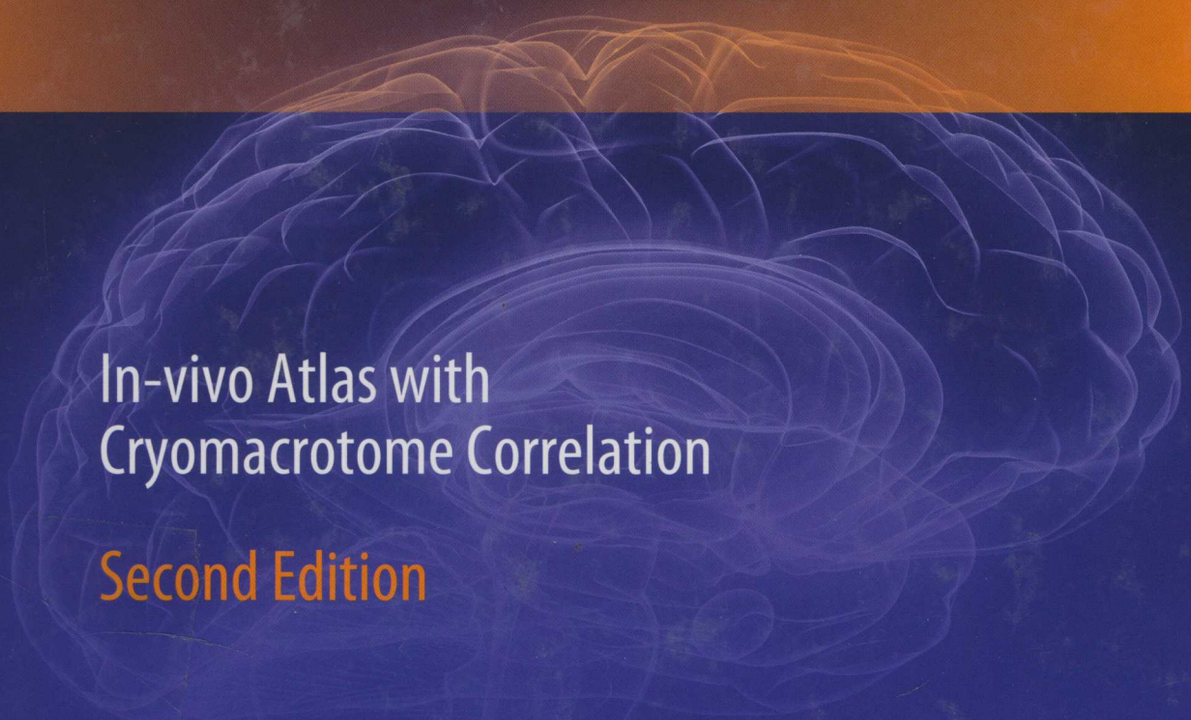
Zang-Hee Cho
Editor

7.0 Tesla MRI Brain Atlas



In-vivo Atlas with
Cryomacrotome Correlation

Second Edition

Springer

Zang-Hee Cho
Editor

7.0 Tesla MRI Brain Atlas

In-vivo Atlas with Cryomacrotome Correlation

Second Edition

Editor
Zang-Hee Cho
Neuroscience Research Institute
Gachon University
Incheon
Korea
Republic of (South Korea)

ISBN 978-3-642-54397-5 ISBN 978-3-642-54398-2 (eBook)
DOI 10.1007/978-3-642-54398-2
Springer Heidelberg New York Dordrecht London

Library of Congress Control Number: 2014957396

Printed on acid-free paper

Springer is part of Springer Science+Business Media (www.springer.com)

7.0 Tesla MRI Brain Atlas

This work is dedicated to Dr. Gil-Ya Lee,
founder of the Neuroscience Research Institute,
Gachon University of Medicine and Science.

New Brain Atlas

Ultrahigh-Resolution Human Brain Maps, Obtained by 7.0 T MRI In Vivo and Cadaver Cryomacrotome, Based on New Reference System

7.0 T MRI Imaging

**Zang-Hee Cho, Ph.D[1,8]

Young-Bo Kim, MD, Ph.D[1]
Jae-Yong Han, Ph.D[1]
Hoon-Ki Min, M.Sc[1,8]
Sang-Han Choi, M.Sc[1]

Cryomacrotome Imaging

*Min Suk Chung, MD, Ph.D[2]

Jin Seo Park, Ph.D[5]
Jun-Won Lee, B.S.[2]
Hyo-Seok Park, B.S.[5]
Dong Sun Shin, Ph.D[2]
Dong-Hwan Har, Ph.D[6]
Do-Hee Cho, M.Sc.[6]

Neuroanatomy

*Je-Geun Chi, MD, Ph.D[3]

Chan-Woong Park, MD, Ph.D[1]
Cheol-Wan Park, MD, Ph.D[1]
Young-Bo Kim, MD, Ph.D[1]
Jong-Min Lee, Ph.D[7]
James H. Fallon, Ph.D[8]

Neurology

*Duk L. Na, MD, Ph.D[4]

So-Young Moon, MD[2]
Sang Won Seo, MD[4]
Sook-Hui Kim, MD[4]
Seok-Min Go, MD[4]

**Principal Author

*Coprincipal Authors

1. Neuroscience Research Institute (NRI), Gachon University of Medicine and Science, Incheon, Republic of Korea
2. Department of Anatomy, Ajou University School of Medicine, Suwon, Republic of Korea
3. Seoul National University College of Medicine, Seoul, Republic of Korea
4. Department of Neurology, Samsung Medical Center, Sungkyunkwan University School of Medicine, Seoul, Republic of Korea
5. Department of Anatomy, Dongguk University College of Medicine, Gyeongju, Republic of Korea
6. Graduate School of Advanced Imaging Science, Multimedia & Film, Chung-Ang University, Seoul, Republic of Korea
7. Department of Biomedical Engineering, Hanyang University, Seoul, Republic of Korea
8. University of California, Irvine, School of Medicine, Irvine, CA, USA

Foreword

I write this Foreword in gratitude to Professor Zang-Hee Cho, one of the great innovators and proponents of progress in the field of magnetic resonance imaging. The "New Brain Atlas," prepared by Professor Cho and his colleague at the Neuroscience Research Institute, Gachon University of Medicine and Science, will set new standards in neuroanatomy. It is indeed fascinating to browse through this atlas, which has been produced both from cadaver macrotomes and from 7.0 T magnetic resonance images (MRI). Indeed, this volume illustrates the great power and usefulness of modern MRI, which has been developed and perfected during the past decades by numerous scientists and engineers all around the world. The research group of Professor Zang-Hee Cho was instrumental in these astounding developments.

Studying more closely the pictures in the Atlas reveals a wealth of details of the brain stem and midbrain structures, which were once thought impossible to visualize in vivo. I am convinced that these remarkable achievements are a triumph of modern advanced MRI and medical technology in general. MRI has already been very helpful in the past for localizing early tumors and receiving timely information on the formation of strokes and spinal cord degeneration. MRI is now entering a new era of finding deformations and atrophy of the hippocampus, which many experts believe to be the main causes of Alzheimer's disease and epilepsy. The new ultrahigh-field MRI investigations are not only capable of imaging the minute details of the mentioned deformations and atrophy of the hippocampus but are also in a position to distinguish the normal and abnormal neuromorphology of the substantia nigra, the key neuronal site for major movement disorders such as Parkinson's disease . In addition to all those fine structures of the brain—the most intricate of all in our human body—it can be used for finding the sites of therapeutic targets such as the subthalamic nucleus and globus pallidus, previously impossible to find in vivo, serving the important deep brain stimulation (DBS) surgery. Today, it is possible to rely on the cadaver brain atlas and apply computer fitting to low-resolution MRI or CT images, taking advantage also of the microelectrode molecular probe. The same procedure could be applied in the field of submillimeter precision neuroanatomy in vivo.

In close analogy to the discoveries with astronomical telescopes, where each time we are capable of improving resolution and are finding new galaxies previously unknown, in the same manner we experience new revelations in medicine and biology by improving our instruments. Especially in brain science, there is still much to be discovered, and much is waiting for interpretation and understanding at the macroscopic

and morphological levels as well as on biomolecular and cellular grounds. Magnetic resonance studies, especially ultrahigh-field MRI, will continue to play a fundamental role in this field. I am convinced that the NEW BRAIN ATLAS will provide many answers and new inspiration for further experimental studies. It is thus a very valuable addition to any respectable library of medicine and an inexhaustible source for specialists and students.

Zurich, September 9, 2008

Richard R. Ernst*

ETH Zürich
Laboratorium für Physikalische Chemie
Zürich, Switzerland

*Professor Ernst received the Nobel Prize in Chemistry in 1991 for his contribution to the development of Fourier Transform NMR, which not only revolutionized modern NMR but is also the backbone of MRI—magnetic resonance imaging—to which mankind owes so much today.

Preface

As is true in any scientific field, the advances in neuroanatomy have been made possible by the improvement of the tools available to researchers. These tools have undergone revolutionary changes in the past 100 years. When one of the first Nobel prizes was awarded to neuroscientists Camillo Golgi and Santiago Ramon y Cajal in 1906, the main research technique available to neuroscientists was staining or coloring nerve cells and observing the effect either visually or under an optical microscope. When various forms of much more powerful scanning electron microscopy were introduced later in the twentieth century, they were immediately applied to neuroanatomy, thus greatly benefiting it.

Among all tools and techniques available in neuroanatomy, imaging techniques allowing the researcher to study the human brain in vivo play a special role. These imaging techniques include CT scanners using X-rays, the nuclear imaging techniques PET and SPECT, and MRI. Recent advances in MRI, especially those in the area of ultrahigh-field (UHF) MRI such as 7.0 Tesla (T), have attracted significant attention in the field of brain imaging for neuroscience research as well as for clinical applications. Many physical and engineering problems related to UHF MRI are yet to be resolved. For example, due to the increased radio frequency (RF) in UHF MRI, the RF field suffers from inhomogeneity and introduces image distortions. Nevertheless, 7.0 T MRI has begun to reveal unseen images of numerous fine structures in the human brain in vivo. With these images providing drastically improved contrast as well as resolution, researchers have begun to demonstrate that MRI is indeed capable of showing very small brain structures. These structures include the subthalamic nucleus, the substantia nigra and its surroundings in the midbrain area, as well as various abnormalities. Since these new images began to reveal numerous, strikingly fine structural details in the human brain in vivo, many experts in the field began to wonder how high-resolution MRI would affect modern medicine and neuroscience research as a whole.

The advances in neuroanatomy are no longer of interest only to the anatomist. In the nervous system, structural organization is most essential in understanding functional concepts. Therefore, a solid understanding of the subtle details of the brain structure became important for a lucid communication among clinicians, scientists, and other specialists working in the field of neuroscience and clinical medicine. The wealth of information offered by modern imaging techniques made it imperative for the interpreter of the images to be thoroughly familiar with the anatomical minutiae of the brain. A specialized knowledge of the brain anatomy is a prerequisite, which goes beyond merely that of gross anatomy, including a complete familiarity with the brain in sections in various planes. It is no longer adequate to use such vague terms as

the "frontoparietal region" or "basal ganglia." The gyrus or a specific nucleus involved in the pathological process should be precisely defined and described.

New applications of neuroimaging arise almost every day. It used to be important just to locate and determine the extent and the exact position of an intracranial space-occupying lesion. Now, that goal has been extended to define non-neoplastic lesions, i.e., cerebral hemorrhage, edema, and infarction as well as demyelinating diseases and various neurodegenerative processes.

Let us consider the following analogy: When a new generation of giant cosmic telescopes became available to astronomers, the significance of these new tools was not limited to an increased resolution or to clearer and more informative images. They brought about a new level of understanding of the universe. Similarly, with increased field strength in MR imaging and hence with increased resolution, we began to obtain images of unprecedented resolution and contrast that had not even been anticipated. Improvements came from several different avenues besides the obvious signal-to-noise improvement predicted by the laws of physics. We began to see various changes in physical parameters such as changes in T1 and T2 relaxation times or, rather, in their combinations. On another front, we have witnessed great advances in the imaging of human cadavers using cryomacrotome with increased sophistication and techniques. Now, one can create cadaver images of unprecedented resolution and contrast with markedly conserved brain structures. With all these super-resolution images that can be obtained with UHF MRI such as 7.0 T and the advanced cryomacrotome technology developed recently, we thought that development of a New Brain Atlas would be an important and timely contribution to the medical and neuroscience community.

Therefore, in this book, we made a set of ultrahigh-resolution brain images obtained from a cadaver by cryomacrotome and by reconstructed partner images (sagittal and coronal), together with corresponding in vivo ultrahigh-resolution human brain images obtained by 7.0 T MRI. Thus, we have been able to obtain a complete set for the entire brain atlas with axial, sagittal, and coronal images of the cadaver and a 7.0 T MRI of the in vivo brain. In this book, we applied a reference system that can be applicable to both cadaver gross anatomy and MRI anatomy. In addition, a system of Cartesian axes is defined on the midpoint of the central intercommissural distance with coordinates expressed in mm and +/− in axial, coronal, and sagittal planes. This system will enable us to standardize the sectional planes and the levels of the slices in any brain that may be encountered in practice.

We have also applied a "reference adjusted unit," which is designed for the reader, the MRI user, to predict the structure to be seen at any level of plane regardless of the absolute size of the brain that is obtained by clinical MRI. We expect that our image-numbering system could contribute to the establishment of clinicopathologic mapping of the human brain through massive global feedback of related information. Eventually, we hope that this book will serve as a roadmap both in the clinical arena and for neuroscience researchers for years to come.

Zang-Hee Cho
Min Suk Chung
Je-Geum Chi
Duk L. Na

Preface to the Second Edition

Since the publication of the first edition of this Atlas, we were convinced that the precise localization of the reference system was much in need for easier identification; therefore, we have integrated a new coordinate system in this new edition.

In this revised edition, therefore, we have put a coordinate matrix in every image, both cadaver and MRI, based on a central intercommissural line to make a more convenient approach for the readers. By doing this, readers would be able to compare their images with those of others based on the same coordinate system.

The other major revision is that we have reduced the book size for handiness without reduction of real brain size of the original images seen in the first edition. Because of the reduction of the book size, all the labels are abbreviated and explained at the bottom of every image.

As we are also working on the 7.0 T MRI Tractography Atlas, we have learned many new fiber tracts "hidden" in the white matter, and therefore, some of the tracts are newly labeled in this Atlas based on cadaver and MRI images.

For this edition, we would like to appreciate Dr. Jin Seo Park for his critical review of the revision and Sang-Han Choi for editing the manuscripts.

Zang-Hee Cho
Min Suk Chung
Je-Geum Chi
Duk L. Na

Introduction

Reference of Brain Image Setting

The cadaver brain used in this atlas was designated as the "reference" brain; this is because this brain was used as a reference to be compared with brain images obtained by 7.0 T MRI. However, note that the cadaver image does not mean the "standard" brain image. All the slices are shown in a 2 mm interval (or distance) starting from the zero point in the axial and coronal axis images, ±2 mm from the center, with the anterior commissure (AC) and posterior commissure (PC) line being aligned as the midline of the axial slice and the center point of the AC-PC line as the midline of the coronal slice. In sagittal slices, both cadaver and MRI images start from ±2 mm from the center point, with the AC-PC line being aligned to the midline.

Images of the cadaver (reference) brain were juxtaposed with 7.0 T MRI images of a living subject to compare the anatomy of the brain. In each set of images, the cadaver (reference) brain image is placed on the left page while the corresponding MRI image is placed on the right page to facilitate a comparison. We have attempted to match the MRI brain images as closely as possible with the cadaver images. This type of presentation will facilitate correlational visualization of the anatomy of the reference image with that of the corresponding MR image.

Orientation of Brain Images

Orientation of Image Sections and Planes

Even though several common protocols exist, there is no fully defined standard for the orientation of sectional images up to now. There has been considerable confusion about axial images, for example. It is true that all the coronal images in clinical practice are now viewed as shown in Fig. 1 (i) as if the examiner and the patient viewed each other face to face. The left side of the sagittal image is seen on the right side as if we looked face to face (See Fig. 1 (ii)). The axial-view images are also shown as if the examiner looked at a patient from the bottom up.

This type of arrangement of axial-, sagittal-, and coronal-view images has been widely adopted in recent years. Therefore, we will follow that convention in our New Brain Atlas also (see Fig. 1).

Standard of the Sectional Brain Image Planes and Sizes

For the sake of convenience, we have presented all the images of the reference brain as well as the MRI brain in our atlas on the scale of 1:1. In other words, both cadaver and MRI images are all in the actual metric base frames and systems except for the expanded images. It is known that the average shrinkage of the cerebral hemisphere resulting from freezing is approximately 1 %; therefore, that shrinkage may be neglected. For the reader's convenience, we have displayed a few selected view images with expanded views to visualize the details of the images. We believe that the expanded or magnified images provide information not previously available.

Extracerebral reference lines have been generally used in radiography, computed tomography (CT), and MRI studies. In 1962, the World Federation of Radiology defined Reid's base line as the line between the infraorbital margin and the upper margin of the external auditory meatus. In radiological practice, however, the canthomeatal line has been more frequently used. The canthomeatal line is the line between the lateral canthus and the central point of the external auditory meatus. The line is tilted approximately 10° nose up with respect to Reid's base line, which approximately parallels the "true" horizontal line. However, intracerebral reference points have not been standardized. In stereotactic surgery, the foramen of the Monro-posterior commissure line or the anterior commissure–posterior commissure line has been used. Schaltenbrand et al. and Talairach et al. suggested that anterior and posterior commissures might be considered to have a constant relationship with the deep cerebral structures. They proposed using the line between these two structures as the basic reference line.

In our New Brain Atlas, the horizontal plane passing through the central point of the anterior commissure (AC) and the posterior commissure (PC) of the reference brain is designated as the reference axial plane defined as the central AC–PC intercommissural line. This differs from the convention used in stereotaxy and functional MRI, where the tangential AC–PC line passes through the superior edge of the AC and the inferior edge of the PC (see Fig. 2).

The central AC–PC line is approximately 10° nose up with respect to Reid's base line. We thought, therefore, that the central AC–PC line is equivalent to the extracerebral canthomeatal line and can be used as an intracerebral reference axial line for the anatomical horizontal plane (see Fig. 3).

We have extended the concept of the central AC–PC line to the entire brain. We found that our AC–PC line is easy to define and independent of the sizes of the AC and the PC, which vary from 3 to 6 mm and from 2 to 4 mm, respectively. We also found that our central AC–PC line is approximately parallel to the canthomeatal line. This line is approximately parallel to the "true" horizontal plane. We thought, therefore, that the central AC–PC line could be designated as an anatomical horizontal plane of the brain. This is close to the normal position of the head in the living subject.

In our book, as mentioned earlier, we have adopted the system of Cartesian coordinates, where the x-axis is defined by the central AC–PC line and by the midpoint of the intercommissural distance as $x = 0$. The horizontal plane is defined as an axial plane, i.e., an x-y plane, which contains the AC–PC line at the center, with a positive sign superiorly (axial plane) and a negative sign inferiorly. The y-z plane, which contains the AC–PC line, is defined as the center plane of the sagittal planes. Similarly for the coronal plane, the x-z plane is assumed, and those planes anterior to the midline plane are set with a positive sign, while posterior planes are noted as negative. As implied, the central coronal image is defined as the image plane at the center of the AC–PC line. For the sagittal-view images, those on the left side are set as negative, while those at the right are denoted as positive. The midline image is set with the longitudinal cerebral fissure as the origin. In this book, the axial planes are sequenced from superior (1) to inferior (2), whereas the coronal planes progress from anterior (1) to posterior (2). The sagittal planes are arranged from right (1) to left (2) (see Figs. 1 and 3).

Adjustment of the MRI Brain to the Reference Brain

In order to easily accommodate the anatomical images of the reference brain to different sizes of in vivo brain images that will be obtained by an MRI, we have introduced a "Reference Adjusted Unit (RAU)" noted in millimeters (mm). The RAU (mm) represents the MRI image, which resembles the cadaver images. For example, the thalamus lies at the same RAU for both a given MRI and a cadaver image but not in the actual mm scale given in the atlas.

Recognizing that the actual measurements of brains are subject to individual variations, all three standard planes of the MRI in this atlas are generated from the same individual, a 27-year-old healthy man. The actual lengths in millimeters from the reference points are shown in every slice of MRI in this atlas. Their actual measurements were shown in mm, and the corresponding RAU in mm was shown as No. X. We put the actual mm values in parenthesis next to the RAU number.

For instance, "Axial-MRI: No. 162 (166 mm)" means "an axial MR image that is located at 66 mm superior to the reference axial plane (AC–PC plane), which also corresponds to the cadaver (reference) brain image at 62 mm superior to the reference axial plane, which is "No. 162." A similar compensation technique is applied to individual variations in both the coronal and sagittal planes.

Terminology and Labeling

Different authors use different names for the same brain structures. In this atlas, in an attempt to use the most up-to-date anatomical terminology, we have adopted the standards used in *Terminologia Anatomica* by the International Federation of Associations of Anatomists published in 1998. It supersedes the previous standards in *Nomina Anatomica*.

Many commonly used positional and directional notations are abbreviated. For example, ant. stands for anterior, post. for posterior, sup. for superior, inf. for inferior, lat. for lateral, med. for medial, int. for internal, and ext. for external.

Every identifiable anatomical structure was labeled on both the cadaver brain and the MRI brain. Because of the structural difference between the right and left hemispheres, important structures were labeled on both sides. The cerebral gyri were generally labeled at the white matter core rather than the cortical surface. In the brainstem, the major nuclei and tracts are labeled in the expanded views. We have also divided all the brain sections into major anatomical compartments, i.e., frontal lobe, temporal lobe, parietal lobe, occipital lobe, brainstem, and cerebellum, and also depicted the laterality such as right (R) and left (L). The structures that appear more than once were labeled in number (this does not apply in expended views).

Data Collection System for Clinicopathologic Brain Mapping

If a clinicopathologic mapping of the human brain was available, it would be a useful supplementary source of information for clinical diagnosis by neuroradiologists as well as for the scientist in neuroscience research. We have to admit, however, that this clinicopathologic brain mapping could only be established by collecting massive amounts of data from clinicians, particularly radiologists handling MRI, scattered throughout the world. Through the collaboration and unselfish support of radiologists and clinicians, we might be able to establish a valuable database that could benefit everyone in this field.

For instance, a focal lesion of any size could be traced via the image-numbering system that is presented in this New Brain Atlas. First, all MR images should be produced based on x-, y-, and z-axes at the midpoint (0, 0, 0) of the anterior commissure and the posterior commissure so that those images are consistent with our atlas in Cartesian coordinates. Images are then normalized to our New Brain Atlas. The determination of a location of the pathological finding could then be possible simply by using the grid system consisting of coronal (x), sagittal (y), and axial (z) section lines (Fig. 3). The target point is obtained, then would be indicated as single dot, or indicating a midpoint of a target area, identifying a lesion, for instance, in three dimensions. For instance, C(y) – 10, S(x) + 28, A(z) – 20 indicates axial 20 mm inferior to the AC–PC plane, coronal 10 mm posterior to the midpoint of the AC–PC distance, and sagittal 28 mm right to the midsagittal plane. This three-dimensional location of the lesion would be reported to the NRI center with pertinent neurological findings, together with an identification of the patient (see, e.g., Figs. 4 and 5).

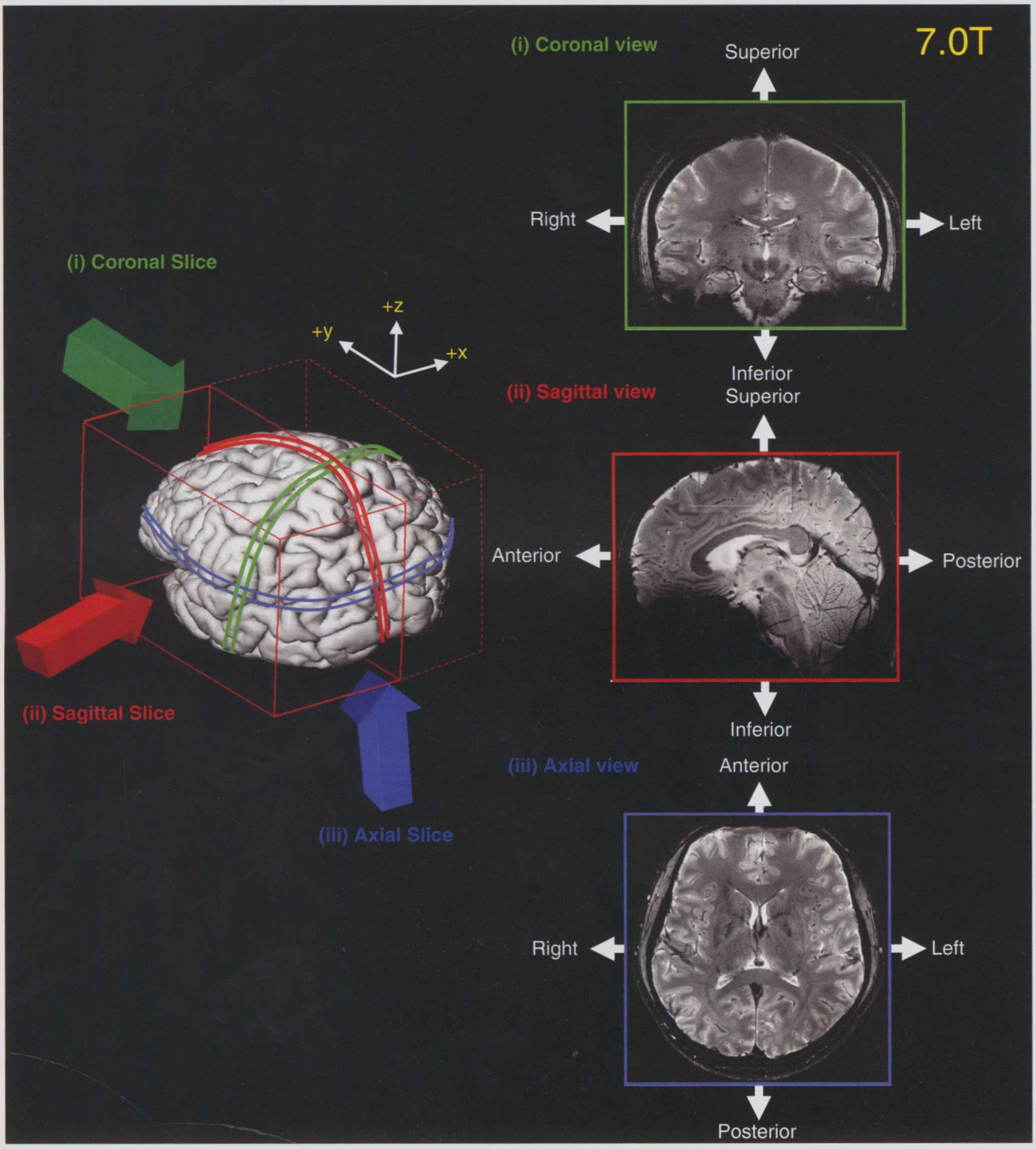


Fig. 1 Views and directions of the brain image

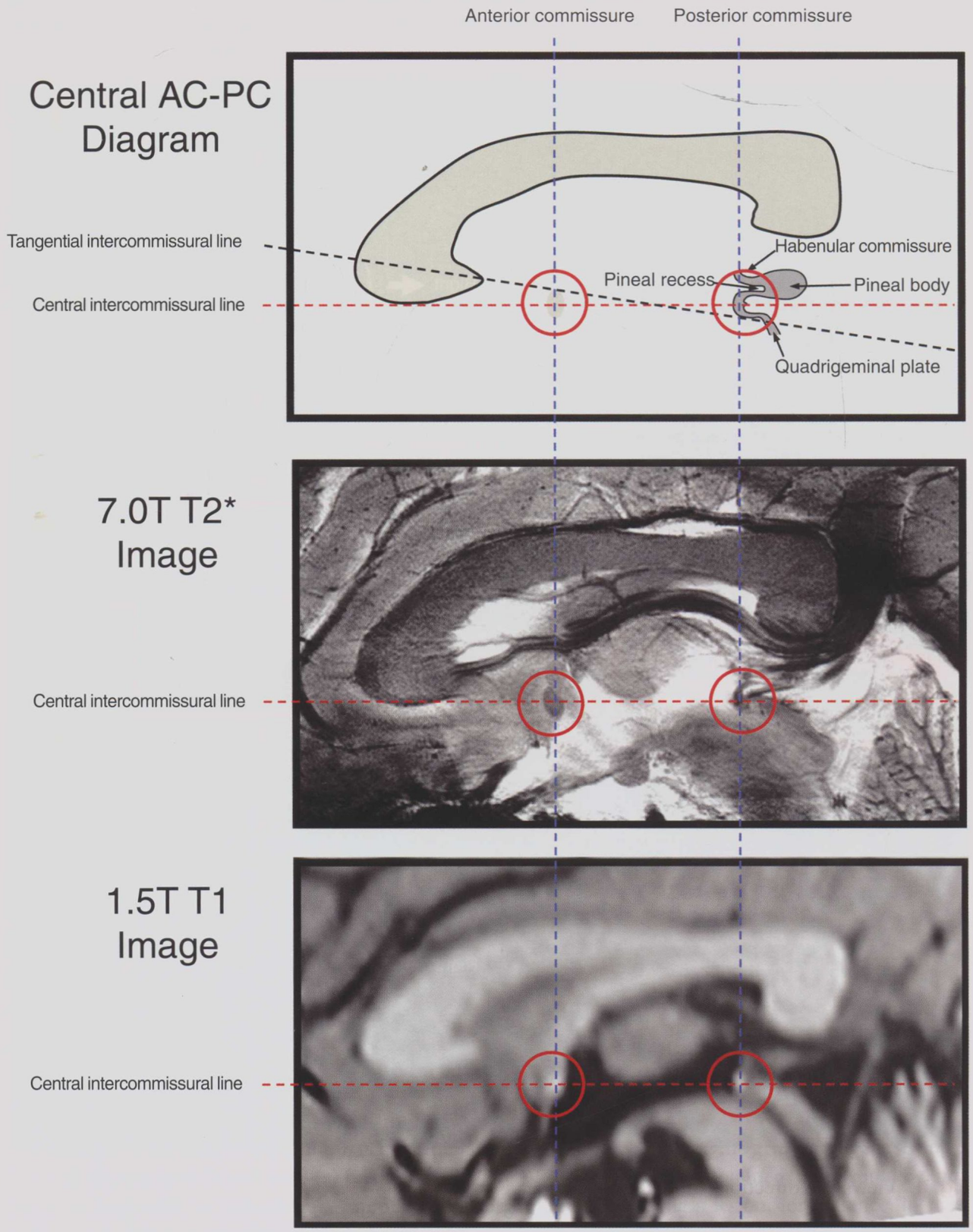
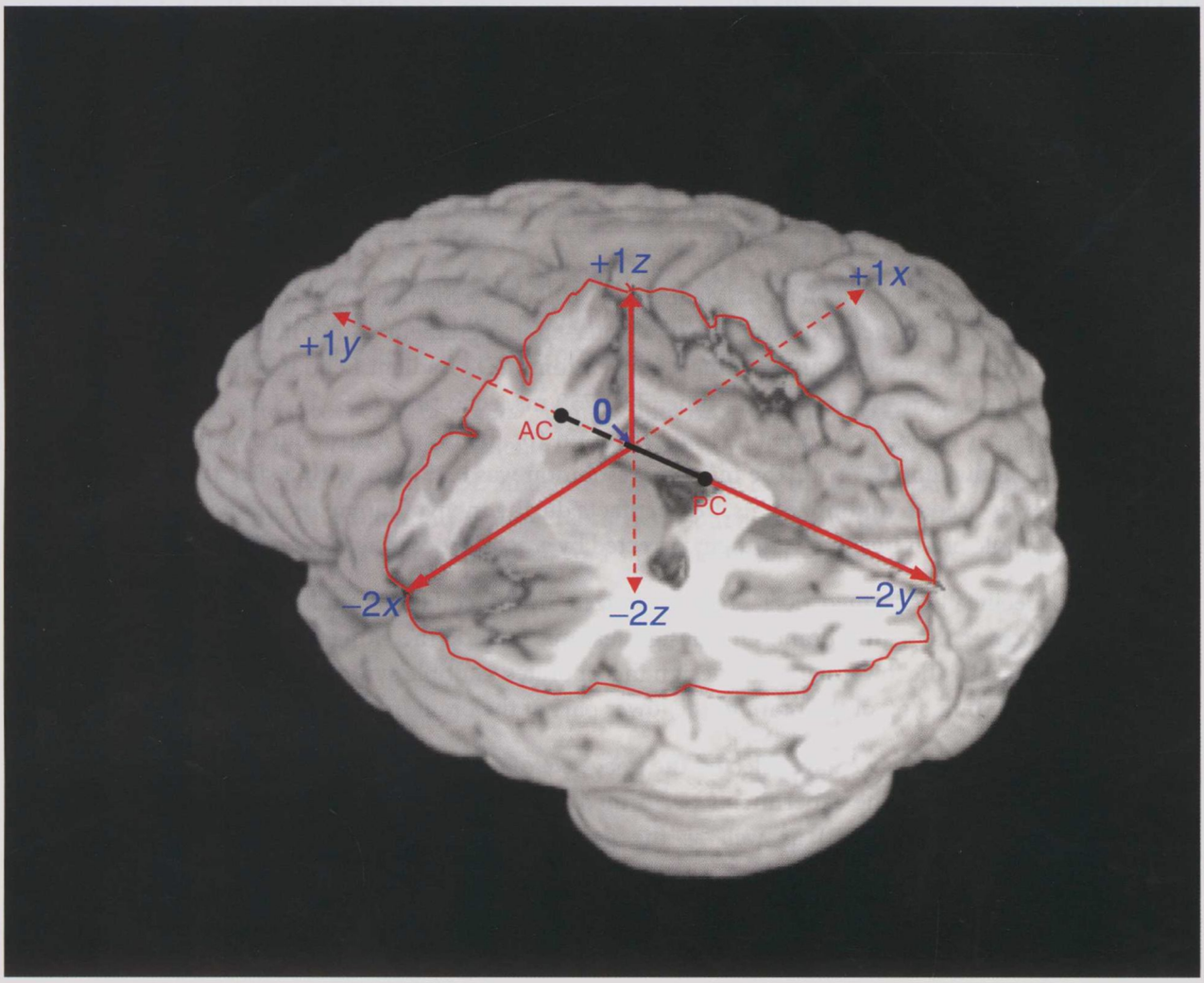


Fig. 2 Definition of central intercommissural line (central AC–PC line)



Sign of data slice

Coronal(x)	Anterior side of center of AC-PC line	+y (+)
	Posterior side of center of AC-PC line	–y (–)
Sagittal(y)	Right side of AC-PC line	+x (+)
	Left side of AC-PC line	–x (–)
Axial(z)	Superior side of AC-PC line	+z (+)
	Inferior side of AC-PC line	–z (–)

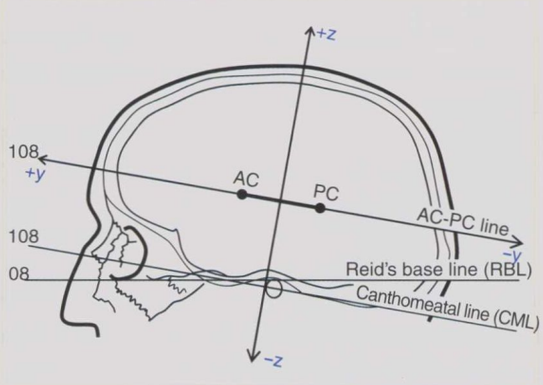


Fig. 3 Standardization and data set