Voxel volume $2 \text{ mm}^3 = 8$ $1 \text{ mm}^3 = 1$ $8 \times 8 \times 8 \text{ mm}^3$ $4 \times 4 \times 4 \text{ mm}^3$ $2 \times 2 \times 2 \text{ mm}^3$ $1 \times 1 \times 1 \text{ mm}^3$

- SNR is proportional to the imaged volume
- Higher magnetic field = SNR = higher spatial resolution

Benefits of high-field MRI

- Signal-to-noise ratio (SNR)
- Contrast (anatomical & functional)
High-resolution vascular imaging

• High-resolution fMRI applications
• Anatomical contrast @ 7T MRI
• Clinical applications of @7T MRI

**High Resolution Vascular Imaging**
(Time-of-flight / inflow effects)

In a T₁-weighted sequence, long T₁ spins are saturated because they don't have time to recover.

- Arteries are bright due to unsaturated fresh blood fast inflow into slab
- Veins are dark due to elevated concentration of deoxyhemoglobin (BOLD)

Cat, 9.4T
In-vivo High Resolution Vascular Imaging
Maximum Intensity Projections (MIP)

Cat, 9.4T


High Resolution Vascular Imaging
(Time-of-flight / inflow effects)

3D Vessel Reconstruction
Vessel Classification

Veins
Arteries

Cat, 9.4T


High Resolution Vascular Imaging
(SEM)

Ex-vivo

Weber et al., Cereb. Cortex 2008

Scanning electron micrographs of a vascular corrosion cast from monkey visual cortex (superior temporal gyrus)
**BOLD signal and the underlying vascular system**

Cat. 9.4T
Multi slice BOLD fMRI:
Voxel size: 0.25 x 0.25 x 0.5 mm

Harel et al., Front Neuroenergetics 2010

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**High Resolution fMRI Applications**

Anatomical Image
Functional Image

Squash, Tan, Menon, Ellermann, Kim, Merkle, Ugurbil, PNAS.1992

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**Advantages of high-field for fMRI**

4 Tesla
7 Tesla

Yacoub, 2003
Functional-units (cortical columns) are believed to be the basic computational unit in the brain.

Ogawa, Tank, Menon, Ellermann, Kim, Merkle, Ugurbil. PNAS. 1992

Brain Function and Localization

Neurons with similar response properties tend to cluster together in 'columns' extending through the entire cortex.
Functional Domains in Visual Cortex - Ocular Dominance Columns -
Optical Imaging - Monkey

V2
V1

Monocular stimulation

Ts' et al., 1990

Columns Mapping in Humans V1
Ocular Dominance Columns (ODC)

Anatomical (post-mortem)

Horton & Hedley-Whyte, 1984; Horton, 2006

Functional (fMRI)

Menon et al., 1997
Deichstein & Frahm, 2000
Goodyear & Menon, 2001
Cheng et al., 2001

Yacoub et al., 2007

Image resolution: 0.5 x 0.5 x 3 mm

Menon et al., 1997

SE-BOLD 7 T

Monocular stimulation

ODC Spatial Organization

Cheng et al., 2001
Electrophysiological Recording

Cell Discharge

Stimulus model

“Ice cube” model

Hubel & Wiesel, 1968

Optical Imaging - Cat

Bonhoeffer & Grinvald, 1991; 1993; Blasdel 1992

“Pinwheels”

Phase 0°

Phase Map - fMRI

1 mm

Bonneste & Grinvald, 1991-1993; Spurrell 1992

Orientation selective regions in Human V1

Phase Map - fMRI
Does the fMRI-Phase Map Reveal Orientation Specific Activation Zones?

**Spatial Relationships Between Ocular Dominance and Orientation Columns**

1. Radial arrangement of orientation columns (pinwheels)
2. Pinwheels rotate in opposite directions
3. Pinwheels centers (singularities) tend to concentrated in the center of ocular dominance columns
4. Iso-orientation lines intersect the borders between ocular dominance borders at right angles (linear zones)

**Orientation Columns – Human fMRI (pinwheel)**

- Optical Imaging - cat
- Optical Imaging - monkey
- Yacoub, Nowel & Ugurbil, PNAS 2008
**ODC & Phase maps in human V1**

Scalebar = 0.5 mm

Yacoub, Harel & Ugurbil, PNAS 2008

**Ocular Dominance & Orientation Columns in Human V1**

Scalebar = 0.5 mm

Yacoub, Harel & Ugurbil, PNAS 2008

1. **Radial (pinwheel) arrangement**

Scalebar = 0.5 mm

Yacoub, Harel & Ugurbil, PNAS 2008
2. Clockwise & Counter Clockwise directions

Yacoub, Harel & Ugurbil, PNAS 2008

3. Pinwheels centered in ODCs

Yacoub, Harel & Ugurbil, PNAS 2008

4. Linear zones

Orientation preference changes along straight axes orthogonal to ODCs

Yacoub, Harel & Ugurbil, PNAS 2008
Orientation Columns in Primary Visual Cortex

Human fMRI (SE, 7T)
~4 mm
Yacoub, Harel & Ugurbil, PNAS 2008

Monkey Optical Imaging
~4 mm
Obermayer & Blasdel, JNS 1993

Anatomical Imaging at Ultra-high Field MRI

Benefits of high-field (7 Tesla) MRI

1.5 T (clinical)  7 T
Noam Harel, University of Minnesota / CMRR
Benefits of High-field MRI

7T, T2W, 0.4 x 0.4 x 2 mm

Benefits of high-field MRI include improved anatomical contrast and the ability to detect susceptibility differences more clearly.

Susceptibility-Weighted Imaging (SWI)

Phase contrast in the primary visual cortex

Duyn J et al. PNAS 2007;104:11796-11801

Susceptibility-weighted imaging (SWI) is a technique that enhances the visualization of small vessels and iron deposits.

Anatomical contrast @ 7T

STN: subthalamic nucleus
SN: substantia nigra
RN: red nucleus

7T, T2W, T1W, SWI

Anatomical contrast at 7T includes a range of imaging sequences to provide detailed structural information.

STN: subthalamic nucleus
SN: substantia nigra
RN: red nucleus

Abosch, Yacoub, Ugurbil, Harel. 2010
**Susceptibility-Weighted Imaging @ 7T**

- **STN** = Subthalamic Nucleus
- **SN** = Substantia Nigra

Magnet: 7T
Resolution: 0.4 x 0.4 x 0.8 mm

**Susceptibility-Weighted Imaging @ 7T**

- **Schaltenbrand and Wahren Atlas**
- **SWI @ 7T** (In-vivo)
- **GP** = Globus pallidus

**Thalamus level**

- **Vim** = DBS Target for Essential Tremor
- **Vim** = Ventralis intermedius (motor thalamus)
- **Vc** = Ventralis caudalis

Abosch, Yacoub, Ugurbil, Harel. 2010
Detections of Brain Structures with 7 Tesla MRI

Patient-Specific Anatomical Model

Thalamus (Tha)
Subthalamic nucleus (STN)
Substantia nigra (SN)
Red nucleus (RN)
Globus Pallidus
GPI
GPa

Diffusion Weighted Imaging Tractography (DTI / HARDI)

Gray matter: neuronal cell bodies
White matter: myelinated axons that transmit signals between regions

Nigrostriatal tract

Tractography (diffusion-weighted imaging - HARDI)

7T, 1.5 x 1.5 x 1.5 mm³
128 directions, b = 1500 s/mm²
Probabilistic tractography (FSL)
Tractography
Basal Ganglia and Thalamus

1. Tracts identified in individual subjects
2. Tracts are reproducible across subjects
3. Variability across subjects


Clinical applications of high-resolution 7T MRI

Direct Visualization of Parkinson's Disease by In Vivo Human Brain Imaging Using 7.0T Magnetic Resonance Imaging

Movement Disorders
Volume 26, Issue 4, pages 713-718, 21 JAN 2011
Clinical applications of high-resolution 7T MRI

What is Deep Brain Stimulation (DBS)?

- A surgically implanted medical device - “brain pacemaker”
- Sends electrical impulses to the brain

FDA approved DBS applications:
  Movement disorders, including:
  - Parkinson’s disease
  - Essential tremor

Humanitarian Device Exemption (HDE):
  - Obsessive-Compulsive Disorder (OCD)
  - Major Depression
  - Epilepsy
  - Dystonia

Under clinical trials:
  - Alzheimer’s disease
  - Tourette’s Syndrome

Over 120,000 DBS cases worldwide

DBS = Deep Brain Stimulation

DBS Surgery Today

Limitation of Current Procedure

2D - Stereotactic atlas

Microelectrode recording (MER)

Patient awake during surgery

Consensus Coordinates (STN):
  - Lateral: 12 mm
  - Posterior to MCP: 4 mm
  - Below MCP: 5 mm

Success of DBS surgery is critically dependent on the precise placement of the electrodes into the target structures
Can 7T images be used for DBS targeting?

7T-MRI for Clinical Surgical Targeting

Post-Surgery DBS: active contacts
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