Stroke Atlas: a 3D Interactive Tool Correlating Cerebrovascular Pathology with Underlying Neuroanatomy and Resulting Neurological Deficits

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SUMMARY – *Understanding stroke-related pathology with underlying neuroanatomy and resulting neurological deficits is critical in education and clinical practice. Moreover, communicating a stroke situation to a patient/family is difficult because of complicated neuroanatomy and pathology. For this purpose, we created a stroke atlas. The atlas correlates localized cerebrovascular pathology with both the resulting disorder and surrounding neuroanatomy. It also provides 3D display both of labeled pathology and freely composed neuroanatomy. Disorders are described in terms of resulting signs, symptoms and syndromes, and they have been compiled for ischemic stroke, hemorrhagic stroke, and cerebral aneurysms. Neuroanatomy, subdivided into 2,000 components including 1,300 vessels, contains cerebrum, cerebellum, brainstem, spinal cord, white matter, deep grey nuclei, arteries, veins, dural sinuses, cranial nerves and tracts. A computer application was developed comprising: 1) anatomy browser with the normal brain atlas (created earlier); 2) simulator of infarcts/hematomas/aneurysms/stenoses; 3) tools to label pathology; 4) cerebrovascular pathology database with lesions and disorders, and resulting signs, symptoms and/or syndromes. The pathology database is populated with 70 lesions compiled from textbooks. The initial view of each pathological site is preset in terms of lesion location, size, surrounding surface and sectional neuroanatomy, and lesion and neuroanatomy labeling. The atlas is useful for medical students, residents, nurses, general practitioners, and stroke clinicians, neuroradiologists and neurologists. It may serve as an aid in patient-doctor communication helping a stroke clinician explain the situation to a patient/family. It also enables a layman to become familiarized with normal brain anatomy and understand what happens in stroke.*

Introduction

Stroke is a leading cause of death and the major cause of permanent disability. Understanding stroke-related pathology with underlying neuroanatomy and the resulting neurological deficits is critical in education and clinical practice. In addition, communicating a stroke situation to a patient and/or his or her family is difficult because of a complicated neuroanatomy and pathology, particularly in a “time is brain” condition.

For this purpose, we created a stroke atlas, a three-dimensional (3D) interactive tool correlating cerebrovascular pathology with the un-

derlying surface and sectional neuroanatomy as well as the resulting neurological deficits. The stroke atlas contains a 3D, parcellated and labeled brain atlas of normal anatomy equipped with exploration tools along with a cerebrovascular pathology database with synthesized cerebrovascular lesions providing disorder-localization relationships, each lesion labeled with the disorder and the corresponding signs, symptoms, and/or syndromes. To our best knowledge this type of atlas has not yet been constructed. Moreover, in a recent trend in radiology aiming to enhance doctor-patient communication, the stroke atlas presented here may serve as an illustration for fields

Figure 1 User interface of the stroke atlas.

other than stroke on how this kind of tool can be designed and what sort of functionality it should provide.

Material and Method

A 3D interactive brain atlas of normal anatomy was first created from 3 Tesla and 7 Tesla scans¹⁻⁴. The atlas contains cerebrum, cerebellum, brainstem, spinal cord, white matter, deep grey nuclei, arteries, veins, dural sinuses, white matter tracts, cranial nerves with nuclei, and systems. The cerebral model is parcellated in about 2,000 3D components, fully labeled, and uniquely colored. The creation of the cerebrovascular model, its surface modeling and simplification techniques have already been described¹. The vasculature is parcellated into 1,300 vessels, each labeled with name and diameter; the smallest vessels are 80 microns in diameter¹. The cortex is parcellated into lobes, gyri, and gyri with sulci². The cranial nerves

(CN) contain 440 components: all 12 pairs of CN (CN I-CN XII) with the brainstem CN nuclei⁴.

A computer application was developed comprising: 1) anatomy browser with the normal brain atlas; 2) simulator of cerebrovascular pathologies (infarcts, hematomas, aneurysms and stenoses); 3) tools to label pathology with clinical signs, symptoms and/or syndromes; 4) cerebrovascular pathology database with lesions and disorders, and the resulting signs, symptoms and/or syndromes.

The anatomy browser provides exploration operations, including 3D display and manipulation (rotate, zoom, pan, and set view), brain compositing/decompositing, individual components and group selection, two-way (3D view-index) mapping, 3D labeling, component highlighting, distance measuring, 3D brain cutting in seven directions, and axial/coronal/sagittal MR (magnetic resonance) triplanar display.

The neuroanatomy-cerebrovascular pathology index is formed as a list, which is hierar-

chical with respect to anatomy and linear with respect to disorders. For each disorder, a sub-list of signs, symptoms and/or syndromes was compiled. This index is subdivided into cerebral ischemia, cerebral hemorrhage, and cerebral aneurysms. The cerebral ischemia part, in turn, is further subdivided into the arterial system with the anterior and posterior circulations, and the venous system.

To model cerebrovascular pathology, a customized pathology editor was developed to create different types of pathologies, with various shapes, sizes and locations, and label them with the resulting disorders along with associated signs, symptoms and/or syndromes. In order to model cerebrovascular pathology in 3D, the following convention was used: a lesion was modeled as a white sphere, stenosis as a white cylinder, aneurysm as a semitransparent sphere of the same color as the diseased vessel, and emboli in TIA (transient ischemic attack) as small white balls within a semitransparent vessel; pathology of a structure in case of ischemia or hemorrhage was depicted by making the surface of this structure white.

The cerebrovascular pathology database correlates cerebrovascular lesions with the resulting disorders. Each lesion was linked and labeled with the corresponding disorder and a description of the resulting signs, symptoms and/or syndromes. This description was compiled from the literature.

Results

A hierarchical anatomy index along with a linear index of disorders was created (see Appendix). The stroke atlas was designed and developed, and its user interface is presented in Figure 1. The disorder database has been populated with 70 cerebrovascular lesions compiled from textbooks⁵⁻⁹. The initial view of each disorder was preset in terms of lesion location, size, surrounding surface and sectional neuroanatomy, and lesion and neuroanatomy labeling. Figure 2 illustrates the cerebrovascular pathology correlated with the resulting disorder and the surrounding surface and sectional neuroanatomy as follows: a) stenosis of the left posterior communicating artery; b) vertebrobasilar TIA; c) infarction of the left pontine arteries region; d) bilateral infarction of the calcarine arteries; e) left medullary hemorrhage; f) unruptured basilar artery aneurysm.

Discussion

This stroke atlas work is multidisciplinary, spanning neuroradiology, neurology and neuroinformatics. Though the current atlas realization may still be perceived as limited as it contains only 70 sites, we believe that the concept itself and the tool already developed have many advantages.

Advantages. The stroke atlas correlates localized cerebrovascular pathology with both the resulting disorder and the surrounding neuroanatomy. This atlas also provides a 3D display both of the labeled pathology and neuroanatomy, freely composed by the user. Disorders are described in terms of the resulting signs, symptoms and/or syndromes, and they have been compiled for ischemic stroke, hemorrhagic stroke, and cerebral aneurysms. The surface neuroanatomy is available in about 2,000 3D components, while sectional neuroanatomy is presented in the form of axial, coronal, and/or sagittal MR triplanar images suitable from a radiological perspective. One of advantages of our atlas design is rapid brain compositing and decompositing from individual and group components. It allows the user to build any neuroanatomy of interest surrounding the studied pathology with a few clicks of the mouse. The user can study it from any angle, at a wide range of magnifications, and label each component. In addition, the preset views with labeled pathology and neuroanatomy facilitate and speed up the use of this atlas, which is critical in situations when "time is brain".

This tool is also well-aligned with a recent trend in radiology aiming to enhance doctor-patient communication. Communicating a stroke situation is complicated and time-consuming in a time critical condition, and we believe new tools are needed for this purpose. The stroke atlas proposed here may serve as an illustration on how this kind of tool can be designed and what functionality it should provide. Moreover, as this stroke atlas is self-explanatory and easy to use, with this kind of tool nurses potentially could assist doctors to communicate with patients.

Figure 2 Illustration of cerebrovascular pathology → correlated with the resulting disorder and the surrounding surface and sectional neuroanatomy: A) stenosis of the left posterior communicating artery; B) vertebrobasilar TIA; C) infarction of the left pontine arteries region; D) bilateral infarction of the calcarine arteries; E) left medullary hemorrhage; and F) unruptured basilar artery aneurysm.

Applications. The stroke atlas is potentially useful for medical students, residents, nurses, general practitioners as well as for stroke clinicians, neuroradiologists and neurologists, as it contains both normal brain anatomy and cerebrovascular pathology correlated with disorders presented in a visual and interactive way. This atlas also has a potential usefulness for patients and their families. The atlas may serve as an aid in patient-doctor communication helping a stroke clinician explain the situation to the patient and/or his or her family. It also enables a layman to become familiarized with normal brain anatomy and understand what happens in stroke.

Limitations. This stroke atlas has limitations in terms of neuroanatomical content, size of the cerebrovascular pathology database, accuracy of pathology modeling, stroke presentation, and quantification of atlas benefits.

Adding more lesions to the cerebrovascular pathology database with the current tools is technically easy, but there are two concerns to be considered first before extending the database. We think that the current version of the cerebrovascular pathology database covers most typical stroke situations, so the increase in database size with new, probably rarer, cases will make the atlas more complicated to the patient. Moreover, the inclusion of more literature materials, which sometimes are not consistent and may require more specialized domain knowledge, could cause the atlas to be potentially confusing and too difficult for a layman to use.

We employ simple geometrical objects to model pathology, including spheres (to model lesions, aneurysms, and emboli), cylinders (to model stenoses), and the surfaces of the original (non-deformed) anatomical structures to indicate ischemic and hemorrhagic regions. Actual pathology may be much more complicated and it usually distorts the patient's neuroanatomy.

Stroke presentation is limited as actual stroke cases may require more detailed data, including clinical presentation, radiologic findings, diagnosis and clinical findings.

Though we have identified several evident benefits of this atlas, they have not been measured yet. Any feedback from the patients, nurses, and doctors, not available at present, would facilitate improving this tool.

Future work. Overcoming the current limitations guides our future work. The brain atlas of normal anatomy has been under continuous enhancement and extension in terms of its content, quality, operations, user interface, and interaction.

The current 3D labeling of normal anatomy will be extended to 2D labeling of the MR triplanar images. The pathology database has been under extension to include diseases other than cerebrovascular pathologies, such as those in the regional anatomy and CN-related disorders.

Taking into account the above-mentioned concerns regarding pathology database extension, the future development will result in two versions of the atlas of disorders: 1) a simple version for general practitioners, nurses, medical students, patients and the general public; and 2) an advanced version for medical professionals with the extended normal anatomy, expanded pathology database, and additional material from clinical textbooks. Actual cases will be included from the existing sources, such as ¹⁰, to provide more detailed presentation, including clinical presentation, radiologic findings, diagnosis, differential diagnosis, clinical findings, treatment, complications and prognosis.

Another major issue is how to make this kind of atlas available. We have considered a few avenues. We plan to develop a simple version on iPad and make it available on App-Store. Another effort is to put the stroke atlas on the World Stroke Organization (WSO) website (discussions with the WSO are ongoing). This, however, may require further simplification and development of a web-based version.

Conclusions

This stroke atlas is a new tool providing disorder-localization relationships in stroke along with neuroanatomy exploration. It presents various cerebrovascular pathology situations in 3D labeled with the resulting disorders and associated signs, symptoms and/or syndromes along with the surrounding neuroanatomy parcellated into 2,000 components, including 1,300 vessels.

The atlas is potentially useful for medical students, residents, nurses, general practitioners as well as for stroke clinicians, neuroradiologists and neurologists as it contains both normal brain anatomy and cerebrovascular pathology correlated with neurological disorders.

Considering a recent trend in radiology aiming to enhance doctor-patient communication, this atlas may serve as an aid helping a stroke clinician explain the situation to the patient and/or his or her family. Part of this commu-

nication can be taken over by nurses. As the atlas is self-explanatory and easy to use, this also enables a layman to become familiarized with normal brain anatomy and understand what happens in stroke. The design of this stroke atlas in terms of content, functionality and interaction can help in the development of similar applications in other fields to facilitate doctor-patient communication.

Finally, this work forms the foundation for the development of new types of atlases, both

patient-oriented and medical professional-oriented. In addition, pathologies other than cerebrovascular disorders can be easily handled by the existing tool.

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Appendix Neuroanatomy-cerebrovascular pathology index, hierarchical with respect to anatomy and linear with respect to disorders (in italic).

Cerebral Ischemia

Arterial system

Anterior circulation

Internal carotid artery (ICA)

Anterior circulation stroke

ICA TIA

ICA (anterior circulation) stroke

ICA terminus ("T") occlusion

Ophthalmic artery (OphthA)

OphthA occlusion

Posterior communication artery (PComA)

PComA occlusion

Anterior choroidal artery (AChA)

Unilateral AchA infarction

Bilateral AchA infarction (which is rare)

Anterior cerebral artery (ACA)

Unilateral ACA infarction

Bilateral ACA infarction

Artery of Heubner (distal medial striate artery) (HA)

HA infarction

Middle cerebral artery (MCA)

MCA stem occlusion

Lenticulostriate arteries (LA)

LA occlusion

MCA superior division

MCA superior division occlusion

MCA inferior division

MCA inferior division occlusion

Posterior circulation

Vertebrobasilar artery (VBA)

Posterior circulation stroke

VBA TIA

Vertebral artery (VA)

VA occlusion

Posterior inferior cerebellar artery (PICA)

PICA infarction

Anterior spinal artery (ASA)

ASA infarction

Basilar artery (BA)

Dorsal (apex of) BA infarction

BA main stem occlusion

Anterior inferior cerebellar artery (AICA)

AICA occlusion

Labyrinthine (auditory) artery (AA)

AA occlusion

Pontine arteries (PAs)

PAs territory stroke

Superior cerebellar artery (SCA)

SCA occlusion

Occlusion of peripheral branches of SCA

Posterior cerebral artery (PCA)

Unilateral PCA infarction

Bilateral PCA infarction

Infarction of PCA hemispheric branches

Dominant PCA infarction

Nondominant PCA infarction

Infarction of PCA penetrating branches

Thalamic arteries

Anterior thalamic infarction

Dorsal thalamic infarction

Paramedian thalamic infarction

Posterolateral thalamic infarction

Lateral posterior choroidal artery (LPChA)

LPChA infarction

Calcarine artery (CA)	<i>CA unilateral occlusion</i> <i>CA bilateral occlusion</i>
Venous system	
Cerebral veins and venous sinuses	<i>Acute thrombosis of cerebral veins and sinuses</i>
Superior sagittal sinus (SSS)	<i>SSS thrombosis</i>
Superior sagittal sinus with cortical veins (CV)	<i>SSS with CV thrombosis</i>
Cavernous sinus (CS)	<i>CS thrombosis</i>
<i>Cerebral Hemorrhage</i>	
Brain	<i>Intracranial hemorrhage</i>
Cerebrum	
Lobes	<i>Lobar hemorrhage</i>
Frontal lobe	<i>Frontal lobe hemorrhage</i>
Temporal lobe	<i>Temporal lobe hemorrhage</i>
Parietal lobe	<i>Parietal lobe hemorrhage</i>
Occipital lobe	<i>Occipital lobe hemorrhage</i>
Putamen	<i>Putaminal hemorrhage</i>
Caudate	<i>Caudate hemorrhage</i>
Thalamus	<i>Thalamic hemorrhage</i> <i>Anterior thalamic hemorrhage</i> <i>Posteromedial thalamic hemorrhage</i> <i>Posterolateral thalamic hemorrhage</i> <i>Dorsal thalamic hemorrhage</i> <i>Whole thalamic hemorrhage</i>
Ventricular system	<i>Intraventricular hemorrhage</i>
Cerebellum	<i>Cerebellar hemorrhage</i>
Brainstem	<i>Mesencephalic hemorrhage</i>
Mesencephalon	<i>Whole pons hemorrhage</i> <i>Hemipontine hemorrhage</i> <i>Dorsolateral tegmental pontine hemorrhage</i>
Pons	<i>Medullary hemorrhage</i>
Medulla	
<i>Cerebral Aneurysms</i>	
Internal carotid artery (ICA)	<i>Carotid-cavernous fistula</i> <i>(due to ruptured aneurysm)</i> <i>Unruptured cavernous ICA aneurysm</i>
Posterior communicating artery (PComA)	<i>PComA aneurysm</i>
Middle cerebral artery (MCA)	<i>Middle cerebral artery aneurysm</i>
Basilar artery (BA)	<i>Unruptured BA aneurysm</i>