior 2/3 of tongue and palate
	GSA	Principal sensory trigeminal nucleus (tactile)	Dorsal pons (see description under trigeminal nuclei)	Fig. 4	Pinna and external acoustic meatus
		Spinal trigeminal nucleus (thermal, pain)	Pons–upper cervical cord	Figs. 1, 2, 3	Pinna and external acoustic meatus
Vestibulocochlear	SSA	Dorsal and ventral cochlear nuclei	Caudal pons dorsolateral and lateral to inf. cerebellar peduncle	Not visualized*	Cochlea—auditory
		Vestibular nuclear complex: superior inferior, medial, and lateral vestibular nuclei	Dorsolateral caudal pons extending into rostral medulla	Fig. 2 (micro only)	Cristae ampullaris of semicircular canals
				Fig. 3	Maculae utriculi and sacculi of the utricle and saccule
Glossopharyngeal	GVE	Inferior salivary nucleus	Rostral medulla, dorsolateral reticular formation medial to nucleus solitarius	Not visualized	Myoepithelial cells of parotid gland
	SVE	Nucleus ambiguus	Medulla, ventrolateral reticular formation, between spinal trigeminal nucleus and inferior olivary nuclei	Not visualized	Stylopharyngeus muscle & possibly superior pharyngeal constrictor
	GVA	Nucleus solitarius	Rostral dorsolateral medulla	Fig. 2 (micro only)	Mucosa of tympanum, mastoid air cells, eustachian tube, tonsil, pharynx, soft palate Carotid sinus baroreceptors Carotid body chemoreceptors
	SVA	Nucleus solitarius	Rostral dorsolateral medulla	Fig. 2 (micro only)	Taste, posterior 1/3 of tongue

Table 1 continues

TABLE 1—*Continued*

Nerve	Type of Fibers	Nucleus of Origin or Termination	Location of Nucleus	Figure	Peripheral Sensory or Motor Ending
	GSA	Main sensory trigeminal nucleus (tactile)	Dorsal pons	Fig. 4	Cutaneous area behind ear
		Spinal trigeminal nucleus (thermal, pain)	Pons– upper cervical cord	Figs. 1, 2, 3	Cutaneous area behind ear
Vagus	GVE	Dorsal motor nucleus	Dorsal medulla, in floor of 4th ventricle	Fig. 2	Thoracic and abdominal viscera
	SVE	Nucleus ambiguus	Medulla, ventrolateral reticular formation, between spinal trigeminal nucleus & inferior olivary nuclei	Not visualized	Skeletal muscle of pharynx except stylopharyngeus, larynx, upper 2/3 of esophagus, palate (except tensor palati)
	GVA	Nucleus solitarius	Rostral dorsolateral medulla	Fig. 2 (micro only)	Visceral sensation from tonsils, larynx, thoracic and abdominal viscera, carotid sinus, carotid body
	SVA	Nucleus solitarius	Rostral dorsolateral medulla	Fig. 2 (micro only)	Taste from epiglottis
	GSA	Main sensory trigeminal nucleus	Dorsal pons	Fig. 4	Sensation from pinna, external acoustic meatus, tympanic membrane
		Spinal nucleus trigeminal nerve (thermal, pain)		Figs. 1, 2, 3	
Accessory nerve (spinal root)	GSE or SVE	Spinal nucleus of accessory nerve	Anterior gray column of spinal cord	Not visualized	Motor for sternocleidomastoid and trapezius
Accessory nerve (cranial root)	SVE	Nucleus ambiguus	Medulla	Not visualized	Skeletal muscle of palate & larynx except tensor palatini
	GVE	Dorsal motor nucleus of vagus	Dorsal medulla in floor of 4th ventricle	Fig. 2	Cardiac muscle (through myocardial branches of vagus)
Hypoglossal	GSE	Hypoglossal nucleus	Rostral medulla, paramedian, in floor of 4th ventricle	Fig. 2	Somatic skeletal musculature of tongue

* Nuclei inadvertently removed with cerebellum.

Note.—GSE = General somatic efferent; GVE = general visceral efferent; GSA = general somatic afferent; GVA = general visceral afferent; SVE = special visceral efferent; SSA = special somatic afferent; SVA = special visceral afferent.

tracts were of low signal intensity on short and long TR sequences (e.g., medial longitudinal fasciculus and medial lemniscus). Loosely compacted, less myelinated fibers, such as the spinothalamic tract, were not as distinct as myelinated tracts. The scans showed excellent gray-white contrast on short TR/TE sequences. Brainstem nuclei had intermediate signal intensity on short TR/TE sequences. These nuclei were more or less distinct depending on the signal characteristics of the surrounding fiber bundles. Table 1 lists the cranial nerve nuclei, the sections on which they were visible, and a brief review of their function.

Discussion

In vitro imaging demonstrates the internal architecture of the brainstem to a degree unavailable with current in vivo MR or CT. Contrast resolution is maximized in vitro by using long scan times and small surface coils. Formaldehyde fixation improves gray-white differentiation. This may be due to much greater T1 shortening of gray matter relative to white matter in fixed specimens [7–9]. Enhanced gray-white differentiation is observed on short TR/TE sequences and long TR/short TE sequences [10]. Fixation appears to shorten T1 relaxation more than T2 relaxation [7].

The sections are made parallel to Reid's baseline and are more useful than a conventional atlas for the radiologist. In vitro scans facilitate comparison between histologic sections and clinical images.

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