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NEWS ITEM

3D Atlas of the Brain, Head and Neck in 2953 pieces

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Introduction

Brain atlasing is a vital field of research and development in neuroinformatics. Numerous brain atlases have been constructed in health and disease having a wide spectrum of use ranging from education to research to clinical applications. Some reviews of brain atlases are presented elsewhere.[1]

Our contribution to the field has been in brain atlas building and developing atlas-based applications. This work along with the taxonomy of the created atlases has been summarized in.[2] Our efforts have resulted in 35 commercial brain atlases (along with numerous research prototypes), licensed to 67 companies and institutions, and made available to medical societies, organizations, medical schools and individuals in about 100 countries. These atlases have been employed in education, research and clinical applications. Hundreds of thousands of patients have been treated by using our atlases available in surgical workstations.

The design of our atlases is top-down, holistic, and has been guided by research, clinical and market perspectives. After the development of several commercial 2D[3] and 3D[4]

[1] Selected brain atlas reviews:
Dickie, D. A., Shenkin, S. D., Anblagan, D., Lee, J., Blesa Cabez, M., Rodriguez, D., Boardman, J. P., Waldman, A., Job, D. E., Wardlaw, J. M. (2017, Jan 19). Whole Brain Magnetic Resonance Image Atlases: A Systematic Review of Existing Atlases and Caveats for Use in Population Imaging. *Front Neuroinform, 11,* 1. doi: 10.3389/fninf.2017.00001. eCollection2017.
Nowinski, W. L., Fang, A., Nguyen, B. T., Raphel, J. K., Jagannathan, L., Raghavan, R., Bryan, R. N., Miller, G. (1997). Multiple brain atlas database and atlas-based neuroimaging system. *Computer Aided Surgery, 2*(1), 42–66.
Nowinski, W. L. (2009). *Anatomical and probabilistic functional atlases in stereotactic and functional neurosurgery.* In A. Lozano, P. Gildenberg, R. Tasker (Eds.), *Textbook of Stereotactic and Functional Neurosurgery* (pp. 395–441). Springer.
Thompson, P. M., Mega, M. S., Toga, A. W. (2002). Subpopulation brain atlases. In A. W. Toga, J. C. Mazziotta (Eds.)**,** *Brain Mapping. The Methods, 2nd ed* (pp. 757–796). Amsterdam: Academic Press.

[2] Nowinski, W. L. (2015). Towards the holistic, reference and extendable atlas of the human brain, head and neck. *Brain Informatics, 2*(2), 65–76. http://link.springer.com/article/10.1007/s40708-015-0012-4

[3] Selected 2D brain atlases:
Nowinski, W. L., Bryan, R. N., Raghavan, R. (1997). *The Electronic Clinical Brain Atlas. Multiplanar Navigation of the Human Brain*. New York – Stuttgart: Thieme.
Nowinski, W. L., & Thirunavuukarasuu, A. (2004). *The Cerefy Clinical Brain Atlas on CD-ROM.* New York: Thieme.

[4] Selected 3D brain atlases:
Nowinski, W. L., Chua, B. C., Qian, G. Y., Marchenko, Y., Puspitasari, F., Nowinska, N. G., Knopp, M. V. (2011). *The Human Brain in 1492 Pieces: Structure, Vasculature, and Tracts* (version 1.0). New York: Thieme.
Nowinski, W. L., & Chua, B. C. (2014). *The Human Brain in 1969 Pieces: Structure, Vasculature, Tracts, Cranial Nerves, Systems, Head Muscles, and Glands* (version 2.0). New York: Thieme.

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brain atlases (as required by our former funding Agency), ranging in applications from education[5] to referencing[6] to functional imaging[7] to neurologic support[8] and to surgical planning,[9] our recent, most complex and most advanced atlas is made available free of charge for its users graciously to its publisher Thieme.[10] It contains about 3000 3D components and is extended to the head and neck. The atlas has been created over many years by means of an "atlas by atlas" approach. Initially, the atlas of structure has been built[11] followed by the construction of the atlases of intracranial vasculature,[12] white matter tracts,[13] cranial nerves,[14] head muscles and glands,[15] skull[16] and extracranial vasculature,[17] each of them separately validated.

This report overviews this latest free atlas covering materials and methods, atlas content, functionality and features, installation, user interface, advantages, limitations, and applications.

[5] Nowinski, W. L., Thirunavuukarasuu, A., Bryan, R. N. (2002). *The Cerefy Atlas of Brain Anatomy. An Introduction to Reading Radiological Scans for Students, Teachers, and Researchers.* New York: Thieme.

[6] Nowinski, W. L., Bryan, R. N., Raghavan, R. (1997). *The Electronic Clinical Brain Atlas. Multiplanar Navigation of the Human Brain*. New York – Stuttgart: Thieme.

[7] Nowinski, W. L., Thirunavuukarasuu, A., Kennedy, D. N. (2000). *Brain Atlas for Functional Imaging. Clinical and Research Applications*. New York: Thieme.

[8] Nowinski, W. L., Chua, B. C., Wut Yi, S. H. (2014). *3D Atlas of Neurologic Disorders* (version 1.0). New York: Thieme.

[9] Nowinski, W. L., Thirunavuukarasuu, A., Benabid, A. L. (2005). *The Cerefy Clinical Brain Atlas. Extended Edition with Surgery Planning and Intraoperative Support.* New York: Thieme.

[10] Nowinski, W. L., Chua, B. C., Thaung, T. S. L., Wut Yi, S. H. (2015). *The Human Brain, Head and Neck in 2953 Pieces.* New York: Thieme. http://www.thieme.com/nowinski/

[11] Nowinski, W. L., Chua, B. C., Qian, G. Y., Nowinska, N. G. (2012). The human brain in 1700 pieces: design and development of a three-dimensional, interactive and reference atlas. *Journal of Neuroscience Methods, 204*(1), 44–60.

[12] Nowinski, W. L., Chua, B. C., Puspitasari, F., Volkau, I., Marchenko, Y., Knopp, M. V. (2011). Three-dimensional reference and stereotactic atlas of human cerebrovasculature from 7 Tesla. *NeuroImage, 55*(3), 986–998.

[13] Nowinski, W. L., Chua, B. C., Yang, G. L., Qian, G. Y. (2012). Three-dimensional interactive human brain atlas of white matter tracts. *Neuroinformatics, 10*(1), 33–55.

[14] Nowinski, W. L., Johnson, A., Chua, B. C., Nowinska, N. G. (2012). Three-dimensional interactive and stereotactic atlas of cranial nerves and nuclei correlated with surface neuroanatomy, vasculature and magnetic resonance imaging. *Journal of Neuroscience Methods, 206*(2), 205–216.

[15] Nowinski, W. L., Chua, B. C., Johnson, A., Qian, G., Poh, L. E., Wut Yi, S. H., Aminah, B., Nowinska, N. G. (2013). Three-dimensional interactive and stereotactic atlas of head muscles and glands correlated with cranial nerves and surface and sectional neuroanatomy. *Journal of Neuroscience Methods, 215*(1), 12–18.

[16] Nowinski, W. L., Thaung, T. S. L., Chua, B. C., Wut Yi, S. H., Ngai, V., Yang, Y. et al. (2015). Three-dimensional stereotactic atlas of the adult human skull correlated with the brain, cranial nerves and intracranial vasculature. *Journal of Neuroscience Methods, 246,* 65–74.

[17] Nowinski, W. L., Thaung, T. S. L., Chua, B. C., Wut Yi, S. H., Yang, Y., Urbanik, A. (2015). Three-dimensional stereotactic atlas of the extracranial vasculature correlated with the intracranial vasculature, cranial nerves, skull and muscles. *The Neuroradiology Journal, 28*(2), 190–197.

Material and Method

Multiple *in vivo* 3/7 Tesla MRI and high-resolution CT scans of the same male, normal head specimen have been acquired over many years. From these scans, 3D digital virtual models of the brain, head and neck have been constructed with about 3000 components. A process of anatomic model building was done in the following steps: *in vivo* scan acquisition, scan segmentation, 3D surface modeling, 3D model simplification (decimation or compressing), 3D surface editing, 3D model color-coding, 3D object naming based on *Terminologia Anatomica,*[18] and model validation. The anatomic models were placed in the Talairach stereotactic coordinate system[19] to provide distances and stereotactic coordinates.

The models of the brain, head muscles and glands were constructed from a 3 T magnetization-prepared rapid gradient echo (MP-RAGE) scan with a $224 \times 300 \times 320$ resolution and a $0.8 \times 0.8 \times 0.8$ mm^3 voxel size. The brain was segmented by means of a dedicated contour editor, a 3D model constructed, and the cortex parcellated into lobes, gyri, and sulci. A 3D model of the intracranial vasculature with about 1300 vascular segments was created from multiple 3 and 7 T magnetic resonance angiography (MRA) scans, including 3D time of flight (the main sequence with a $384 \times 320 \times 272$ resolution and a $0.52 \times 0.52 \times 0.5$ mm^3 voxel size), spoiled gradient recovery, and susceptibility weighted imaging. The extracranial vasculature was created from the same MRA scans as the intracranial vasculature and additionally from a 3D phase contrast MRA neck scan with a 352x352x261 matrix and a $0.568182 \times 0.568182 \times 1.0$ mm^3 voxel size. The cranial nerves (CN) extracted initially from the MP-RAGE scan were modeled as tubes, and further extended and fine-tuned. The CN model contains all 12 pairs of CN I - CN XII along with the brainstem nuclei. A 3D model of the skull was created from a high resolution spiral CT scan with 526 axial slices of 0.75 mm thickness, 0.5 mm increment, 512×512 matrix and 0.46875×0.46875 mm^2 pixel size.

The atlas is equipped with a user-friendly browser providing a mechanism for structure assembling and disassembling (to build any region of interest and to present a local anatomy within its global context); brain dissections in 7 cutting planes to see through the brain; real-time structure and scan manipulation; 3D labeling of surface and sectional MRI anatomy; highlighting of a selected 3D structure; interaction combined with animation; quantification (linear distances, vessel diameters, and stereotactic coordinates); and capturing the composed and labeled scenes.

[18] Federative Committee on Anatomical Terminology (FCAT). (1999).*Terminologia Anatomica*. Stuttgart – New York: Thieme.

[19] Talairach, J., & Tournoux, P. (1988). *Co-Planar Stereotactic Atlas of the Human Brain*. Stuttgart - New York: Georg Thieme Verlag/Thieme Medical Publishers.

Atlas Content

The atlas contains the following 3D components: *brain* divided into the left and right hemispheres, cerebrum, cerebellum, and brainstem; *cerebellum* divided into the left and right hemispheres; *brainstem* divided into the left and right parts, and parcellated into the midbrain, pons and medulla; *cerebral cortex* parcellated into lobes, gyri, and gyri with sulci; *spinal cord* divided into the left and right parts; *white matter* parcellated into cerebral, posterior fossa, and deep white matter; *gray matter nuclei* parcellated; *ventricular system* parcellated; *intracranial vasculature* with arteries, veins, and dural sinuses parcellated into more than 1300 vessels, the smallest of 0.08 mm in diameter; *intracranial arteries* grouped into the internal carotid, anterior cerebral, middle cerebral, posterior cerebral, vertebral and basilar arteries, and the circle of Willis, each group parcellated; *intracranial veins* grouped into superficial, deep, and posterior fossa veins, each group parcellated; *dural sinuses* parcellated; *extracranial vasculature* grouped into arteries and veins, each group parcellated; *white matter tracts* grouped into associations, commissures, projections, and posterior fossa tracts, each group completely parcellated; *cranial nerves* grouped into CN I – CN XII, each group parcellated, along with the brainstem nuclei with more than 630 components; *head muscles* grouped into extra-ocular, facial, masticatory, and other muscles, each group parcellated; *glands* grouped into mouth and other glands, each group parcellated; *skull* parcellated into all 29 bones; *skin* divided into the left and right parts; *auditory* and *visual* systems parcellated; and *cervical spine* parcellated into vertebrae C1-C6.

This atlas content is grouped into 17 modules (tissue classes): central nervous system, deep gray matter structures, ventricles, white matter, white matter tracts, intracranial arterial system, intracranial venous system, head muscles, glands, extracranial arteries, extracranial veins, skull, skin, neck, visual system, and auditory system.

Functionality and Features

The atlas is 3D, interactive, stereotactic, fully parcellated, completely labeled, advanced, detailed, accurate, reference, realistic, high resolution, spatially consistent, user friendly, extendable (scalable), composable, dissectible, explorable, and modular.

The atlas provides functions for manipulation and exploration of surface and sectional anatomy that are grouped into seven clusters to provide: *structure selection* (select/deselect all, (tissue) class clusters, classes, groups, individual structures, and left/right/both sides for a fast scene assembly/disassembly); *3D model real-time manipulation* (rotate, zoom, pan, and predefined view set); *virtual dissections* (by 7 cutting planes to see through the brain); *scan manipulation* (on the triplanar); *atlas content querying* (about structure's name (label) or location); *coordinates and distance readout* as the atlas is stereotactic (3D coordinates of any location are provided and a distance between any two atlas points can be measured); and *supporting functions* (image save, clear labels, and get information and help).

Any configuration of the brain, intra- and extracranial vessels, white matter connections, deep gray matter nuclei, visual and auditory systems, cranial nerves, head muscles and glands, and bone can be composed, explored, labeled, and quantified. Real-time continuous navigation is supplemented with axial, coronal, and sagittal 2D images (displayed on the triplanar as 3D objects) of the MRI (MP-RAGE) scan along with brain cutting in 7 directions. Any 3D anatomical scene or configuration assembled by the user can be viewed from any position and at a wide range of magnification. The composed configuration can freely be labeled in terms of the selected components and label placement as well as any distances measured and vessel diameters read.

Installation

This atlas entitled *The Human Brain, Head and Neck in 2953 Pieces* published by Thieme, New York, is available publically at http://www.thieme.com/nowinski/ and www.WieslawNowinski.com/FreeBrainAtlas (redirecting to Thieme's site). To get a copy of the atlas, download the setup from any of the above sites and install the atlas by running the setup.exe (the default installation folder is C:\Program Files (×86)\The Human Brain, Head and Neck in 2953 Pieces). Run the program by clicking on *The Human Brain, Head and Neck in 2953 Pieces* icon.

The atlas runs on Windows XP Service Pack 2 or later, Windows 7, 8 and 8.1 (there is no version for MAC OS). The minimum system requirements are the following: 2GHz Intel Core 2 Duo or higher; 1GB RAM or greater; graphics card that supports OpenGL 2.1 (recommended but not mandatory) with at least 512 MB of video memory; 150 MB hard disk space; and monitor resolution 1280 × 1024 pixels (recommended not mandatory), minimum 1280 × 720 pixels. In order to facilitate operation, the program contains a compact info and help. Moreover, the introductions to this and earlier editions available on the Home page provide more insights into the atlas.

User Interface

Figure 1 illustrates the user interface along with its main components: 3D main view, module matrix, tissue panels, indices, and controls.

Advantages

To our best knowledge, this is the first truly de/composable 3D atlas of the adult human brain, head, and neck that is fully parcellated and automatically labelable, enabling the user a continuous, real-time navigation of the surface and sectional anatomy. The use of the same specimen allowed us to build from multiple scans the 3D anatomic models that are spatially consistent and this approach will enable extending them consistently in the future with new scan acquisitions. The models are polygonal with a higher spatial resolution in comparison to volumetric models in other atlases. The component anatomical models were earlier validated, so the entire atlas can be considered as typical (normal). The testimonials of top neurosurgeons, neuroradiologists, and brain educators about our brain atlas work are provided at www.WieslawNowinski.com under *Reviews*.

Limitations

The atlas does not allow for importing user's data; this features is available in some of our previous atlases, such as the *Brain*

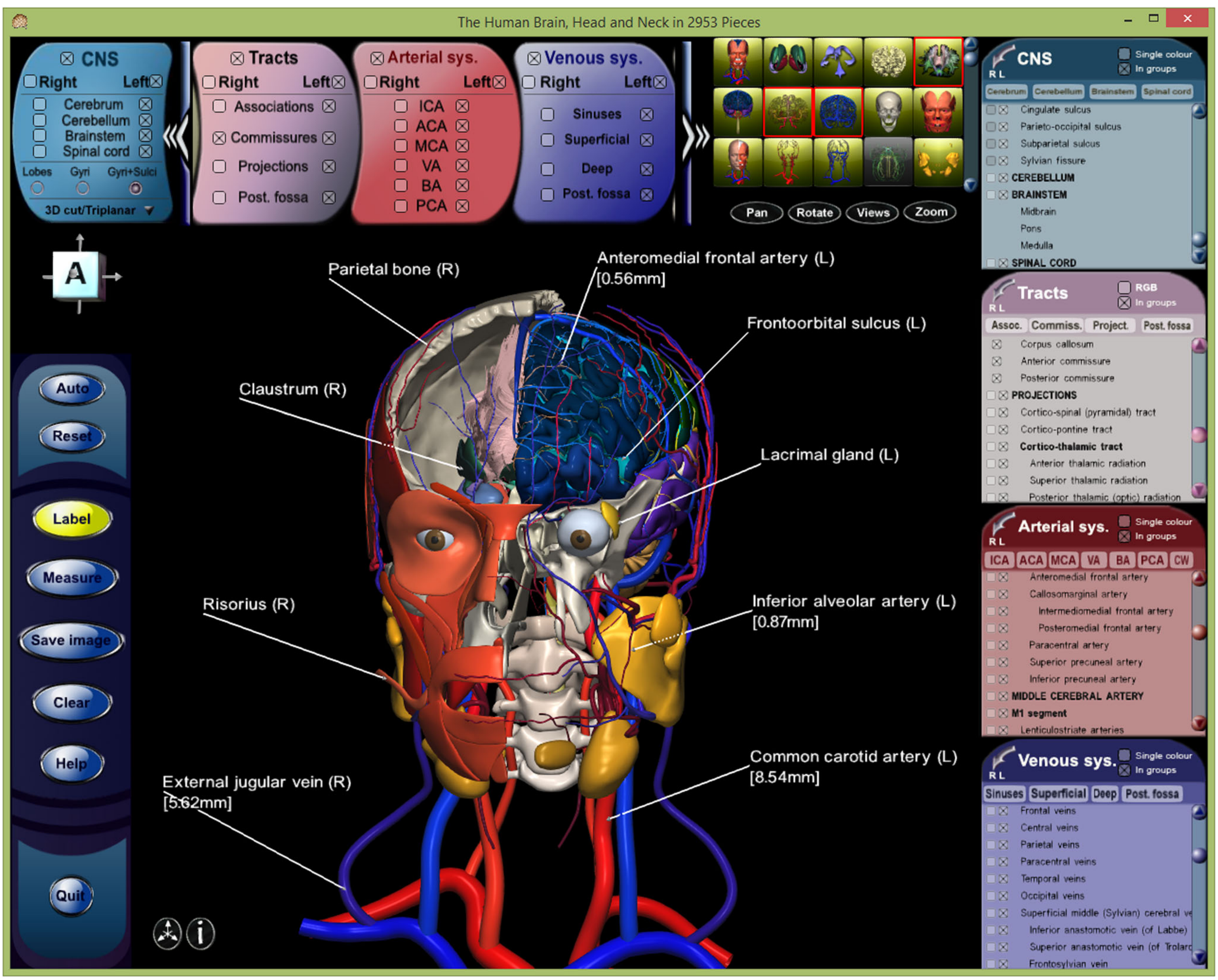

Fig. 1 User interface of the atlas: 3D main view with a composed 3D model (center) with some selected components of the brain, head (the skull is open on the right side to see the subcortical structures and white matter connections) and neck, several of them labeled; matrix of selectable modules/tissue classes (top-right); horizontally scrollable tissue panels for left/right side and group selections (top-left); individual indices for all the selected tissue classes synchronized with their corresponding panels (right); controls including help (left); and info "i" (bottom-left in the 3D main view)

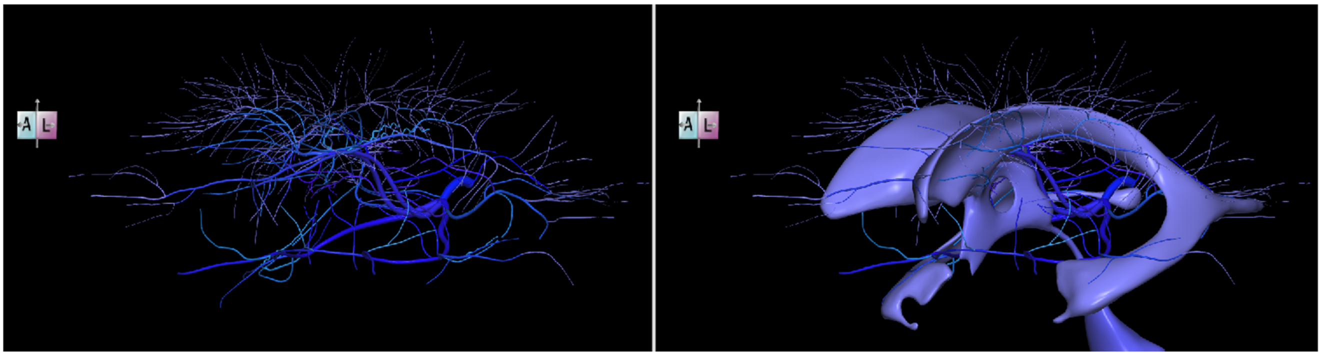

Fig. 2 Illustration of a context-wise exploration: left) antero-lateral view of the deep cerebral veins (the vascular pattern looks chaotic, complicated and difficult to be understood); right) the similar view of the deep cerebral veins in the context of the ventricular system (the course of the veins is easy to grasp as they follow the surfaces of the ventricles)

Atlas for Functional Imaging[20] for functional image analysis[21] and *The Cerefy Clinical Brain Atlas. Extended Edition with Surgery Planning and Intraoperative Support*[22] with a morphological atlas and probabilistic functional atlas[23] for stereotactic and functional neurosurgery.[24]

The atlas does not contains functional description of structures, which feature is available in *The Cerefy Atlas of Brain Anatomy. An Introduction to Reading Radiological Scans for Students, Teachers, and Researchers.*[25]

The atlas does not allow the user to export its structures; for this purpose, dedicated brain atlas libraries for stereotactic and functional neurosurgery have been created (see e.g.[26]). Exported atlas structures could be employed for registration as well as in brain databases for spatial quantification and online referencing within a rich context.

Applications

The atlas is a self-education tool providing a wide range of material for 3D visualization and exploration. The composition-decomposition mechanism allows for a context-wise exploration of the cerebral structures as illustrated in Fig. 2. The atlas also serves as a built-in generator of teaching materials. Composed images (captured by clicking on the *Save image* button, see Fig. 1) are saved in the TIFF format to an external file in a quadruple increased size. In addition, animation (activated by clicking on the *Auto* button, see Fig. 1) facilitates capturing movies by any external tools, such as publically available FRAPS www.fraps.com.

The atlas serves as a reference and enables for a quantitative analysis of cerebral structures by providing stereotactic coordinates, distances, and vessel diameters, as illustrated in Fig. 3.

Summary

The presented 3D atlas is an easy and useful free tool for studying, understanding and teaching of the brain, head and neck. It allows the user to create any configuration, and explore and measure it, which enhances the understanding of anatomy just with a few mouse clicks, making it useful for medical students, residents, teachers, and clinicians. The atlas is also a helpful tool for generating teaching materials.

[20] Nowinski, W. L., Thirunavuukarasuu, A., Kennedy, D. N. (2000). *Brain Atlas for Functional Imaging. Clinical and Research Applications*. New York: Thieme.

[21] Nowinski, W. L., Thirunavuukarasuu, A. (2001). Atlas-assisted localization analysis of functional images. *Medical Image Analysis, 5*(3), 207–220.

[22] Nowinski, W. L., Thirunavuukarasuu, A., Benabid, A. L. (2005). *The Cerefy Clinical Brain Atlas. Extended Edition with Surgery Planning and Intraoperative Support.* New York: Thieme.

[23] Nowinski, W. L., Belov, D., Benabid, A. L. (2003). An algorithm for rapid calculation of a probabilistic functional atlas of subcortical structures from electrophysiological data collected during functional neurosurgery procedures. *NeuroImage, 18*(1), 143–155.

[24] Nowinski, W. L., Belov, D., Pollack, P., Benabid, A. L. (2005). Statistical analysis of 168 bilateral subthalamic nucleus implantations by means of the probabilistic functional atlas. *Neurosurgery, 57*(4 Suppl), 319–330.

[25] Nowinski, W. L., Thirunavuukarasuu, A., Bryan, R. N. (2002). *The Cerefy Atlas of Brain Anatomy. An Introduction to Reading Radiological Scans for Students, Teachers, and Researchers.* New York: Thieme.

[26] Nowinski, W. L., & Benabid, A. L. (2002). New directions in atlas assisted stereotactic functional neurosurgery. In I. M. Germano (Ed.), *Advanced techniques in image-guided brain and spine surgery* (pp. 162–74). New York: Thieme.

Nowinski, W. L. (2009). Anatomical and probabilistic functional atlases in stereotactic and functional neurosurgery. In A. Lozano, P. Gildenberg, R. Tasker (Eds.), *Textbook of Stereotactic and Functional Neurosurgery* (pp. 395–441). Springer.

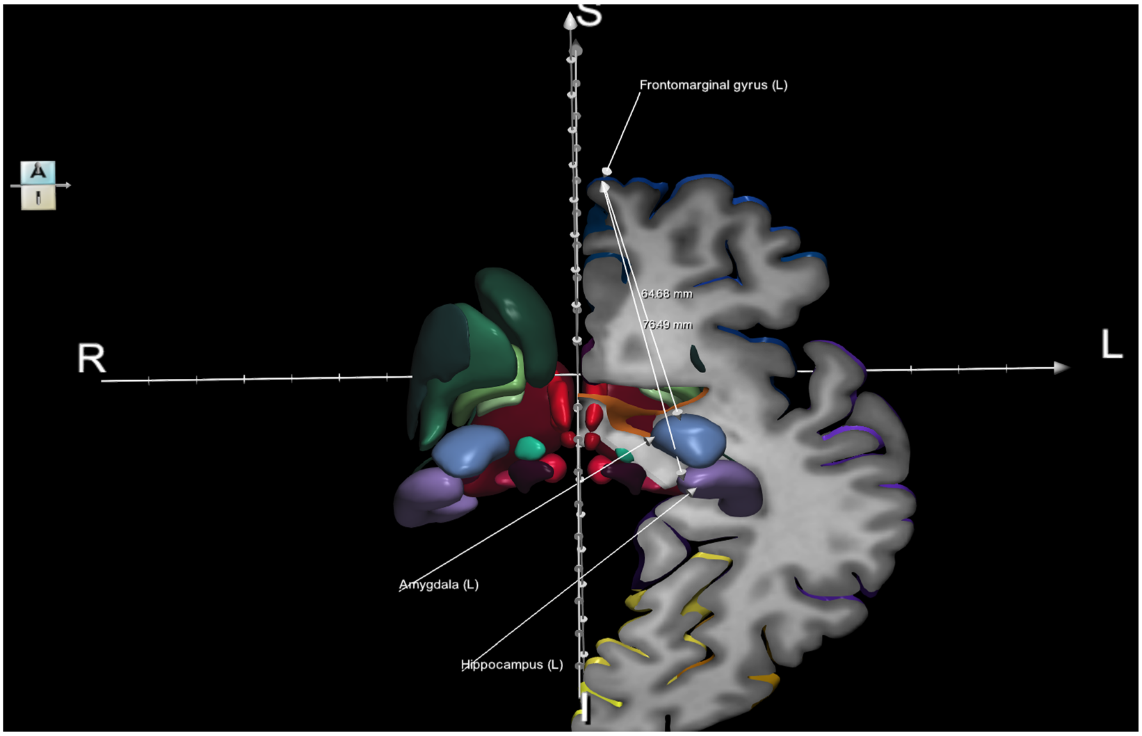

Fig. 3 Spatial analysis of deep gray matter cerebral structures. The distances between the most anterior points of the hippocampus and amygdala, and the frontal pole for the left hemisphere are measured (a piece of the left cerebral hemisphere is presented as a slab by using the superior and inferior cutting planes to facilitate the measurements and visualization of the measured values)

Information Sharing Statement

This atlas is available publically at http://www.thieme.com/nowinski/ and www.WieslawNowinski.com/FreeBrainAtlas.

The testimonials on our brain atlases are provided at www.WieslawNowinski.com under Reviews.

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