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Modeling the Human Brain's Major Structures and White Matter Connectivity Using Magnetic Resonance and Diffusion Tensor Imaging

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Abstract

The goal of this research was to develop a procedure for rapid prototyping a replica of the human brain that details its primary areas of function and white matter tracts. It was the first time ever that a one-to-one model with such detail and complexity was produced. Neurosurgeons can use such a model to describe the brain and its functions to their patients, as well as how those particular sections of the brain could relate to the patients' particular disorders. Each of the brain's major structures is displayed in the left hemisphere of the brain model. The location and geometry of these structures were determined with common knowledge of a human brain's anatomy. The right hemisphere of the brain model displays the white matter connections between each of these structures. Diffusion tensor imaging was used to determine the location, orientation, and anisotropy of the white matter tracts within the human brain. Each of the brain's major structures, as well as the anisotropy of the white matter tracts is color-coded. Mimics software was used to compile and refine the magnetic resonance images of a whole brain into a three-dimensional model. Each of the brain's major structures was also compiled into three- dimensional models. These models were used to overlay the left hemisphere of the full brain model. The diffusion tensor images compiled by Mimics were used to overlay the right hemisphere of the brain. A Spectrum Z510 3D-Printer was used to produce the three- dimensional model. The Z510 was chosen for its ability to produce three-dimensional models in color. The neurosurgeons and teachers can use the full model to describe the anatomy of the brain, the specifics of a particular treatment or procedure, and how an ailment affects their patients.

Keywords: Human Brain, White Matter, Imaging, 3-D modeling, Rapid Prototyping

1. Introduction

Brain surgery is a high risk procedure that requires the surgeon to have a great deal of skill and experience. Careful planning is essential to the success of the surgery and any deviation from the planning would likely result in the fatality of the patient. As a result, the idea of having brain surgery is likely to make the patient very nervous and even doubt if the benefits outweigh the risks of such a procedure. A tangible model of the brain that depicts the primary areas of function and white matter tracts would be extremely useful for neurosurgeons. It would help the surgeon connect with a patient, and allow the surgeon to explain how the brain functions and how their particular condition may be affecting brain function. A neurosurgeon would also be able to provide the patient with an overview of the surgical process using the prototype. Such conversations could build a working relationship between the neurosurgeon and patient and help the surgeon build a sense of trust with his/her patients.[1] Three-dimensional models also make good educational resources. Though most textbooks provide excellent illustrations of the brain's anatomy, a two-dimensional image is nothing in comparison to an accurate three-dimensional prototype.

1.1. Rapid Prototyping

Rapid prototyping (RP), also known as additive manufacturing, generates a three-dimensional model of an object from the surface of said object, layer upon layer.[2] The feasibility of producing three-dimensional replicas of human organs, including the human brain, has been shown time and time again.[3,4] Products and replicas are often completed with Computer-Aided Design (CAD) software. The replica is usually printed in slices by depositing layer upon layer of material. The Z Corporation Spectrum Z510 3D color printer (Z Corp Printer) was chosen for its color

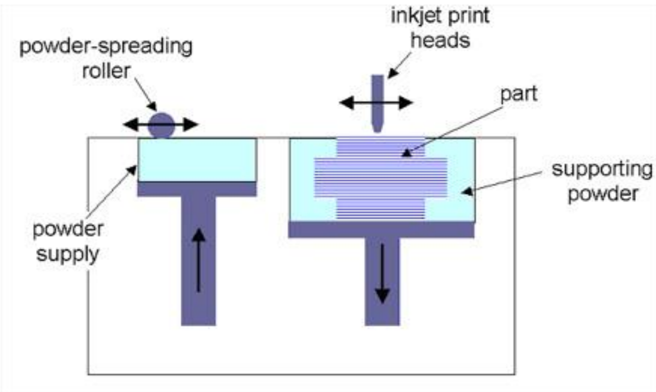

Figure 1. An illustration of the Z Corp printer's rapid prototyping process.

Figure 2. Z corporation Spectrum Z510 3D color printer.

printing capabilities. The Z Corp Printer creates successive cross-section of three-dimensional objects from a plaster powder. The layers are built in the machine's build bed, and the powder is fed into the bed with a roller. The parts are sprayed with a binder solution by means of an inkjet. The bed is lowered and a new layer of powder is added. After the entire part is completed, excess powder is blown off the part, and the part is infiltrated with a glue to improve its strength. The Z Corp printer is fast (2 layers per minute) and cost effective, but the surface finish, accuracy, and strength are lacking compared to other rapid prototyping methods.[5]

1.2. Nuclear Magnetic Resonance Imaging

Nuclear Magnetic Resonance Imaging (NMRI) is a form of medical imaging that exploits the magnetic properties of protons. Since all elements contain protons, the various forms of NMRI must focus on particular elements. The characteristics of a good candidate element for Magnetic Resonance Imaging (MRI) applications include: a strong magnetic moment, physiological concentration, and isotopic abundance. Table 1 suggests that hydrogen makes a perfect candidate element, having a very large magnetic moment and physiologic concentration.[6] It is common knowledge that water is comprised of two hydrogen atoms and makes up 70% of a human's composition. When activated by the MRI, the proton that makes up the hydrogen absorbs radio frequency (RF) electromagnetic waves, bumping the proton up an energy level. The proton however prefers being in the ground state and will release the RF wave to get back down to its ground state. The signal received by the MRI machine is dependent upon the RF wave's frequency, as well as the environment surrounding the water molecule. This produces a high resolution image of the tissue that is much less invasive than other forms of medical imagery.[6]

Table 1. The factors that determine a good element for MRI applications are magnetic moment, physiologic concentration, and isotopic abundance.

Element	Magnetic Moment	Physiologic Concentration	% Isotopic Abundance
Hydrogen	2.79	100	99.98
Oxygen	1.89	50	0.04
Iron	2.63	4E.6	100

1.3. Anatomy Of The Brain

Table 2. The Cerebrum's surface is divided into four lobes based on function and geometry. .[7]

Lobe	Function	Lobe	Function
Frontal	Voluntary motor control of skeletal muscles; Personality; higher intellectual processes; verbal communication	Temporal	Interpretation of Auditory Sensation; Storage of auditory and visual experiences
Parietal	Somatesthetic interpretation; understanding language; and formulating language.	Occipital	Integration of movements in focusing the eye; correlation of visual images with previous experiences; conscious perception of vision.

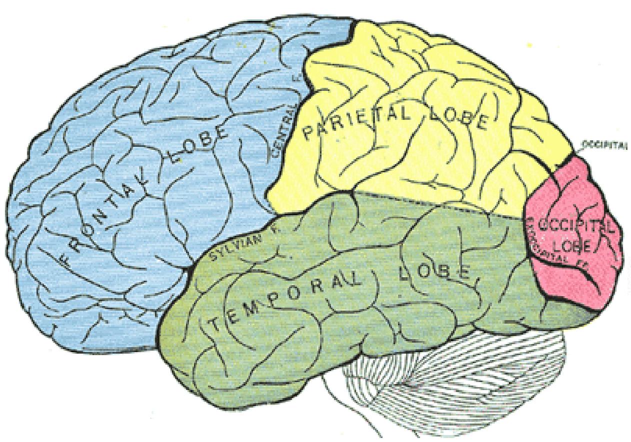

Figure 3: The surface of the cerebrum is often divided Into four lobes based on geometry and function. [7]

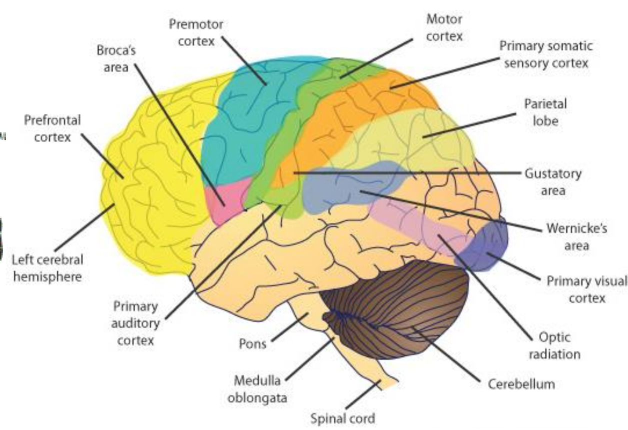

Figure 4: There are various sections of the brain that are responsible for everyday human function. These Primary areas of function are made up of grey matter And connected by white matter. [8]

The brain is very complex in structure and function. Though very little is known about the human brain, the advent of nuclear magnetic resonance (NMR) technology has brought a greater understanding of the human brain. Figure 3 shows that the surface of the brain is often divided into four lobes: frontal, parietal, temporal, and occipital. Each of these lobes is associated with a different function, as shown in Table 2. Furthermore, certain areas of these lobes are responsible for primary areas of function, as shown in figure 4.[9] These areas are known as the motor cortex (frontal), somatosensory cortex (parietal), primary visual cortex (occipital), primary auditory cortex (temporal), Broca's Area (frontal), and Wernicke's area (parietal). Broca's area has been associated with the production of language, whereas Wernicke's area has been linked with understanding language.[10]

The brain is composed of grey and white matter. Grey matter consists of either nerve cells connected by dendrites or bundles of unmyelinated axons. Grey matter makes up the convoluted outer layer of the cerebrum and the cerebellum. Each major area of function is comprised primarily of grey matter. White matter forms the many tracts within the cerebrum and cerebellum. It consists primarily of myelinated axons and dendrites. White matter can be thought of as a massive computer network. It transfers information to and from the various parts of the brain and connects the brain to the rest of the central nervous system.[9]

1.4. Project Overview

In 2008, Sung Kwon created an accurate three-dimensional model of the human brain. He was only able to differentiate between white and grey matter, however it was an excellent model that laid the foundation for this research.[11] What makes this research project unique is that the model accurately shows which areas of the brain are responsible for each particular function, as well as how those areas are connected. The left hemisphere of the brain shows each of the primary areas of function. Each of these areas are color-coded to differentiate one from the other. The right hemisphere of the brain shows the various white matter tracts' anisotropy using Diffusion Tensor Imaging (DTI) data. This hemisphere shows which areas of the brain are connected to each other. The brain was constructed using MRI and DTI images.

2. Procedure

2.1. Data Acquisition

The MRI images were supplied by the Center for Advanced Magnetic Resonance Imaging (CAMRI) at Northwestern University. The MRI scan was performed using a Siemens 3 Tesla TIM Trio scanner. The MRI scan contained 141 axial slices of a human brain with an image resolution of 256 x 256 each. Each slice was 1mm thick. Each of the primary areas of function was isolated from these MRI scans to form new images. DTI scans were also taken of the right hemisphere. Originally in a red-green-blue (RGB) color format, the images were converted into grey scale images based on the red, green, and blue channels of each image. Each image set was saved in a PNG file format.

2.2. Data Analysis

Mimics software was used to produce a three-dimensional model of the human brain; however Mimics does not have the capability to process images saved with a PNG file format. As a result, a scripted image processor was used to convert each of the images to a TIFF file format. The images were then compiled using Mimics Software's new project wizard. The region of interest was isolated by creating a mask with grey scale threshold values between 107 and 254. The region growing feature was used to remove tissue that was not connected to the brain. Portions of the skull and peripheral tissues with similar grey scale values to the brain tissue were removed manually by using the edit feature. This brain model was used as a foundation for the complete model. The primary area of function and diffusion tensor images was overlaid onto it.

The MRI images of each anatomical area of the brain did not match up well enough with the base brain model. This obstacle was overcome by creating a new mask for each part on the original brain scan. By using the contour lines of the anatomical images as a reference, the edit feature was used to define each of the brain's primary areas of function to the new masks. These new masks were overlaid onto the original brain scan images. A three-dimensional image was calculated to check the progress and accuracy of the masks.

The DTI data was also compiled using Mimics software. The blue channel images were used for the project. Masks were created for each of the DTI's colors. These masks were defined by three equal threshold ranges on the image's grey-scale. Blue was defined from 0 to 84, green between 85 and 169, and red from 170 to 254. These masks were overlaid onto the base brain model.

Each of the finished masks was loaded into the same project file. Many of the masks overlapped. Since the Z Corp printer's software would likely have problems with the overlap, Boolean operations were used to remove the areas of the base brain mask that overlapped with the other masks. Smoothing operations removed any remaining roughness. The masks were exported as stereolithography (STL) files to be processed in Magics. In Magics, the right hemisphere was sliced in the sagittal plane to show the interior of the brain and the white matter tracts produced by the DTI masks. Three slices were made: one where the right hemisphere meets the left hemisphere and two more in the middle of the right hemisphere. Cylindrical magnets were used be used to hold these slices together, so Boolean operations removed cylindrical sections out of each of the slices interior surfaces. The magnets have a radius and height of 1/16 inches. The masks were then exported to the Z Corp printer's managing software for production.

2.3. Production

The Z Corp printer was chosen for its color-printing ability. In order to differentiate between each of the brain's primary areas of function and white matter tracts, color coding was necessary for the model. A 1:1 scale model of the brain was printed with a layer thickness of 0.1 mm. While the model was being infiltrated, the 1/16 inch magnets were inserted into each of the right hemisphere's slices.

3. Results

The completed model of the brain depicts each of the primary areas of function as well as the white matter tracts in high detail. However the model is diminished by the surface finish and its fragile nature. The left hemisphere, figure 5, portrays the primary areas of function. Broca's area (magenta), motor cortex (green), somatosensory cortex (purple), auditory cortex (cyan), and Wernicke's area (yellow) are all displayed on this side of the model. Figure 6 displays the anterior of the brain where the visual cortex (orange) is located. The right hemisphere, figure 7, portrays the DTI data. Anisotropy is represented by red (left→right), blue (superior→inferior), and green (anterior→posterior). Figure 8 shows the DTI data inside the right hemisphere of the brain.

Figure 5: The left hemisphere of the finished brain model. This hemisphere depicts the primary areas of function.

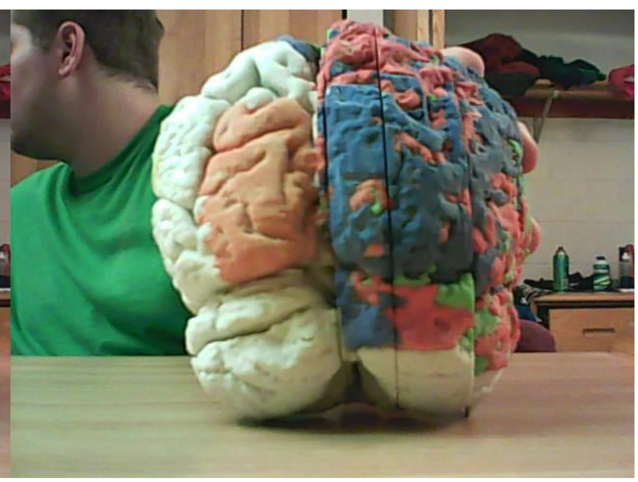

Figure 6. Anterior side of the brain model. This side displays the visual cortex and DTI data.

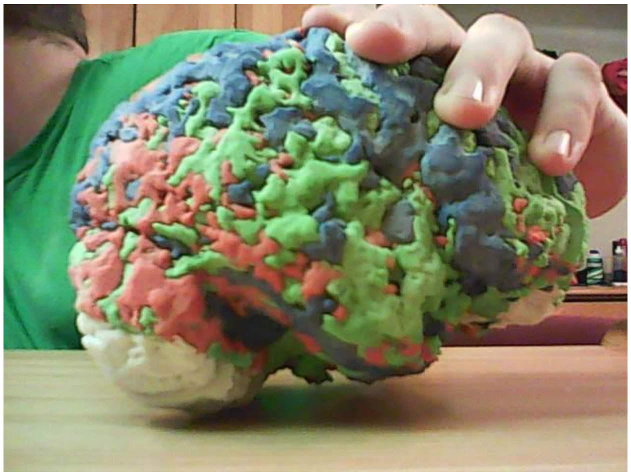

Figure 7: The right hemisphere of the finished brain model. This hemisphere depicts the DTI data and white matter tracts

Figure 8: Slice in the middle of the right hemisphere. These two surfaces are held together by magnets.

4. Discussion

The creation of a model such as this is very unique. This research endeavor is the first time that rapid prototyping has been used to create an accurate three-dimensional replica of an actual human brain that depicts the primary areas of function and white matter tracts using MRI technology. As a result, human error has been kept to an absolute minimum. The edit feature in Mimics was only used to remove tissue that was obviously not brain matter, and each of the primary areas of function were well defined by an expert. Free-form editing was considered to refine the replica; however it would have opened up the probability of human error by far too much, so the concept was abandoned.

The model is also unique for its potential to be used as a platform for education on multiple different levels. The accuracy and attention to detail make it an excellent tool for teaching students with an interest in neurosciences. At the same time, the use of color and simplicity would make it possible for a high-school teacher to use it as a tool in an introductory biology course.

The model's potential in education goes hand in hand with its potential in the hands of a neurosurgeon. Though a patient's trust in a doctor usually starts at a generic level, it can be refined in the absence of a bad experience.[1] Traditionally trust correlates with effective knowledge transfer.[12] The model would allow a neurosurgeon to describe the brains anatomy and how it functions to people regardless of educational background. A neurosurgeon would also be able to give a more in-depth description of a person's disorder and describe the goals of an impending surgery using the prototype. It would allow the patient to see, or even touch, the human brain's anatomy and function first-hand rather than having to conceptualize what the surgeon is explaining. A patient will hopefully gain more knowledge from such a presentation, and therefore trust his/her surgeon more.

5. Conclusion

In this research, a process was laid out for developing three-dimensional model of the human brain using rapid prototyping. This model is a great tool for teachers and neurosurgeons alike. It details the primary areas of function and the white matter tracts throughout the brain. MRI images were compiled and refined using Mimics software to produce a three-dimensional computer model. It was printed using the Z Corp color printer.

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