Advanced MRI Techniques (and Applications)

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(Selected) Advanced MRI Techniques

- Gradient Echo MRI
  - High resolution anatomic imaging
  - Magnetic Resonance Angiography
- Echo Planar MRI
- Diffusion MRI
  - Diffusion-weighted MRI
  - Diffusion Tensor MRI
- Perfusion MRI (contrast passage)
- Diffusion and Perfusion MRI for acute stroke assessment
Gradient Echo MRI
Gradient (Recalled) Echo Imaging

- More efficient than “conventional” forms of MRI
  - Makes 3-dimensional MRI practical
  - Time needed for a 3D acquisition is 6-15 min
- TR is much shorter than in conventional MRI
  - Inherently produces T1-weighted contrast
3-Dimensional Gradient Echo MRI

- 3-dimensional gradient echo imaging is becoming more practical due to advances in MRI hardware design.

Conventional Spin Echo Multiple Slice T1-weighted MRI (3 mm slice thickness) vs. 3D Volumetric T1-weighted MRI (1 mm isotropic voxels)
Rendering of surface anatomy from MRI
3-Dimensional Gradient Echo Imaging

(Thompson PM et al)

- Quantification of brain tissue composition
Image-guided Neurosurgery
Magnetic Resonance Angiography (MRA)

- Imaging of the blood vessels using MRI
  - Usually arteries
  - Sometimes veins

- Most MRA techniques use gradient echo MRI
  - Time-of-flight (TOF) MRA
  - Contrast enhanced MRA
  - Phase contrast MRA (not covered in this lecture)
Arteries appear as very hyperintense signal.
Time-of-Flight MRA

1 mm slice from volume acquisition

Volume maximum intensity projection
Magnetic Resonance Angiography (MRA) with Contrast Agents.

Magnevist
Contrast Enhanced MRA

- Fast Gradient echo MRI
  - Usually 2D
  - 2 - 10 sec per time frame
- Venous injection of MRI contrast agent
- Image acquisition is timed such that the image is collected when the contrast agent is in the arteries
Contrast Enhanced MRA

- Complete angiographic coverage from aortic arch to Circle of Willis
- Other peripheral vascular applications
Echo Planar Imaging (EPI)
Echo Planar Imaging (EPI)

- Collects an entire slice in one TR (2 – 4 sec)
  - Greater degree of image distortion
- 10-20 slice images per second
  - Facilitates studies that require large numbers of images
- Typically provides T2-weighted images
- Typical resolution of 2 mm x 2 mm x 5 mm
EPI-based Applications

• Diffusion imaging
• Diffusion tensor imaging
• Perfusion imaging
• BOLD Functional imaging
• Uncooperative patients
Diffusion MRI
“Flavors” of Diffusion MRI

- Diffusion Weighted Imaging (DWI)
- Apparent Diffusion Coefficient Imaging (ADCI)
- Diffusion Tensor MRI (DTI)
Robert Brown (1773 – 1858) is acknowledged as the leading British botanist to collect in Australia during the first half of the 19th century.

Brown was born in Montrose, Scotland on 21 December 1773. He studied medicine at the University of Edinburgh, where he was a classmate of Thomas Dick. He joined the army as a surgeon in 1795. In December 1800 he accepted an offer of the position of naturalist on board the *The Investigator* under Matthew Flinders, which was about to depart on its historic voyage to chart the coast of Australia. The *Investigator* arrived in King George Sound in what is now Western Australia in December 1801. For three and a half years Brown did intensive botanic research in Australia, collecting about 3400 species, of which about 2000 were previously unknown. A large part of this collection was lost, however, when the *Porpoise* was wrecked on route to England.

Brown remained in Australia until May 1805. He then returned to England where he spent the next five years working on the material he had gathered. He published numerous species descriptions; in Western Australia alone he is the author of nearly 1200 species. In 1810, he published the results of his collecting in his famous *Prodromus Florae Novae Hollandiae et Insulae Van Diemen*, the first systematic account of the Australian flora. That year, he succeeded Jonas C. Duyvendak as Sir Joseph Banks' librarian, and on Banks' death in 1820 inherited his library and herbarium. This was transferred to the British Museum in 1827, and Brown was appointed Keeper of the Banksian Botanical Collection.

In 1827, while examining pollen grains and the spores of mosses and *Equisetum* suspended in water under a microscope, Brown observed minute particles within vacuoles in the pollen grains executing a continuous jittery motion. He then observed the same motion in particles of dust, enabling him to rule out the hypothesis that the motion was due to pollen being alive. Although he himself did not provide a theory to explain the motion, the phenomenon is now known as Brownian motion in his honour. In a paper dated 1828, Brown named the cell nucleus. The nucleus had been observed before, first by the Dutch microscopist Leeuwenhoek, but it was Brown who first noted its ubiquitous occurrence and gave it the name it bears to this day.

In recent years it was generally held that Brown's microscopes were insufficient to reveal phenomena of this order, or to resolve the nucleus. Brown's discoveries were denied in a brief paper in *Scientific American* vol 265 p 20 (1991) entitled "Did Robert Brown observe Brownian Motion: probably not". Shortly thereafter, in a hastily-compiled illustrated presentation, British microscopist Brian J. Ford presented to Inter Micro 1991 in Chicago a reprise of the demonstration. His video sequences substantiated the observations of Brown and were subsequently published in *The Microscope* vol 39 pp 161-171 (1991).

After the division of the Natural History Department of the British Museum into three sections in 1837, Robert Brown became the first Keeper of the Botanical Department, remaining so until his death at Soho Square in London on June 10, 1858. He was succeeded by John Joseph Bennett.

Brown is buried in Kensal Green Cemetery in London.

Brown's name is commemorated in the Australia herb genus *Brunonia*, as well as numerous Australian species such as *Eucalyptus brownii*. 
Diffusion-Weighted MRI (DWI)

Diffusion-Weighted MRI (DWI)

• The degree to which the pulse sequence is sensitive to diffusion is expressed through the “b-value” or “b-factor”

• The signal intensity of diffusion weighted images are
  – inversely related to the b-value
  – directly related to the degree of diffusion restriction (at a particular b-value)
  – directly related to T2
MRI of Acute Stroke

T2w
PDw
T1w
MRI of Acute Stroke

T2w

PDw

T1w

DWI (b = 1000)
Cell Swelling Hypothesis

Intracellular diffusion is slower than extracellular diffusion

Swollen intracellular volume
Increased volume average DWI
Reduced volume average ADC
DWI Hyperintensity in Stroke

• A marker of cytotoxic (cellular) edema seen in acute ischemic stroke
Diffusion MRI

- Typical diffusion-weighted MRIs are also T2-weighted
  - “T2 shine through”

- Apparent Diffusion Coefficient (ADC) calculation using a series of diffusion-weighted images provides diffusion rate without the influence of T2
Diffusion-Weighted MRI (DWI)

ADC Calculation

\[ \text{ln}(S_b) \]

L/R gradient sensitization
S/I gradient sensitization
A/P gradient sensitization

Average Slope = - ADC
Directionally averaged gradient sensitization
Apparent Diffusion Coefficient (ADC) Imaging

T2w  DWI  ADC
(b = 1000)
Apparent Diffusion Coefficient

- Quantitative measure of diffusion rate
  - Higher values mean less restricted diffusion
  - Lower values mean more restricted diffusion

- A diffusion “speedometer”

- Independent of T2

- “Numbers” that are comparable across subjects
Diffusion Tensor Imaging (DTI)

• Formal evaluation of the “directionality” of the diffusion

• Relies on the ability to measure the diffusion speed in any arbitrary direction
  – Possible because of the directional specificity of the gradient hardware
White Matter Diffusion Restriction

- Water diffuses more readily parallel to the fiber bundles than perpendicular to the fiber bundles.

- Typical values of water diffusion coefficient in brain:
  - Gray matter or white matter (directionally averaged): 750 - 1000 micron$^2$/sec
  - Parallel to white matter bundle: 1200 – 1500 micron$^2$/sec
  - Perpendicular to white matter bundle: 200 – 400 micron$^2$/sec
  - CSF: 3000 micron$^2$/sec
$$\text{ADC}_{L/R} \gg \text{ADC}_{A/P} = \text{ADC}_{S/I}$$
Diffusion Tensor Imaging

- Measure the component of the ADC
  - In at least 6 unique anatomic directions
  - In each voxel

- Determine in each voxel
  - The direction in which the ADC is maximal
  - The value of the directionally averaged ADC
Diffusion Tensor Imaging

- Voxel is likely white matter fiber if there is a great difference in the ADC between directions

- The direction showing the maximal ADC is parallel to the fiber
ICBM Protocol
UCLA
1.5 T Sonata
5 acquisitions
March 4, 2005

A/P fiber bundles
L/R fiber bundles
S/I fiber bundles
Parametric DTI Images

- Trace (or ADC) conveys the “average” diffusion speed
  - ADC is a quantitative measure that can be compared across patients

- Fractional Anisotropy (FA) conveys the degree of directional coherence within the voxel
  - FA is an “index” such that $0 < FA < 1.0$
  - FA is a quantitative measure that can be compared across patients
Behavioral/Systems/Cognitive

Genetics of Brain Fiber Architecture and Intellectual Performance

Ming-Chang Chiang, Marina Barysheva, David W. Shattuck, Agatha D. Lee, Sarah K. Madsen, Christina Avedissian, Andrea D. Klunder, Arthur W. Toga, Katie L. McMahon, Greig I. de Zubicaray, Margaret J. Wright, Anuj Srivastava, Nikolay Balov, and Paul M. Thompson

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DTI Fiber Tractography
White Matter Fiber Tracking with DTI

Connect the principal direction between voxels with smooth stream lines

R. Bammer et al
Eur J Radiol 2003;45:223-234
White Matter Fiber Tracking with DTI

D. Jones
Institute of Psychiatry
King’s College, London
**Language pathways**
- conduction aphasia
- transcortical aphasias
- auditory agnosia, phonagnosia
- prosody repetition deficits
- auditory hallucination
- auditory working memory deficits

**Dorsal fronto-parietal networks**
- hemispatial neglect
- visual apraxia, oculomotor apraxia
- tactile apraxia
- optic ataxia
- visual working memory deficits
- anarchic hand

**Corpus callosum**
- apraxia
- left unilateral astereognosis
- disconnection agraphia in left handed anarchic hand

**Occipito-temporal visual networks**
- pure alexia
- objectagnosia, prosopagnosia
- visual hypoemotinality
- visual amnesia
- depersonalization/derealization
- TLE-associated symptoms
- Human Kluver-Bucy syndrome

**Limbic pathways**
- amnesia
- TLE-associated symptoms
- Human Kluver-Bucy syndrome
Contrast Bolus Passage
“Perfusion” MRI
Perfusion

- Perfusion is a physiologically-defined parameter
- Passage of blood through capillaries
Field Distortion Around Capillaries Filled with Contrast Agent

- Gradient echo sequences are sensitive to magnetic field gradients
- Signal from water molecules outside of the capillaries is reduced due to magnetic field gradients

MRI Bolus Passage Perfusion Imaging

**Design**

- Perfusion imaging is performed using a timed bolus of contrast given during rapid image acquisition
  - Gradient echo echo planar imaging conveys sensitivity to the passage of contrast
  - 2 sec time resolution for each 3D image

- Image intensity becomes hypointense as contrast passes
Perfusion Imaging using Contrast Passage
Contrast Bolus Passage Perfusion Imaging

• Qualitative information
  – Tissue volumes that experience low contrast delivery
  – Tissue volumes experience delayed contrast delivery

• Quantitative information
  – Fractional Cerebral Blood Volume
  – Cerebral Blood Flow (limited accuracy)
  – Mean Transit Time (limited accuracy)
Bolus max

\(T_{\text{MAX}}\) (sec)

\(T_{\text{TPP}}\) (sec)

\(\text{CBF} (R_0)\quad \text{ml/100 g/min}\)

\(\text{CBF} (R_{\text{max}})\quad \text{ml/100 g/min}\)

\(\text{CBV}\quad \text{ml/100 g}\)

\(\text{FHD}\)

\(\text{FKH}\)

\(\text{FHS}\)
DSC-MRI-CBF Images
3T RRUCLAMC-1
MP-RAGE  GRE  FLAIR  

PET-CBF  MRI-CBF  

cc per 100g per min  cc per 100g per min  

0  100  1000  

Normal  Same day  Slice # 23
Stroke
Diffusion and Perfusion MRI

• The combined use of diffusion and perfusion MRI for acute stroke is based on the concept of the “ischemic penumbra”

• The “ischemic penumbra” is believed to be what can be saved with prompt treatment

• The combination of diffusion and perfusion MRI offers a means of visualizing the size of the ischemic penumbra
Stroke Penumbra Imaging
Diffusion and Perfusion MRI

- Perfusion MRI shows the entire affected territory
- Diffusion MRI shows the already damaged and unrepairable territory
- The penumbra is the difference (the mismatch)
Diffusion-Perfusion Mismatch

Tmax
Diffusion-Perfusion Mismatch

At Risk

Tmax
Diffusion-Perfusion Mismatch

Tmax

At Risk

DWI
Diffusion-Perfusion Mismatch

Tmax

DWI

At Risk

Core
Diffusion-Perfusion Mismatch

T_max

DWI

At Risk

Core

At Risk
Diffusion-Perfusion Mismatch

Tmax

At Risk
Salvageable
Core

At Risk

DWI
Stroke Diffusion and Perfusion MRI

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Advanced MRI Techniques

• Gradient Echo MRI
  – 3D brain morphometry
  – Magnetic Resonance Angiography
  – Neurosurgical planning

• Diffusion MRI
  – Diffusivity Imaging
    • Stroke assessment
  – Diffusion Tensor Imaging
    • Visualization of white matter structure
    • Visualization of white matter connections

• Perfusion MRI (contrast passage)
  • Stroke assessment
Commonplace as such [NMR] experiments have become in our laboratories, I have not yet lost a feeling of wonder, and of delight, that this delicate motion should reside in all the ordinary things around us, revealing itself only to him who looks for it. I remember, in the winter of our first experiments, just seven years ago, looking on snow with new eyes. There the snow lay around my doorstep – great heaps of protons quietly precessing in the earth’s magnetic field. To see the world for a moment as something rich and strange is the private reward of many a discovery.

Edward M. Purcell (1953, Nobel Lecture)