Three-Dimensional Interactive Atlas of Cranial Nerve-Related Disorders

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SUMMARY – *Anatomical knowledge of the cranial nerves (CN) is fundamental in education, research and clinical practice. Moreover, understanding CN-related pathology with underlying neuroanatomy and the resulting neurological deficits is of vital importance. To facilitate CN knowledge anatomy and pathology understanding, we created an atlas of CN-related disorders, which is a three-dimensional (3D) interactive tool correlating CN pathology with the underlying surface and sectional neuroanatomy as well as the resulting neurological deficits. A computer platform was developed with: 1) anatomy browser along with the normal brain atlas (built earlier); 2) simulator of CN lesions; 3) tools to label CN-related pathology; and 4) CN pathology database with lesions and disorders, and the resulting signs, symptoms and/or syndromes. The normal neuroanatomy comprises about 2,300 3D components subdivided into modules. Cranial nerves contain more than 600 components: all 12 pairs of cranial nerves (CN I – CN XII) and the brainstem CN nuclei. The CN pathology database was populated with 36 lesions compiled from clinical textbooks. The initial view of each disorder was preset in terms of lesion location and size, surrounding surface and sectional neuroanatomy, and disorder and neuroanatomy labeling. Moreover, path selection from a CN nucleus to a targeted organ further enhances pathology-anatomy relationships. This atlas of CN-related disorders is potentially useful to a wide variety of users ranging from medical students and residents to general practitioners, neuroradiologists and neurologists, as it contains both normal brain anatomy and CN-related pathology correlated with neurological disorders presented in a visual and interactive way.*

Introduction

Anatomical knowledge of the cranial nerves (CN) and their nuclei is fundamental in education, research and clinical practice. In addition, understanding CN-related (and, generally, any brain-related) pathology with underlying neuroanatomy and the resulting neurological deficits is of vital importance. Therefore, one of our major goals is to create a 3D interactive atlas of neurological disorders able to provide the correspondence between damage to any cerebral location with the resulting disorders. Towards this objective, we have already built a 3D *Stroke Atlas*¹ providing this correspondence for cerebrovascular lesions. This work extends our previous effort towards CN pathology.

The atlas of CN-related disorders is a three-dimensional (3D) interactive tool correlating CN pathology with the underlying neuroanat-

omy and the resulting neurological deficits. It contains a 3D, parcellated, labeled and explorable atlas of normal neuroanatomy along with a pathology database. Normal neuroanatomy, available in the brain atlas, is subdivided into about 2,300 components and contains cerebrum, cerebellum, brainstem, spinal cord, arteries, veins, dural sinuses, tracts, cranial nerves, white matter, deep gray nuclei, ventricles, visual system, muscles and glands. The pathology database comprises synthesized CN lesions providing disorder-localization relationships, such that each lesion is labeled with the disorder and the resulting signs, symptoms, and/or syndromes. These relationships are compiled from the literature.

However, literature descriptions typically do not specify the lesion size, shape, and location. Therefore additionally to the abovementioned approach, the assessment of a resulting deficit

may be facilitated visually by presenting the complete “anatomical path” from a CN nucleus to a CN nerve with its branches to a targeted muscle or muscles/organs. Then, placing a virtual lesion mentally on the anatomical path allows the investigator to observe which part of this path (and potentially other paths depending on the size of the lesion) will be affected. And conversely, having identified a damaged muscle with all the anatomical paths supplying it could facilitate a potential localization of the lesion. The anatomical path concept for the cranial nerves, enabled by brain compositing and decompositing operations available in the brain atlas, is implemented here.

Material and method

In order to create the atlas of CN-related disorders, we used an approach employed earlier to build the *Stroke Atlas*¹ The *Stroke Atlas* is a 3D interactive tool, which correlates cerebrovascular pathology with the underlying neuroanatomy and the resulting neurological deficits. It is based on a 3D brain atlas of normal anatomy created from 3 and 7 Tesla scans and described in detail earlier²⁻⁶. The normal neuroanatomy is subdivided into modules⁶, and the module with the cranial nerves contained (originally) 440 components: all 12 pairs of cranial nerves (CN I – CN XII) and the brainstem CN nuclei⁵.

The main components of the *Stroke Atlas* reused and extended here are: 1) atlas of normal surface and sectional neuroanatomy along with anatomy browser; 2) simulator of cerebral pathologies; 3) tools to label pathology; and 4) pathology database. Surface neuroanatomy is presented in the form of about 2,300 3D components represented as polygonal objects. Sectional neuroanatomy is presented in the form of axial, coronal, and/or sagittal MR triplanar displayed as 3D textures. The anatomy browser enables the user to make rapid brain compositing and decompositing from individual and/or group components with a few clicks, and to study the composite from any angle and at a wide range of magnifications.

The pathology database correlates lesions with the resulting disorders. Each disorder is described in terms of the corresponding signs, symptoms and/or syndromes. In order to model CN pathology in 3D, a lesion was depicted as a white sphere and pathology along a CN as a white dilated cylinder. An index correlating

neuroanatomy with CN pathology was structured as a list, which is hierarchical with respect to anatomy and linear with respect to disorders. For each disorder, a sub-list of signs, symptoms and/or syndromes was compiled from materials reported in the literature⁷⁻⁹. The initial view of each disorder was preset in terms of lesion location and size, surrounding surface and sectional neuroanatomy, and lesion and neuroanatomy labeling.

To enable the investigator to make a visual assessment of muscle-CN relationships, the existing CN module⁵ was extended and enhanced in terms of branching patterns, nerve course, anatomical index, number of branches, and branch length. The course of cranial nerve branches was lengthened to reach the targeted muscles/organs or edited to have more precise entry location. Several new nerve and branch names were added into the anatomical index. Moreover, 163 new CN branches were created (37% increase in the number of CN components), mostly of the facial nerve. There is a great variation regarding branching patterns and the number of branches^{10,11}. Therefore, the branching patterns were updated in the atlas to correspond to the most frequent patterns described in the literature. The temporal branch was partitioned in the atlas into anterior and posterior branches below the zygomatic arch, as it usually divides in this way¹¹ (the temporal branch courses along the zygomatic system as one (14%), two (57%), three (14%) or four (14%) branches¹²). There are generally multiple zygomatic branches¹¹ and two branches were created in our atlas. The buccal and cervical branches are usually single¹¹ and they remain single in the atlas. Two marginal mandibular branches were implemented in the atlas, as there are typically two of them¹¹ (this branch may have one (21%), two (67%), three (9%) or four (3%) major branches¹³). The course of several nerves and branches was edited to run on the superficial or deep surface of the innervated muscle. The nerve entry locations, when available, were also edited. The CN-muscle relationships were compiled from the following sources¹⁰⁻¹⁸.

Results

A hierarchical index of anatomy integrated with a linear index of CN disorders was constructed (see Appendix for the list of disorders and Figure 1 for the sub-lists of signs, symp-

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← Figure 1 Illustration of CN pathology correlated with the resulting disorder and the surrounding surface and sectional neuroanatomy. The images are composed by means of the anatomy browser which provides: 1) exploration operations for 3D display and manipulation (rotate, zoom, pan, and set view), 2) brain compositing/decompositing of individual components and/or group selection, 3) two-way (3D view-index) mapping, 4) 3D labeling and component highlighting, 5) 3D brain cutting in 7 directions, and 6) axial/coronal/sagittal MR (magnetic resonance) triplanar display. The orientation box in the top-left corner provides the viewing direction (S – superior, I – inferior, A – anterior, P – posterior, L – left, and R – right). a) CN I; b) CN II; c) CN III; d) CN IV; e) CN V; f) CN VI; g) CN VII; h) CN VIII; i) CN IX; j) CN X; k) CN XI; l) CN XII.

toms and/or syndromes for individual CN lesions). The disorder database was populated with 36 CN lesions (meaning that, on average, there are three lesions per CN). The views and labeling of all CN-related lesions were preset. Examples of CN pathology correlated with the resulting disorder and the surrounding surface and sectional neuroanatomy for all 12 pairs of the cranial nerves are illustrated in Figure 1.

The CN-muscle correlation (with the state-of-the-art review and as implemented in the atlas) is presented in Table 1. The extended facial nerve and the facial muscles along with all the cranial nerves are illustrated in Figure 2.

Discussion

The atlas of CN-related disorders correlates localized CN pathology with both the resulting disorder and the surrounding neuroanatomy. It also provides a 3D interactive display both of labeled pathology and neuroanatomy, freely composed by the investigator. Disorders are described in terms of the resulting signs, symptoms and/or syndromes, and they have been compiled for each pair of the cranial nerves as well as for some groups of them. The preset views with labeled pathology and neuroanatomy facilitate and expedite the use of this atlas, while allowing the investigator to quickly update the studied 3D scene, if needed. Path selection from a CN nucleus to a targeted organ further enhances pathology-anatomy relationships. To the best of our knowledge, this is the first 3D, interactive atlas of CN-related disorders. The atlas is potentially useful for medical students, residents, general practitioners, neuroradiologists and neurologists, as it contains both normal brain anatomy and CN-related pathology correlated with disorders presented in a visual and interactive way.

This atlas has limitations in terms of the accuracy of pathology modeling and the size of the pathology database. In order to model pathology, we used spheres (to model lesions) and

dilated cylinders (to model pathology along cranial nerves). However, actual pathology may be much more complex and it often distorts patient's neuroanatomy.

The current CN pathology database contains 36 lesions. We were able to compile the complete disorder index covering deficits of each of 12 pairs of the cranial nerves along with their nuclei and some multiple cranial nerve deficits based on only three textbooks. Although increasing the number of sources would provide more materials, this would also potentially increase material inconsistency. On average, there are three lesions per cranial nerve and the largest number of lesions (i.e., 14) is set in the CN II (generally, in the visual system). The materials on locations of lesions in the visual system and the resulting deficits are also the most consistent across the textbooks used here. Some of CN-related deficit descriptions are complementary across these sources and they were combined here. In the case of differences (such as lesions of the CN VII), we used a single source.

Anatomical descriptions, however, are often contradictory and confusing, partly because of the inconsistent nomenclature¹⁰. Moreover, many past anatomical studies used preserved cadaveric heads and structures were more difficult to separate and identify¹⁰. We also observe a discrepancy between the courses of the facial nerve branches in our atlas (based on the textbook descriptions) and those presented in several drawings. Here, we referred to multiple sources to deal with these inconsistencies, and the configurations implemented in the atlas are indicated in Table 1.

The relationships between the head muscle and the cranial nerves available in the atlas correspond to the usual branching patterns, however, the current version of the atlas does not contain any variants. Moreover, despite creating more than 600 CN segments, this CN network is still oversimplified to balance between the complexity of the cerebral model and the performance of the application.

Table 1 Muscle-CN correlation (options/conditions in italics are implemented in our atlas).

Muscles	Cranial nerves
Auricularis anterior	<i>Posterior rami of temporal branch</i> of CN VII ⁴ p22. Temporal branches of CN VII ⁷ p619, ⁸ p1368.
Auricularis posterior	Posterior auricular branch of CN VII ⁷ p619, ⁸ p1247, ⁸ p1368. Posterior auricular nerve of CN VII ⁶ p79. <i>Auricular branch of posterior auricular nerve</i> of CN VII ⁸ p1246.
Auricularis superior	<i>Temporal branches</i> of CN VII ⁷ p619, ⁸ p1368.
Buccinator	<i>Buccal branch</i> of CN VII ⁷ p487. Innervated from the <i>superficial surface</i> ³ p97.
Corrugator supercillii	Temporal branches of CN VII ⁵ p103, ⁷ p486. <i>Temporal (frontal) branch</i> of CN VII innervates the <i>transverse head</i> and a <i>zygomatic-buccal branch</i> of CN VII supplies the <i>oblique head via a lower eyelid and medial canthus</i> ⁴ p8. <i>Pierced by supratrochlear nerve</i> of V ₁ of CN V ⁴ p40.
Depressor anguli oris	<i>Buccal and marginal mandibular branches</i> of CN VII ³ p97, ⁷ p487. Innervated from the <i>deep surface</i> ³ p97.
Depressor labii inferioris	<i>Marginal mandibular branch</i> of CN VII ⁵ p103, ⁷ p487. Innervated from the <i>deep surface</i> ³ p97.
Depressor septi nasi	<i>Buccal and sometimes zygomatic branches</i> of CN VII ⁷ p549. <i>Zygomatic branches</i> of CN VII ⁵ p103.
Depressor supercillii	<i>Zygomatic-buccal branch</i> of CN VII <i>via a lower eyelid and medial canthus</i> ⁴ p8. <i>Temporal or zygomatic-buccal branch</i> of CN VII ⁴ p9.
Inferior oblique	<i>Branch to inferior oblique</i> enters the muscle on the <i>interconal surface</i> at its <i>mid-position</i> ⁴ p119.
Inferior rectus	<i>Inferior branch</i> of CN III enters the <i>superior surface</i> ⁷ p660. Motor nerve enters at the junction of the <i>posterior one third</i> and <i>anterior two thirds</i> of the muscle ⁴ p119.
Lateral pterygoid	<i>Lateral pterygoid nerve</i> of V ₃ of CN V <i>enters the deep surface</i> of the muscle ¹ p51. <i>Buccal nerve</i> of V ₃ <i>passes through it</i> (between the two heads) ⁸ p1237. <i>Lateral pterygoid nerve</i> , a branch of V ₃ of CN V ⁶ p48. <i>Buccal nerve</i> of V ₃ innervates the upper head and the lateral part of the lower head; a branch arising from V ₃ supplies medial part of the lower head ⁷ p539. <i>Branch from anterior trunk</i> of V ₃ of CN V ⁸ p801.
Lateral rectus	<i>Abducens nerve</i> (CN VI) enters the <i>medial surface</i> ⁷ p660. Motor nerve enters at the junction of the <i>posterior one third</i> and <i>anterior two thirds</i> of the muscle ⁴ p119.
Levator anguli oris	<i>Zygomatic and buccal branches</i> of CN VII ⁷ p486. Innervated from the <i>superficial surface</i> ³ p97.
Levator labii superioris	<i>Zygomatic and buccal branches</i> of CN VII ⁷ p486. Innervated from the <i>deep surface</i> ³ p97.
Levator labii superioris alaeque nasi	<i>Zygomatic and superior buccal branches</i> of CN VII ⁷ p549.
Levator palpebrae superioris	<i>Superior branch</i> of CN III enters the <i>inferior surface</i> ⁷ p659.
Masseter	<i>Masseteric nerve</i> of V ₃ of CN V ¹ p50, ⁷ p538.
Medial pterygoid	<i>Medial pterygoid nerve</i> of V ₃ of CN V ¹ p50.
Medial rectus	<i>Inferior branch</i> of CN III enters the <i>lateral surface</i> ⁷ p660. Motor nerve enters at the junction of the <i>posterior one third</i> and <i>anterior two thirds</i> of the muscle ⁴ p119.
Mentalis	<i>Marginal mandibular branch</i> of CN VII ⁵ p103, ⁷ p486. Innervated from the <i>superficial surface</i> ³ p97.
Nasalis, alar part	<i>Buccal and sometimes zygomatic branches</i> of CN VII ⁷ p549. <i>Zygomatic branches</i> of CN VII ⁵ p103.
Nasalis, transverse part	<i>Buccal and sometimes zygomatic branches</i> of CN VII ⁷ p549. <i>Zygomatic branches</i> of CN VII ⁵ p103.
Occipitofrontalis, frontal belly	Temporal branches of CN VII ⁵ p103, ⁷ p481. <i>Anterior and middle rami of temporal branch</i> of CN VII ⁴ p22. <i>Penetrated medially by supratrochlear nerve</i> of V ₁ of CN V ⁴ p40. <i>Temporal branches enter undersurface</i> of the muscle ² p80.

Occipitofrontalis, occipital belly	Posterior auricular nerve of CN VII ⁷ p481. <i>Occipital branch of posterior auricular nerve</i> of CN VII ⁵ p103.
Orbicularis oculi	<i>Temporal</i> and <i>zygomatic</i> branches of CN VII ⁵ p103, ⁷ p482. Temporal or zygomatic-buccal branch of CN VII supplies the <i>medial superior portion</i> via a lower eyelid and medial canthus ⁴ p9. Anterior and middle rami of temporal branch of CN VII supply the <i>superior portion</i> ⁴ p22. Zygomatic branches cross the zygomatic bone to the lateral canthus supplying the orbicularis oculi ⁴ p1247. Innervated from the <i>deep surface</i> ³ p97. Zygomaticofacial nerve of V ₂ of CN V perforates orbicularis oculi ⁷ p494.
Orbicularis oris	<i>Buccal</i> and <i>mandibular</i> branches of CN VII ⁷ p488. Zygomatic branches supply the superior portion and buccal branches the inferior portion ⁵ p103. Buccal branches ³ p97. Lower buccal and marginal mandibular branches of CN VII ⁸ p798.
Palatine tonsil	<i>Tonsillar</i> branches of CN IX ¹ p149.
Posterior belly of digastric	<i>Digastric</i> branch of CN VII ¹ p85.
Procerus	<i>Temporal</i> and lower <i>zygomatic</i> branches of CN VII ⁷ p549. Temporal branch or lower zygomatic-buccal branch <i>via the lower eyelid</i> and <i>medial canthus</i> ⁴ p7. Temporal branch supplies the <i>upper portion</i> ⁵ p103, (at times) ⁴ p22. Temporal branch ³ p97.
Risorius	<i>Buccal</i> branches of CN VII ⁵ p103, ⁷ p488, ⁸ p799. Innervated from the <i>deep surface</i> ³ p97.
Sternocleidomastoideus	<i>External</i> branch of CN XI ¹ p173.
Superior oblique	<i>Trochlear</i> nerve (CN IV) enters the <i>superior surface</i> ⁷ p660. CN IV enters as 3 or 4 rootlets that penetrate the <i>upper border</i> of the muscle along its <i>posterior third</i> (the only extraocular nerve that does not penetrate the conal surface of its muscle) ⁴ p135.
Superior rectus	<i>Superior</i> branch of CN III enters the <i>inferior surface</i> ⁷ p660. Motor nerve enters at the <i>junction of the posterior one third</i> and <i>anterior two thirds</i> of the muscle ⁴ p119.
Temporalis	<i>Deep temporal</i> nerves of V ₃ of CN V ¹ p50, ⁷ p538. The <i>anterior deep temporal</i> nerve is frequently a branch of the <i>buccal nerve</i> of V ₃ ⁸ p1237.
Temporoparietalis	<i>Posterior rami</i> of <i>temporal</i> branch of CN VII ⁴ p22.
Tongue	<i>Lingual</i> nerve of V3 of CN V (<i>anterior two thirds</i> of the tongue) ¹ p51. Corda tympani of CN VII (taste sensation, anterior two thirds of the tongue) ¹ p86. <i>Lingual</i> branches of CN IX (<i>to posterior one third</i> of the tongue (sensory and taste) ¹ p149. <i>Hypoglossal</i> nerve (CN XII) ¹ p183.
Trapezius	<i>External</i> branch of CN XI ¹ p173.
Zygomaticus major	<i>Zygomatic</i> and <i>buccal</i> branches of CN VII ³ p97, ⁷ p486. Zygomatic branches of CN VII ⁵ p103. Innervated from the <i>deep surface</i> ³ p97.
Zygomaticus minor	<i>Zygomatic</i> and <i>buccal</i> branches of CN VII ⁷ p486. Zygomatic branches of CN VII ⁵ p103. Buccal branches of CN VII ³ p97. Innervated from the <i>deep surface</i> ³ p97.

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Conclusions

The atlas of CN-related disorders is a new tool which provides disorder-localization relationships along with neuroanatomy exploration. It presents various CN pathology situations in

3D labeled with the resulting disorders and associated signs, symptoms and/or syndromes along with the surrounding neuroanatomy parcellated into about 2,300 components, including more than 600 CN-related components. The atlas is potentially useful to a wide variety of

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Figure 2 Facial muscles – CN spatial relationships. A) The extended facial nerve. B) The facial muscles along with all cranial nerves.

users ranging from medical students and residents to general practitioners, neuroradiologists and neurologists, as it contains both normal

brain anatomy and CN-related pathology correlated with neurological disorders presented in a visual and interactive way.

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Appendix

Neuroanatomy – CN pathology index, hierarchical with respect to anatomy and linear with respect to disorders (in italics).

- Olfactory nerve (CN I)
 - *Smell disturbances*
- Optic nerve (CN II)/Visual system
 - *Complete lesions of the optic nerve*
 - *Partial lesions of the optic nerve*
 - *Optic nerve ischemia*
 - *Junctional optic nerve-chiasm lesions*
 - *Centrally-located lesions of the optic chiasm*
 - *Laterally-located lesions of the optic chiasm*
 - *Optic tract lesions*
 - *Lateral geniculate body lesions*
 - *Anterior temporal lobe lesions of the optic radiation*
 - *Parietal or occipital lobe lesions of the optic radiation*
 - *Temporoparietal lobe lesions of the optic radiation*
 - *Lesions of the upper bank of the calcarine cortex*
 - *Lesions of the lower bank of the calcarine cortex*
 - *Lesions of the entire calcarine cortex*
- Oculomotor nerve (CN III)
 - *Oculomotor nerve palsy*
- Trochlear nerve (CN IV)
 - *Trochlear nerve palsy*
- Trigeminal nerve (CN V)
 - *Trigeminal neuralgia*
 - *Corneal reflex absence*
- Abducens nerve (CN VI)
 - *Abducens nerve palsy*
- Oculomotor and abducens nerves (CN III, VI)
 - *Supranuclear palsy of conjugate horizontal gaze*
 - *Nuclear palsy of conjugate horizontal gaze*
 - *Internuclear palsy of conjugate horizontal gaze*
- Facial nerve (CN VII)
 - *Lesions distal to the stylomastoid foramen*
 - *Lesions within the facial canal proximal to the chorda tympani*
 - *Lesions within the internal auditory meatus*
 - *Hemifacial spasm*
- Vestibulocochlear nerve (CN VIII)
 - *Lesion of CN VIII*
- Glossopharyngeal nerve (CN IX)
 - *Lesion of CN IX*
 - *Glossopharyngeal neuralgia*
- Vagus nerve (CN X)
 - *Unilateral lesions of the nucleus ambiguus*
- Accessory nerve (CN XI)
 - *Accessory nerve palsy*
- Hypoglossal nerve (CN XII)
 - *Hypoglossal nerve palsy*
- Multiple cranial nerve deficits
 - *Foster Kennedy syndrome (CN I, II)*
 - *Cavernous sinus syndrome (CN III, IV, VI, V2, VII)*
 - *Cerebellopontine angle syndrome (CN V, VII, VIII)*