Deformable Anatomic Templates Embed Knowledge Into Patient's Brain Images: Part 1. Construction and Display

L. Anne Hayman, MD, Vinodh A. Kumar, MD,† Jackson Hamilton, MD,† Sujit S. Prabhu, MD,‡ Michel Thiebaut de Schotten, PhD,§|| Nagham Al-Zubidi, MD,¶ John Pagani,* Mark Vabulas, BS,* Megan Groneman, BS,* and Ashok J. Kumar, MD†*

Objective: This paper describes the methods used to create annotated deformable anatomic templates (DATs) and display them in a patient's axial 2-dimensional and reformatted volume brain images.
Methods: A senior neuroradiologist annotated and manually segmented 1185 color-coded structures on axial magnetic resonance images of a normal template brain using domain knowledge from multiple medical specialties. Besides the visible structures, detailed pathways for vision, speech, cognition, and movement were charted. This was done by systematically joining visible anatomic anchor points and selecting the best fit based on comparisons with cadaver dissections and the constraints defined on the companion 2-dimensional images.
Results: The DAT is commercially available for use on a picture archiving and communication system or as a standalone workstation.
Conclusions: The DAT can quickly embed extensive, clinically useful functional neuroanatomic knowledge into the patient's brain images. Besides labeling visible structures, DAT displays clinically important, previously uncharted subdivisions of the fiber tracts.

Key Words: deformable anatomic templates (DATs), electronic brain atlas, scan interpretation, validation

(*J Comput Assist Tomogr* 2012;36: 354–359)

Deformable anatomic templates (DATs) have been developed for the brain, head and neck, chest, abdomen, and pelvis. The motivation for the DAT project is to quickly enhance and extend the clinician's personal fund of knowledge. This publication introduces the DAT approach by describing construction of the brain module. The labeling of visible structures in the DAT was straightforward and not controversial, but the DAT contains additional structures which are unique. To enter these structures, the anatomically accurate brain template was used as a framework for a knowledge-based strategy, which establishes reliable anatomic anchor points and systematically manipulates the locations of the intervening connections until they form a pattern in the volume reconstruction. This pattern can be validated by comparison with dissected specimens and superimposition on clinical cases.

From the *Anatom-e Information Systems, Ltd; Departments of †Diagnostic Radiology and ‡Neurosurgery, The University of Texas MD Anderson Cancer Center, Houston, TX; §Natbrainlab, Department of Forensic and Neurodevelopmental Sciences, Institute of Psychiatry, King's College London, London, United Kingdom; ||INSERM-UPMC UMRS 975, G.H. Pitié-Salpêtrière, Paris, France; and ¶Department of Ophthalmology, The Methodist Hospital, Houston, TX.
Received for publication October 25, 2011; accepted November 1, 2011.
Reprints: L. Anne Hayman, MD, Anatom-e Information Systems, Ltd, 2047 University Blvd, Houston, TX 77030 (e-mail: Anne@Anatom-e.com); Vinodh A. Kumar, MD, Department of Diagnostic Radiology, Unit 1482, The University of Texas MD Anderson Cancer Center, 1515 Holcombe Blvd, Houston, TX 77030 (e-mail: vakumarmd@yahoo.com).
The authors report no conflicts of interest.

This report is accompanied by another paper that focuses on confirming the DAT's location of the origin of the corticospinal tract using functional magnetic resonance imaging of the hand. Additional validation papers on the visual system and the language areas are in preparation. The utility of DAT overlays in brains with pathology will be addressed in papers that report surgical results.

MATERIALS AND METHODS

Axial MR Image Acquisition and Resolution

The framework of the DAT was constructed from magnetic resonance (MR) images of a 57-year-old healthy right-handed white woman. The following parameters were used: a T2 fast-relaxation fast-spin echo sequence (TR = 5600 milliseconds, TE = 100 milliseconds) of 1 number of excitations, matrix of 384×224, field of view of 25 cm, and echo train length of 8. The images were obtained on a 1.5-T Signa GE scanner at 2.5 mm thickness with 1.5-mm gaps in the axial plane using the acanthiomeatal reference line.[1] In the authors' experience, this virtual plane through the nasal spine (the acanthion) and the external auditory meati is the most comfortable neutral head position and reproduces the axial plane used in most clinical diagnostic MR imaging. The reader should note that this distinguishes the DAT from other atlases that use one of the following: (1) the bicommissural line between the anterior and posterior commissures, which parallels the canthomeatal plane between the angle of the eyelids (the canthus) and the external auditory canal or (2) Reid base line, which is defined by joining the external auditory meatus and the lower border of the orbit. The resolution of the axial MR images matched that seen in myelin stained brain specimens. Unlike formalin-fixed brain specimens, the white-gray matter relationships were not distorted by uneven shrinkage artifacts.

Alignment

The methodology for embedding the DAT onto axial images containing pathology is straightforward and requires 5 to 10 minutes of a technician's time to process any axial examination. If the axial images have been obtained in the acanthomeatal line, minor reslicing of the patient data is needed. The DAT is manually deformed to fit the patient's brain using an affine (linear) transformation. This manipulation alters the DAT to compensate for the patient's head rotation, head tilt, and variations in chin position. It also resizes the DAT to fit the vertical and horizontal dimensions of the patient's brain. The surface of the cerebral hemisphere is used to size the DAT. The ventricles are not used as a landmark because of wide individual variation.

The landmark for checking the alignment of the DAT in the patient's cerebral hemisphere is the central sulcus. This sulcus was chosen because it is the most constant landmark on the hemispheric convexity. In 92% of individuals, it descends without interruption from posterior to anterior with a 7-degree forward slant. It has a depth of 1.7 cm and it is devoid of real side branches. However, shallow anastomotic furrows are present on the precentral and postcentral gyri. This sulcus is recognized by its distinctive adjacent interlocking vertical gyri, which have 2 sharp curves (the superior genu and the inferior genu).[2]

Strategies for Segmentation

The 55 axial brain images were segmented into a framework which registered any brain structure defined on the 2-dimensional (2D) volume-rendered images. The volume DAT image could be sectioned as often as needed to confirm a structure's location. These virtual dissections could be done in the standard axial, coronal, or parasagittal planes or by a confocal technique, which removed successively deeper curvilinear planes and provided superior views of surface gyri.

A senior neuroradiologist (LAH) with anatomic expertise and more than 30 years of clinical experience manually segmented 1185 color-coded structures on 55 axial T2-weighted 1.5-T MR images of a template brain using domain knowledge. All structures defined on 2D axial images could be reviewed on volume-rendered images to check the accuracy of placement.

Strategies for Segmenting *Visible* Structures

Labeling of the ventricles, deep gray matter, and surface gyral/sulcal patterns was performed on 2D templates and translated into volume images. Gyral and sulcal patterns were constructed (by LAH) using the traditional method of matching the displayed surface anatomy of the gyri and sulci with authoritative anatomic texts.[3–32] Variations in sulcal patterns and depths were annotated in the textual information that was attached to each named item in the DAT.

Strategies for Segmenting *Controversial* Structures

Some important structures are variably defined in the literature. An example is the occipital lobe. In general, it is the pyramid-shaped medial part of the posterior part of the cerebral hemisphere, but there are no reliable anatomic boundaries. Anatomists commonly define the occipital lobe as that part of the hemisphere that lies dorsal to an arbitrary line drawn from the parietooccipital fissure (above) to the preoccipital notch (below). This convention creates confusion because it places the anterior part of the so-called lateral occipital gyri in the temporal lobe, and because the preoccipital notch is not a radiographic landmark. The DAT defines the boundary of the occipital lobe to include all of the lateral occipital gyri but provides text explaining the alternate boundary. Although this may seem to be a minor point, it becomes important in describing the functional contents of the occipital lobe.

Strategies for Segmenting Structures Not Visible on Clinical Imaging

Structures that are not visible on clinical MR were extrapolated within the confines of the anatomically correct framework. Each pathway was reconstructed using its anatomic anchor points and systematically varying the connections. The best fit was judged by comparing the volume representation of the pathway with authoritative anatomic dissections and diffusion tensor imaging (DTI) and by checking the reasonableness of the fit on the 2D images. Pathway placement also took into account well-described relationships with adjacent visible structures. Patterns were validated by comparison with dissected specimens and superimposition on DTI atlases.[33–35] Clinical cases drawn from carefully studied patients recruited from neurosurgical and neurological colleagues were also used. Further fine tuning was provided by the use of intraoperative DTI tract generation and intraoperative stimulation.

An example of the complex pathway of the visual radiations is shown in Figure 1. This pathway was reconstructed by using 12 retinal locations for each eye (two 0- to 10-degree macular fibers for the superior and inferior retina, four 10- to 30-degree and four 30- to 60-degree fibers for the 4 peripheral retinal quadrants, and two 60- to 90-degree fibers for the nasal side of

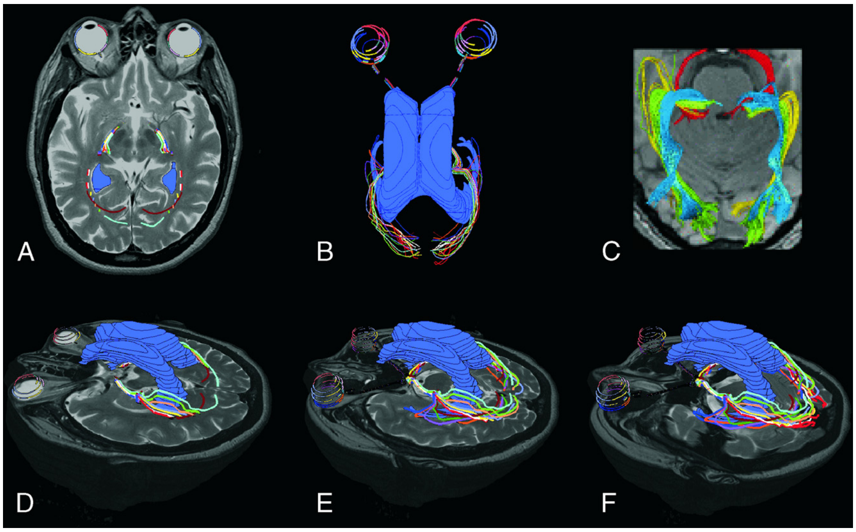

FIGURE 1. Construction of the visual pathways. A, Sample color-coded DAT source image shows parts of many of the 24 divisions of the retinal fibers, which were painstakingly hand-segmented into the 2D template to create the visual pathway which matched anatomic dissections.[116] B, Reconstruction of the visual pathway viewed from above with the lateral ventricular system (blue) included for orientation. C, In vivo 3T DTI of Meyer loop (yellow), the central bundle (green), and the dorsal bundle (blue) (used with permission from Hofer et al[117]). D–F, Serial oblique axial views of volume-rendered DAT show the color-coded reconstruction of the manually segmented data shows the superior visual radiations (dorsal bundle) wrapping around the atrium of the lateral ventricle in all 3 images. E, The fibers of the inferior visual radiations (Meyer loop), which cover the temporal horn, have been added to the volume display. F, The lowest axial section shows the termination of the central bundle (macular fibers in red) in the occipital pole.

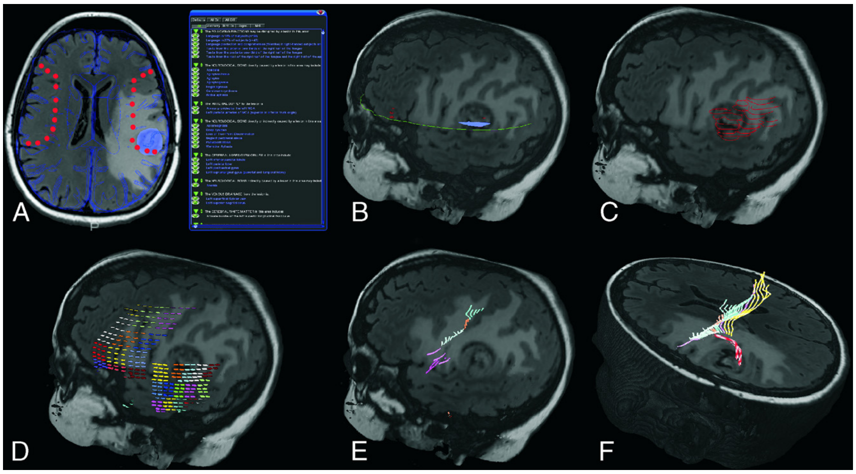

FIGURE 2. Screen captures of Anatom-e software taken during analysis of a glial tumor in the supramarginal gyrus. A, The patient's axial scan has been aligned with the DAT (blue outlines). A region of interest has been manually segmented around the tumor, which is shown in solid blue. This has activated a list of structures, each of which is extensively annotated. At this step in the process, the arcuate tract has been selected and its location is shown in red on the patient's axial image. Its position in the upper posterior quadrant of the tumor was validated at surgery. Additional information was provided to guide the surgeon: (B and C) show the relationship of the tumor to the overlying supramarginal gyrus; (D) shows a probability map of the likelihood of encountering essential language cortex (modified with permission from Ojemann et al[38]); (E) shows the relationship of the tumor to the multicolored corticospinal and corticobulbar tracts; and (F) shows the relationship of the motor tracts and the arcuate to the tumor in an oblique axial view.

the peripheral retinal quadrants). Each of the 24 locations was color-coded and traced from the retina to the appropriate part of the calcarine cortex. The anatomic results were compared to published DTI visual tracts.[36,37]

Strategies for Segmenting *Variable* Structures

Part of the problem of individual variations was resolved by embedding the DAT with probability maps. Figure 2D shows the sites of essential language functions in the left dominant hemisphere, determined by intraoperative cortical stimulation of awake patients.[38] A similar map is provided for patients in whom language is located in the right hemisphere.[39] To account for variations in vascular distributions, the vessel territory and not an arteriogram was used. For example, the area occupied by a cortical artery on 100 arteriograms was plotted to show the range of normal positions.[40] Variations in the arterial origins and anastomoses were included in the text provided for each artery. Variations in the venous sinus drainage were illustrated by showing the *maximum* territory for each sinus as the sum of its independent small regional veins. Overlap between the maximum sinus territories indicates the location of regional vein(s) that can drain to 1 or more sinuses. For example, the superficial sylvian vein drains to any 1 of 4 sinuses (basal vein to the straight sinus, paracavernous vein to the pterygoid sinus, directly to the sphenoparietal sinus, or directly to the sphenopetrosal sinus). Moreover, the territory of the superficial sylvian vein can be replaced by either of 2 veins (the vein of Trolard to the superior sagittal sinus or the vein of Labbé to the lateral sinus). In the DAT, the superior sylvian territory is part of the maximum venous territory of each of the 6 sinuses to which it can drain. When more than one of these sinus territories are selected, the overlap is an intuitive visual display of the variable connections of the superficial sylvian vein.[41]

Strategies Employed for Labeling

Textual information for each of the 1185 color-coded structures was developed by the senior neuroradiologist (LAH). The information crossed domains. The anatomic literature primarily supplied synonyms, functions, variations, and connections[3–32]; whereas the radiographic literature provided imaging landmarks, differential diagnosis, arterial supply, and venous drainage.[42–76] Information on clinical syndromes caused by damage to a structure was drawn from the anatomy, neurology, and ophthalmology literature.[77–117] The pathology literature provided a framework for organizing the brain into vulnerable areas. Examples include the site-specific watershed zones or site-specific areas vulnerable to toxins such as alcohol, carbon monoxide, or Wilson disease.[112,113] The size of each structure was recorded, when it was available. Individual variations were also noted in the text. A list of related items accompanies each structure entry, which allows the user to quickly access information related to the descriptive text.

Strategies for Data Retrieval

Any item in the program can be located by a word search, which produces 4 features. The first is textual information. The second is an option to highlight the structure on every section in the 2D and volume data sets. The third option is to highlight all the related items that have been linked to the term. For example, the occipital lobe would not only highlight the lobe but also show all of the gyri within it and describe alternative definitions. The fourth option is to transport the structure name to PubMed and call forth a literature search of the term.

In addition to a standard word search, the knowledge embedded in the DAT can be retrieved by defining a region of interest on the 2D axial section; all of the structures in and around this area are presented in 1 of 2 lists, anatomic or clinical (Fig. 2A). The terms in the list have all of the options described in the preceding section on labeling.

RESULTS

Two versions of the DAT are commercially available (Anatom-e, 2047 University Blvd, Houston, TX 77030) for clinical, surgical, educational, and research projects. The first version is a knowledge-assisted reporting (KAR) software application, which instantly provides the annotated location of all structures within a region of interest. It is designed for use in tandem with a picture archiving and communication system (PACS) imaging workstation. The second version is a standalone workstation, which embeds the DAT into the patient's volume-rendered brain images. The process of data display and retrieval for each system is described separately.

DAT Display and Retrieval for the PACS Workstation

The simplest version of DAT is the KAR software application, which mounts the DAT on the PACS toolbar. In this application, the templates are not deformed or embedded in the patient images. The templates serve as a resource which the user can quickly scroll through, find the axial sections that contain the area of interest, and circle them. The program instantly provides the outline of all structures within and around the region of interest. This list can be tailored to items of interest and exported to the radiology report. The location of any one of the listed structures can be highlighted in all of the relevant sections. In addition, encyclopedic text concerning the function, clinical deficits, anatomic location, blood supply, venous drainage, and proximal and distal connections of each structure is provided.

DAT Display and Retrieval for the Standalone Workstation

The second version of DAT is a workstation-based program which aligns and volume-renders the patient scans before embedding the annotated structures within them. An information panel allows the user to select relevant structures for display within the patient images. The KAR feature (described previously) is available in this program.

DISCUSSION

A recent review article focused on the limitations of brain atlases.[114] Major objections include issues of individual variations and brain plasticity. It is worth noting that, for practical clinical purposes, these are not problems. Studies using intraoperative stimulation have shown that the major clinically significant areas do not have individual variations or brain plasticity. These important and consistent structures *cannot be surgically resected without producing a permanent neurological deficit*. Together they form the "minimum common brain," which consists of 4 tracts (visual, corticospinal, arcuate, and inferior fronto-occipital) and 11 cortical areas (both calcarine gyri, both precentral and postcentral gyri, the left superior temporal gyrus, both angular gyri, and both supramarginal gyri).[115]

Another limitation of brain atlases is their inability to reproduce the distortions introduced by a mass. Currently, the DAT does not have the ability to focally warp to match the structural deformities created by masses. In cases with significant mass effect, however, DAT provides labeled normal structures on the opposite side, which can be extrapolated to the distorted areas. In other cases, the high-resolution, multiplanar volume-rendered image capability displays the distorted structures to better advantage than traditional sectional images.

In summary, the brain DAT resource was constructed using domain knowledge across anatomic, radiologic, and clinical specialties. The position of structures not visible on clinical imaging was inferred by connecting known anatomic landmarks and fitting the tract on 2D and volume-rendered images. The DAT is designed to quickly extend the clinician's personal fund of knowledge by embedding manually segmented, annotated functional anatomic knowledge templates into volume-rendered images of the patient's brain.

REFERENCES

1. Desasi S, Teh BS, Hinojosa J, et al. Standardization of head and neck contouring using the acanthiomeatal line. *Med Dosim*. 2009;34:225–227.
2. Ono M, Kubik S, Abernathy CD. *Atlas of Cerebral Sulci*. Stuttgart, Germany: Thieme Medical Publishers; 1990:218.
3. Schaltenbrand G, Wahren W. *Atlas for Stereotaxy of the Human Brain With Guide to the Atlas for Stereotaxy of the Human Brain*. Stuttgart, Germany: Thieme Medical Publishers; 2005.
4. Nowinski WL, Chua BC, Marchenko Y, et al. Three-dimensional reference and stereotactic atlas of human cerebrovasculature from 7 Tesla. *Neuroimage*. 2011;55:986–998.
5. Talairach J, Tornoux P. *Co-Planar Stereotaxic Atlas of the Human Brain: 3-Dimensional Proportional System: An Approach to Cerebral Imaging*. Stuttgart, Germany: Thieme Medical Publishers; 1988.
6. Afifi AK, Bergman AR. *Functional Neuroanatomy: Text and Atlas*. New York, NY: McGraw-Hill; 1998.
7. Bayer SA, Altman J. *Atlas of Human Central Nervous System Development*. Vol 2. Boca Raton, Fla: CRC Press; 2002.
8. Bayer SA, Altman J. *The Human Brain During the Late First Trimester*. Boca Raton, Fla: CRC Press/Taylor & Francis; 2006.
9. Brash JC, ed. *Cunningham's Manual of Practical Anatomy*. Vol 3. 12th ed. London, England: Oxford University Press; 1958.
10. Clemente CD. *Anatomy: A Regional Atlas of the Human Body*. Baltimore, Md: Williams & Wilkins; 1997.
11. Duvernoy HM. *The Human Brain: Surface, Blood Supply, and Three-Dimensional Sectional Anatomy*. 2nd ed. Wien, Austria: Springer-Verlag; 1999.
12. Fix JD, Brueckner JK. *High-Yield Neuroanatomy*. Philadelphia, Pa: Wolters Kluwer Health/Lippincott Williams & Wilkins; 2009.
13. Gould DJ, Brueckner JK. *Sidman's Neuroanatomy: A Programmed Learning Tool*. 2nd ed. Philadelphia, Pa: Lippincott Williams & Wilkins; 2008.
14. Gray H. *Gray's Anatomy*. Clemente CD, ed. 13th ed. Philadelphia, Pa: Lea & Febiger; 1985.
15. Haines DE. *Neuroanatomy: An Atlas of Structures, Sections, and Systems*. 7th ed. Philadelphia, Pa: Lippincott Williams & Wilkins; 2008.
16. Heimer L, Záborszky L, Wouterlood FG, et al. *Neuroanatomical Tract-Tracing 3: Molecules, Neurons, and Systems*. New York, NY: Springer-Verlag; 2006.
17. Heimer L. *The Human Brain and Spinal Cord: Functional Neuroanatomy and Dissection Guide*. New York, NY: Springer-Verlag; 1995.
18. Hendelman W. *Atlas of Functional Neuroanatomy*. 2nd ed. Boca Raton, Fla: CRC Press/Taylor & Francis; 2006.
19. House EL, Pansky B. *A Functional Approach to Neuroanatomy*. 2nd ed. New York, NY: McGraw-Hill; 1967.
20. Jaänig W. *The Integrative Action of the Autonomic Nervous System: Neurobiology of Homeostasis*. Cambridge, England: Cambridge University Press; 2008.
21. Lockhart RD, Fyfe FW, Hamilton GF. *Anatomy of the Human Body*. London, England: Faber and Faber; 1959.
22. Krieg W. *Functional Neuroanatomy*. 2nd ed. New York, NY: Blakiston; 1953.

23. Krieg W. *Synoptic Functional Neuroanatomy*. Evanston, Ill: Brain Books; 1973.
24. Mai JK, Voss T, Paxinos G. *Atlas of the Human Brain*. Amsterdam, the Netherlands: Elsevier/Academic; 2008.
25. Matzke HA, Foltz FM. *Synopsis of Neuroanatomy*. New York, NY: Oxford University Press; 1972.
26. McMinn RMH, Hutchings RT, Logan BM. *The Concise Handbook of Human Anatomy*. Stamford, Conn: Appleton & Lange; 1998.
27. Miller RA, Burack E. *Atlas of the Central Nervous System in Man*. 3rd ed. Baltimore, Md: Williams & Wilkins; 1982.
28. Möller TB, Reif E. *Pocket Atlas of Sectional Anatomy: Computed Tomography and Magnetic Resonance Imaging*. Vol 2. Stuttgart, Germany: Thieme Medical Publishers; 2001.
29. Möller TB. *Pocket Atlas of Sectional Anatomy*. Vol 1. Stuttgart, Germany: Thieme Medical Publishers; 2007.
30. Moore KL, Dalley AF. *Clinically Oriented Anatomy*. Philadelphia, Pa: Lippincott Williams & Wilkins; 1999.
31. Nieuwenhuys R, Voogd J, Van Huijzen C. *The Human Central Nervous System: A Synopsis and Atlas*. 2nd ed. Berlin, Germany: Springer-Verlag; 1981.
32. Nowiński WL, Bryan RN, Raghavan R, et al. *The Electronic Clinical Brain Atlas: Multiplanar Navigation of the Human Brain*. New York, NY: Thieme Medical Publishers; 1999.
33. Nowinski WL, Chua BC, Yang GL, et al. Three-dimensional interactive and stereotactic human brain atlas of white matter tracts. *Neuroinformatics*. 2012;10:33–55.
34. Thiebaut de Schotten M, Ffytche DH, Bizzi A, et al. Atlasing location, asymmetry and inter-subject variability of white matter tracts in the human brain with MR diffusion tractography. *Neuroimage*. 2011;54:49–59.
35. Peng H, Orlichenko A, Dawe RJ, et al. Development of a human brain diffusion tensor template. *Neuroimage*. 2009;46:967–980.
36. Wu W, Rigolo L, O'Donnell LJ, et al. Visual pathway study using in vivo DTI tractography to complement classical anatomy. *Neurosurgery*. 2012;70(1 suppl operative):145–156; discussion 156.
37. Yamamoto A, Miki Y, Urayama S, et al. Diffusion tensor fiber tractography of the optic radiation: analysis with 6-, 12-, 40-, and 81-directional motion-probing gradients, a preliminary study. *AJNR Am J Neuroradiol*. 2007;28:92–96.
38. Ojemann J, Lettich E, Berger M. Cortical language localization in left, dominant hemisphere. An electrical stimulation mapping investigation in 117 patients. *J Neurosurg*. 1989;71:316–326.
39. Chang EF, Wang DD, Perry DW, et al. Homotopic organization of essential language sites in right and bilateral cerebral hemispheric dominance. *J Neurosurg*. 2011;114:893–902.
40. Michotey P, Moscow NP, Salmon G. Section II. Anatomy of the cortical branches of the middle cerebral artery. In: Newton TH, Potts DG, eds. *Radiology of the Skull and Brain*. Vol 2, book 2. St Louis, Mo: The CV Mosby Company; 1974:1471–1476.
41. Taber KH, Hayman LA, Muszynski CA. A guide to the venous drainage of the anterior Sylvian fissure. *J Comput Assist Tomogr*. 2000;24:343–346.
42. Barkovich AJ. *Pediatric Neuroimaging*. 3rd ed. Philadelphia, Pa: Lippincott Williams & Wilkins; 2000.
43. Damasio H. *Human Brain Anatomy in Computerized Images*. 2nd ed. New York, NY: Oxford University Press; 2005.
44. Eisenberg RL. *Clinical Imaging: An Atlas of Differential Diagnosis*. 3rd ed. Philadelphia, Pa: Lippincott-Raven; 1997.
45. El-Khoury GY, Bergman RA, Montgomery WJ, et al. *Sectional Anatomy by MRI*. New York, NY: Churchill Livingstone; 1995.
46. Fleckenstein P, Tranum-Jensen J. *Anatomy in Diagnostic Imaging*. Philadelphia, Pa: WB Saunders; 2001.
47. Gentry, LR, ed. *Normal Anatomy of the Head, Brain, and Neck*. Vol 8. Philadelphia, Pa: WB Saunders; 1998. Neuroimaging Clinics of North America.
48. Grossman RI, Yousem DM. *Neuroradiology: The Requisites*. 2nd ed. Philadelphia, Pa: Mosby; 2003.
49. Hayman LA, Hinck VC. *Clinical Brain Imaging: Normal Structure and Functional Anatomy*. St Louis, Mo: Mosby-Year Book; 1992.
50. Jinkins JR, Da Costa Leite C. *Neurodiagnostic Imaging: Pattern Analysis and Differential Diagnosis*. Philadelphia, Pa: Lippincott-Raven; 1998.
51. Keats TE, Sistrom C. *Atlas of Radiologic Measurement*. 7th ed. St Louis, Mo: Mosby; 2001.
52. Krayenbühl HA, Yaşargil MG. *Cerebral Angiography*. Stuttgart, Germany: Thieme Medical Publishers; 1968.
53. Kretschmann H-J, Weinrich W. *Cranial Neuroimaging and Clinical Neuroanatomy: Atlas of MR Imaging and Computed Tomography*. 3rd ed. Stuttgart, Germany: Thieme Medical Publishers; 2004.
54. Latchaw RE. *MR and CT Imaging of the Head, Neck, and Spine*. St Louis, Mo: Mosby-Year Book; 1991.
55. Latchaw RE, Kucharczyk J, Moseley ME. *Imaging of the Nervous System: Diagnostic and Therapeutic Applications*. Vol 1. Philadelphia, Pa: Elsevier-Mosby; 2005.
56. Latchaw RE, Kucharczyk J, Moseley ME. *Imaging of the Nervous System: Diagnostic and Therapeutic Applications*. Vol 2. Philadelphia, Pa: Elsevier-Mosby; 2005.
57. Leblanc Á. *Encephalo-Peripheral Nervous System: Vascularisation, Anatomy, Imaging*. Berlin, Germany: Springer-Verlag; 2004.
58. Matsui T, Hirano A. *An Atlas of the Human Brain for Computerized Tomography*. Tokyo, Japan: Igaku-Shoin; 1978.
59. Mukherji SK, Castelijns JA. *Modern Head and Neck Imaging*. Berlin, Germany: Springer-Verlag; 1999.
60. Naidich TP, Duvernoy HM. *Duvernoy's Atlas of the Human Brain Stem and Cerebellum: High-Field MRI: Surface Anatomy, Internal Structure, Vascularization and 3D Sectional Anatomy*. Wien, Austria: Springer-Verlag; 2009.
61. Newton TH, Potts DG. *Radiology of the Skull and Brain*. Vol 2, book 2. St Louis, Mo: Mosby; 1971.
62. Newton TH, Potts DG. *Radiology of the Skull and Brain*. Vol 2, book 3. St Louis, Mo: Mosby; 1971.
63. Newton TH, Potts DG. *Radiology of the Skull and Brain*. Vol 2, book 4. St Louis, Mo: Mosby; 1971.
64. Newton TH, Potts DG. *Radiology of the Skull and Brain*. Vol 4. St Louis, Mo: Mosby; 1971.
65. Orrison WW. *Functional Brain Imaging*. St Louis, Mo: Mosby; 1995.
66. Osborn AG. *Diagnostic Imaging: Brain*. Salt Lake City, Utah: Amirsys; 2010.
67. Osborn AG, Ross JS, Salzman KL. *Expert dx: Brain and Spine*. Salt Lake City, Utah: Amirsys; 2009.
68. Peterson RR. *A Cross-Sectional Approach to Anatomy*. Chicago, Ill: Year Book Medical; 1980.
69. Reeder MM. *Reeder and Felson's Gamuts in Radiology*. 4th ed. New York, NY: Springer-Verlag; 2003.
70. Ryan SP. *Anatomy for Diagnostic Imaging*. London, England: WB Saunders; 1994.
71. Stephens RB, Stilwell DL. *Arteries and Veins of the Human Brain*. Springfield, Ill: Charles C Thomas Publisher; 1969.
72. Wackenhiem A, Braun JP. *Angiography of the Mesencephalon*. New York, NY: Springer-Verlag; 1970.
73. Wicke L. *Atlas of Radiologic Anatomy*. Philadelphia, Pa: Lea & Febiger; 1994.

74. Wicke L, Firbas W, Schmiedl R, et al. *Atlas of Radiologic Anatomy.* Philadelphia, Pa: Lea & Febiger; 1994.
75. Wood EH, Taveras JM, Tenner MS. *The Brain and the Eye*. Chicago, Ill: Year Book Medical; 1975.
76. van der Zwan A. *The Variabilities of the Major Vascular Territories of the Human Brain*. Utrecht, the Netherlands: University of Utrecht; 1991.
77. Alpers BJ. *Clinical Neurology.* 2nd ed. Philadelphia, Pa: FA Davis; 1949.
78. Blumenfeld H. *Neuroanatomy Through Clinical Cases*. Sunderland, Mass: Sinauer; 2002.
79. Bradley WG. *Neurology in Clinical Practice*. Vol 1. 5th ed. Philadelphia, Pa: Butterworth-Heinemann/Elsevier; 2008.
80. Bradley WG. *Neurology in Clinical Practice*. Vol 2. 5th ed. Philadelphia, Pa: Butterworth-Heinemann/Elsevier; 2008.
81. Brazis PW, Masdeu JC, Biller J. *Localization in Clinical Neurology.* Philadelphia, Pa: Lippincott Williams & Wilkins; 2007.
82. Brodal A. *Neurological Anatomy in Relation to Clinical Medicine*. New York, NY: Oxford University Press; 1981.
83. Conn PM. *Neuroscience in Medicine*. Philadelphia, Pa: Lippincott; 1995.
84. Flaherty A, Rost NS. *The Massachusetts General Hospital Handbook of Neurology.* Philadelphia, Pa: Wolters Kluwer Health/Lippincott Williams & Wilkins; 2007.
85. Gilroy J, Meyer JS. *Medical Neurology.* New York, NY: Macmillan; 1979.
86. Larner AJ. *A Dictionary of Neurological Signs*. New York, NY: Springer-Verlag; 2006.
87. Luhan JA. *Neurology: A Concise Clinical Textbook*. Baltimore, Md: Williams & Wilkins; 1968.
88. Ropper AH, Samuels MA. *Adams and Victor's Principles of Neurology.* 9th ed. New York, NY: McGraw-Hill; 2009.
89. Robertson D. *Primer on the Autonomic Nervous System*. Amsterdam, the Netherlands: Elsevier Academic; 2004.
90. O'Rahilly R, Müller F. *The Embryonic Human Brain: An Atlas of Developmental Stages*. New York, NY: Wiley-Liss; 1994.
91. Pauchet V, Dupret S. *Pocket Atlas of Anatomy.* 3rd ed. London, England: Oxford University Press; 1951.
92. Pernkopf E. *Atlas of Topographical and Applied Human Anatomy.* Vol 1. Philadelphia, Pa: WB Saunders; 1963.
93. Robinson A. *Cunningham's Textbook of Anatomy.* 6th ed. New York, NY: Oxford University Press; 1931.
94. Robinson A, ed. *Cunningham's Manual of Practical Anatomy.* Vol 3. 8th ed. New York, NY: William Wood; 1930.
95. Rohen JW, Yokochi C, Lütjen-Drecoll E. *Color Atlas of Anatomy: A Photographic Study of the Human Body.* Baltimore, Md: Lippincott Williams & Wilkins; 2001.
96. Schlossberg L, Zuidema GD. *The Johns Hopkins Atlas of Human Functional Anatomy.* Baltimore, Md: The Johns Hopkins University Press; 1997.
97. Schmahmann JD, Pandya DN. *Fiber Pathways of the Brain*. New York, NY: Oxford University Press; 2006.
98. Shinnick-Gallagher P. *The Amygdala in Brain Function: Basic and Clinical Approaches*. New York, NY: New York Academy of Sciences; 2003.
99. Sidman RL, Sidman M. *Neuroanatomy.* Vol 1. Boston, Mass: Little Brown & Co Inc; 1965.
100. Sinnatamby CS, Last RJ. *Last's Anatomy: Regional and Applied*. Edinburgh, Scotland: Churchill Livingstone; 1999.
101. Sobotta J. *Sobotta Atlas of Human Anatomy.* Putz R, Pabst R, eds. Taylor AN, trans. Baltimore, Md: Williams & Wilkins; 1997.
102. Spitzer VM, Whitlock DG. *Atlas of the Visible Human Male: Reverse Engineering of the Human Body.* Sudbury, Mass: Jones and Bartlett; 1998.
103. Sporns O. *Networks of the Brain*. Cambridge, Mass: MIT Press; 2011.
104. Standring S, Berkovitz BKB, Ellis H, et al. *Gray's Anatomy: The Anatomical Basis of Clinical Practice*. 39th ed. Edinburgh, Scotland: Elsevier Churchill Livingstone; 2005.
105. Truex RC, Carpenter MB. *Strong and Elwyn's Human Neuroanatomy.* 5th ed. Baltimore, Md: Williams & Wilkins; 1964.
106. Waxman SG. *Clinical Neuroanatomy.* New York, NY: McGraw-Hill; 2010.
107. Willard FH, Perl DP. *Medical Neuroanatomy: A Problem-Oriented Manual With Annotated Atlas*. Philadelphia, Pa: Lippincott; 1993.
108. Kanski JJ. *Clinical Ophthalmology: A Systematic Approach*. Edinburgh, Scotland: Butterworth-Heinemann/Elsevier; 2007.
109. Dorland WAN. *Dorland's Illustrated Medical Dictionary.* Philadelphia, Pa: WB Saunders; 1994.
110. Netter FH. *Atlas of Human Anatomy.* 4th ed. Philadelphia, Pa: Saunders/Elsevier; 2006.
111. Netter FH. *The CIBA Collection of Medical Illustrations*. Summit, NJ: CIBA-Geigy Corp; 1972.
112. Greenfield JG, Graham DI, Lantos PL. *Greenfield's Neuropathology.* 7th ed. London, England: Arnold; 2002.
113. Towbin A. *Brain Damage in the Newborn and Its Neurologic Sequels: Pathologic and Clinical Correlation*. Danvers, Mass: PRM; 1998.
114. Pouratian N, Bookheimer SY. The reliability of neuroanatomy as a predictor of eloquence: a review. *Neurosurg Focus*. 2010;28:E3.
115. Duffau H, Peggy Gatignol ST, Mandonnet E, et al. Intraoperative subcortical stimulation mapping of language pathways in a consecutive series of 115 patients with grade II glioma in the left dominant hemisphere. *J Neurosurg*. 2008;109:461–471.
116. Gluhbegovic N, Williams TH. *The Human Brain: A Photographic Guide*. Hagerstown, Md: Harper & Row; 1980:14.
117. Hofer S, Karaus A, Frahm J. Reconstruction and dissection of the entire human visual pathway using diffusion tensor MRI. *Front Neuroanat*. 2010;4:1–7.

