USA
- Oregon Health, Portland
- Massachusetts General Hospital, Boston
- Center for MR Research, Minneapolis, Minnesota
- University of Pittsburgh Medical Center (UPMC), Pennsylvania
- Hospital of the University of Pennsylvania (HUP), Philadelphia
- New York University, New York City

Germany
- Erwin Hahn Institute for Magnetic Resonance, Essen
- Research Center Jülich
- Leibnitz Institute for Neurobiology, Magdeburg
- Max Planck Institute, Leipzig
- German Cancer Research Center (DKFZ), Heidelberg
- Max Planck Institute, Tübingen
- Max-Delbrück Center, Berlin

France
- Comissariat à l'Énergie Atomique (CEA), Paris

Switzerland
- Center for Imaging in Biomedicine, Lausanne

Austria
- Medical University of Vienna

South Korea
- Neuroscience Research Institute, Gachon University of Medicine and Science, Incheon

A New Field, a New Frontier: 7 Tesla MRI

Ultra-high-field magnetic resonance is not for everyone, but for institutions with interest and expertise in both biomedical – especially neuroscience – research and MRI technology, Siemens MAGNETOM 7 Tesla is becoming a must-have. Siemens academic partners in the 7 Tesla-field are both helping to improve the technology and using this new system to see the body as it has never been seen before.

By Joanna B. Downer, PhD

Magnetic resonance imaging (MRI) has proven to be particularly useful in the brain. Its power comes in part from the numerous imaging parameters that can be exquisitely used to achieve soft tissue contrast, which is not possible with any other imaging modality. In recent years, the next technological advance in magnetic resonance (MR) has become available for human research: ultra-high-field MR systems, in particular Siemens MAGNETOM® 7 Tesla (T) with Tim® (Total imaging matrix) technology. Tim's unique technology with 32 independent receiver channels enables optimized usage and maximized output of ultra-high-field MRI systems.

With ultra-high-field MR, a whole host of applications becomes possible in research on the human brain, including charting the effects of brain activity on important molecules in the brain and mapping the brain's anatomy in a way not even possible by dissection.

However, optimal settings for MR's many imaging parameters all depend on the strength of the static magnetic field, the human body being imaged, and the purpose of the image. These parameters range from the myriad ways to use the gradient magnetic fields that determine the imaging area, to the radiofrequency pulses and sequences that enable differentiating tissues.

Clearing the First Hurdle

"Over the last ten years, we've optimized all these parameters for the 1.5T MAGNETOM system," says Professor Zang-Hee Cho, Director of the Neuroscience Research Institute at Gachon University of Medicine and Science in Incheon, South Korea, and also one of Siemens collaborators for the 7T system. "For the 7T, everything is new."

Experts like Cho agree that one of the greatest challenges in developing and using a 7T system is managing the radiofrequency (RF) fields, which is more complicated at high magnetic-field strength than at low magnetic-field strength. In general, the problem with the RF field in ultra-high-field MR manifests as central brightening in an image of the human brain. "Because the human body influences the radiofrequency field, new approaches had to be found to achieve homogenous image contrast," says Franz Schmitt, Siemens expert on ultra-high-field MR.

Siemens and its first collaborators for the 7T system, Massachusetts General Hospital in Boston, worked together to develop a wide array of specialized, multi-channel RF 'coils' for 1.5T, 3T, and, most recently, the 7T system. Massachusetts General Hospital's 32-channel array coil is enabled by the Siemens unique Tim radiofrequency system with 32 independent receiver channels. The coil is worn by the imaging subject like a hood, providing the best signal-to-noise ratio. One example is the ultra-high resolution, only seen so far with the 7T system, says Schmitt, who is also involved with other ultra-high-field projects at Siemens, including a relationship with Commissariat à l' Energie Atomique (CEA) in Orsay, France, to develop an 11.7T whole-body system.

Cho and his team in South Korea have also been working hard to solve the RF problem; they have developed a series of coils for the head that use sensitivity encoding (known as Parallel Imaging) in order to improve contrast and resolution with reduced scanning time. Cho says their best results have come with their eight-channel and 12-channel Parallel Imaging coils, which extend from the top of the brain to the lower medulla and top of spinal cord. Now, Cho's team is developing more specialized RF coils for use with its Siemens 7T MAGNETOM, which has been up and running since January 2006. "We are making special angiocoils for angiography and visual coils for imaging the eye, especially the retinal plane," says Cho, who is particularly interested in visualizing the microvasculature of the brain. "The RF coil is the essential thing of ultra-high-field imaging, and we are putting a lot of effort into that."

Moving Forward Hand in Hand

Professor Rolf Gruetter is Director of the Center for Biomedical Imaging (CIBM) – a collaboration of the Ecole Polytechnique Federale de Lausanne (EPFL) with the University of Geneva (UNIGE) and the University of Lausanne (UNIL) and its associated research and teaching hospitals (CHUV and HUG) in Switzerland. Gruetter plans to tackle the RF problem as well, but by focusing on improving postprocessing and image reconstruction algorithms instead of RF coils. "The problem of RF on image quality is inherent to the high field, but with current technical advances outlined by the research community, I believe we will make great strides in dealing with this," says Gruetter. "There are good people working on it." RF coils and RF technology are two areas in which Siemens expects its academic research collaborators to continue to make important contributions, even as they also pursue research applications suited to ultra-high-field in the head and the rest of the body, such as musculoskeletal imaging, Schmitt says. Gruetter embraces

Professor Zang-Hee Cho (left) and Professor Rolf Gruetter (right) are pioneering 7T magnetic resonance imaging.

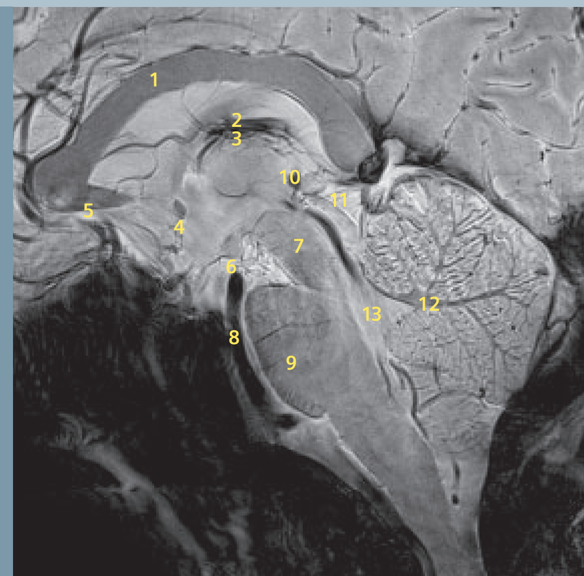
this vision of imaging and science progressing in parallel. "Our expectation is that we will be advancing imaging science very close to the neuroscience application," he says. "We'd like to develop the new tool in a context in which we are already addressing biomedical questions, instead of developing the tool and then seeing what we can study with it."
In many ways, Gruetter already knows what a 7T MR can do. He was part of the planning process that brought a MAGNETOM 7T to the University of Minnesota in 2005, and he conducted some of the first experiments using that machine. The 7T MR installed in Lausanne last fall, however, is different. To further advance his institution's neuroresearch projects, Gruetter wanted to be able to access his imaging subjects from outside the scanner, and thus was looking for a system with a short magnet. Through a relationship with both Siemens and Magnex, he has obtained more than that – the world's first 7T MRI scanner that is actively shielded, and has a zero helium boil-off rate.
The advantages of active shielding go beyond pure science. Gruetter's 7T brain MRI fits in the same space where a commercial 3T scanner would go, and the room doesn't need the extensive iron and concrete shielding required for a typical whole-body 7T MRI scanner, again saving space and construction costs. "The magnet was cooled down as of the end of last year," says Gruetter. "We have ramped up the field, and homogeneity is within specifications."
Gruetter's experience shows that 7T MR technology itself is still evolving four years after the first 7T images were obtained at Massachusetts General Hospital. 7T MR is not approved for routine clinical use, but is approved for research investigations in humans. There are currently 17 Siemens sites around the world with an ultra-high-field MAGNETOM.

Answering Old Questions – and New Ones

Gruetter and Cho are both starting their investigations in healthy volunteers, in part because 'normal' has yet to be defined on the 7T, which has better resolution and higher sensitivity than lower-field scanners. "We are actually preparing to make a brain anatomy book with one millimeter slices of the human brain

Ultra-high-field Brain Imaging

1 Corpus Callosum
2 Internal Cerebral Vein
3 Thalamus
4 Anterior Commissure
5 Anterio Cerebral Artery
6 Mammilary Body
7 Red Nucleus
8 Basilar Artery
9 Basal Pons
10 Pineal Gland
11 Superior & Inferior Colliculi
12 Cerebellum White Matter
13 4thVentricle



This high-contrast image of the brain stem shows exquisitely delineated smallest details in high resolution.

Courtesy of: Prof. Cho, Neuroscience Research Institute at Gachon University of Medicine and Science in Incheon, South Korea.

taken by 7T MR in the T2* mode," says Cho, whose 7T MR is coupled to Siemens highest resolution PET scanner, the high-resolution research tomography (HRRT). "We are working with neuroanatomists on the project, and they are all amazed with the new 7T images that we are producing. Some of the MR images are better than what they have seen using cadavers."
In particular, Cho says their 7T micro-angiography studies are revealing blood vessels that have never been clearly imaged before, adding that it will change classical angiography altogether since it is a noninvasive, in vivo technique without any contrast materials. He and his team are currently preparing to publish a report on the imaging of one hard-to-visualize microvessel. Although MR is capable of imaging in a number of ways, Cho says their best 7T images have a contrast based on T2*, which differentiates tissues from molecular interactions and local magnetic field nonuniformities. By contrast, T1 images use the longitudinal relaxation time of tissues, and T2 images use the transverse relaxation time of tissues.
In ultra-high-field MR, tissue T1 relaxation times are much longer than in lower MR fields. While this fact makes 7T ideal for angiography, it has confounded another of Cho's primary research goals – distinguishing white and grey matter and mapping the brain's connections. "The increasing T1 value at 7T makes it difficult to differentiate between grey and white matter," says Cho. "We think, however, that we should be able to overcome it."
Similarly, Gruetter is eager to establish a baseline for additional studies. His research focus has been on metabolic imaging of the brain, using a technique called magnetic resonance spectroscopy (MRS). MRS is the in vivo equivalent of nuclear magnetic resonance spectroscopy in that both reveal the identity and amounts of certain molecules in a sample as a result of how magnetic fields affect certain atoms in those molecules.
With 7T MR, Gruetter and his team can evaluate a panel of 17 molecules simultaneously to provide what he calls a neurochemical profile, and then see how brain activation changes that profile. The profile includes molecules involved in energy metabolism like glucose and creatine, neurotransmitters like glutamate and gamma-aminobutyric acid (GABA), compounds involved in cell growth like choline or in axon growth like N-acetylaspartate, compounds involved in osmoregulation like taurine and inositol, and molecules that are antioxidants, like glutathione and vitamin C. "At 7T, we expect to be able to measure such a profile with ten

percent precision in a very small volume, so we might be able to measure profiles within a structure like the substantia nigra or hippocampus, or even within multiple sclerosis plaques," says Gruetter. While Cho's microangiography research has important potential application to research in stroke and brain hemorrhages, Gruetter's work is also relevant to research in multiple sclerosis, Alzheimer's disease, brain tumors, and Parkinson's disease. "We are at the cusp of what is technologically possible, so we still need to push levels of understanding to know what normality means," says Gruetter, whose other ultra-high-field scanners include a 9T animal scanner and a brand-new 14T animal scanner.

Branching Out with 7T MR

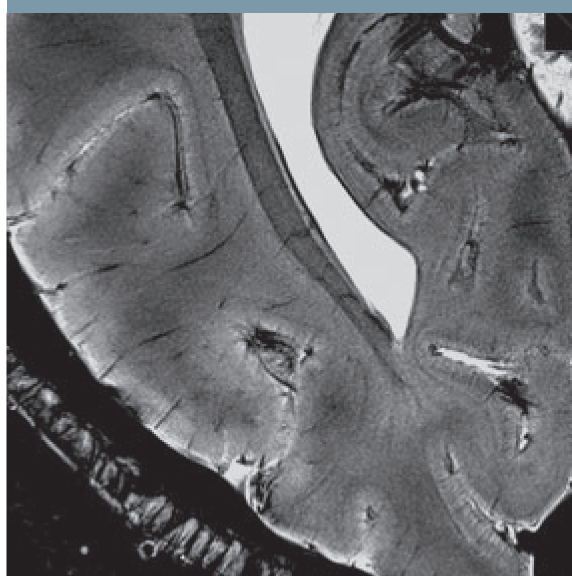
In addition to metabolic and molecular imaging, the 7T researchers in Lausanne will also pursue applications of functional imaging. Gruetter says he also hopes that the 7T will help illuminate the role of astrocytes in neurological disease and allow quantification of neurotransmitter release in the neuronal cleft and the study of its role in disease. One of his personal areas of research interest is understanding how the brain senses blood glucose levels. Gruetter and Cho are also expecting to expand the research applications at their centers through collaborations, and applications will likely expand beyond the brain for centers with the whole-body 7T. "There's a lot of interest in 7T, and there are lots of things going on," says Cho, who has given many lectures on their 7T experience in Southeast Asia and went to Australia in March 2007. "The nature of science is that we can rarely predict surprises we're going to run into, good or bad," adds Gruetter. "We can state some expected improvements with 7T – better sensitivity, specificity, blood flow imaging, functional imaging – but what they practically entail and what we can expect... well, we will see." Indeed, with Siemens technical support for backup, Cho, Gruetter, and Siemens other academic partners in ultra-high-field MR are going where few have gone before.

Highest Resolution MRI – ex vivo – ERC Islands

Courtesy of: B. Fischl, LL. Wald, M. Blackwell, Martinos Center at Massachusetts General Hospital, Boston, USA.

The hippocampus and the entorhinal cortex (ERC) are interconnected structures of the limbic system that are implicated in memory. The image shows a high resolution MR cut (100 x 100 x 100 µm) through the hippocampus and ERC. The lower section shows the ERC. The small white dots (shown in the cutout enlargement) resemble the ERC islands, a collection of 50 to 100 cells. They function as a pathway for memory management in the brain. The disappearance can be a biomarker for Alzheimer's disease.

7T 32-channel Array Coil developed at MGH for Pushing the Limits of Spatial Resolution on Tim-based 7T MR



Courtesy of: G. Wiggins, C. Wiggins, Martinos Center at Massachusetts General Hospital, Boston, USA.

This T2* weighted gradient echo image has a .22 inplane resolution and 1-millimeter slice thickness. The image shows a fantastic array of fine detail. Zooming in, it is possible to see the grey-white-contrast and many tiny blood vessels penetrating the cortex.
Lines which appear to follow fiber bundles can be observed, though the source of this contrast is still being debated.
Finally, the extraordinary contrast and resolution show structures which follow the grey/white matter boundary, very fine striations within the optic radiation, and also very fine details of penetrating vessels in the cortex.

***Joanna Downer**, PhD, is a science writer based in Durham, NC, USA.*