Lecture #15

$^1$H MRS: Single-voxel and Spectroscopic Imaging Studies

• Single-voxel $^1$H MRS
  – Technical considerations
  – Applications and Research

• $^1$H MRSI
  – Technical considerations
  – Applications and Research

• Readings and Handouts
  – de Graaf, Chapters 6, 7, and 9.
MRI and MRS
Anatomy + Biochemistry

- Spatial localization
- Water suppression
- Lipid suppression
- $B_0$ homogeneity

Spectral quantitation
Position Resolved Spectroscopy (PRESS)

- $90^\circ - 180^\circ - 180^\circ$

STEAM: alternative sequence using three $90^\circ$ to localize via a stimulated echo (1/2 the signal but shorter minimum TE)
Water Suppression

Flip angle on last CHESS pulse adjusted to minimize water signal: typically 110°-120°
Single Voxel $^1$H MRS

Excite rectangular volume of tissue (PRESS or STEAM)

Widely available, fully automated. Typical Protocol:

- Graphically prescribe ROI
- Shimming (often automated)
- Data collection: 2-5 min, 3-8 cc voxels

Applications:
- focal ROIs
- diffuse diseases

Reliability high, but still some technical challenges:
- homogeneity
- SNR
Tissue Composition

Gray Matter

White Matter

Cerebellum

Pons

TR/TE=2000/35 ms
Echo Time Considerations
1 month old infant

Echo time (TE) = 35 ms
- Cho
- mL
- Cre
- Glx
- NAA
- Lipids/Lactate

Echo time (TE) = 144 ms
- Cho
- Cre
- NAA
- Lactate
Difficulties: Lipid Contamination

TE = 35 ms

Cho
Cre
NAA

x5

ppm
4.0  3.0  2.0  1.0

TE = 35 ms

ppm
4.0  3.0  2.0  1.0
Difficulties: $B_0$ Inhomogeneity

TE = 35 ms

- Good shim
  - Cho
  - Cre

- Poor shim
  - NAA
Spectroscopic Imaging

- Excite a large volume of tissue, then use gradients for spatial encoding
- Typically 5-15 min acq, 1-3 cc voxels

$^{1}H$ spectrum

TR = 2s
TI = 170ms
TE = 144ms

NAA image
Traditional $^1$H CSI

Water and Lipid Suppression

Excitation

A/D

Gx

Gv

TR

TAD
PRESS MRSI Example

Typical clinical parameters: TR/TE=1000/144 ms, 16x16 matrix, 1.5 cm slice, 24 cm FOV, 3.4 cc voxels. 4 min acquisition.

Pros: robust, automated
Cons: limited coverage

FOV/resolution/imaging time not independent e.g. 16x16x16 voxels requires 2.3 hrs (TR = 2s)
Research Topics

• Technical developments:
  – Volumetric spectroscopic imaging
  – Robust measurement of additional metabolites such as mI, Glu, Gln, GABA, etc
  – Spectral quantification
  – $^1$H MRS in non-brain tissues (primary problems due to motion and lipids)

• Biological/medical questions: better understanding of the roles of these metabolites under normal and pathological conditions.
Motivation for MRSI

SNR considerations should dominate, and SNR is independent of the number of voxels.

\[ \text{SNR} \propto V\sqrt{T_{AD}} \]

single voxel  single slice  volumetric
Increasing Spatial-coverage: 
$k$-space view of MRSI

MRI vs MRSI

\[(k_x, k_y, k_z) \quad (k_x, k_y, k_z, k_f)\]

\[k_f = \text{time}\]

Strategy: use time-varying readout gradients to cover $k$-space

\[\rightarrow \quad \text{EPI, EPSI, spiral-MRSI}\]
**k-space view of MRSI**

- Gradients allow arbitrary movement along $k_x$, $k_y$, and $k_z$ (subject to amplitude and slew rate constraints)
- Must move linearly along $k_f = t$

3DFT vs MRSI with an oscillating readout gradient

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Echo Planar CSI

Spectroscopic U-FLARE
(Dreher, MRM 44:668-72 [2000])

Spectroscopic GRASE
(Dreher, MRI 17:611-21 [1999])
Volumetric Echo-Planar MRSI

16 slices
1.1 cc voxels
TR/TI/TE = 2000/170/144 ms
17 min acquisition
Gridding reconstruction
Spiral MRSI

- Oscillate along two gradient axes

Typical Protocol
- 16 slices, 18 x 18 pixels each
- FOV = 24 x 24 x 10 cm
- TR/TI/TE = 2000/170/144 ms
- FOV$_f$ = 400 Hz, Res$_f$ = 5 Hz
- 46 TRs to cover 4D k-space
- 1.7 min acq
Fast MRSI
Given that SNR constraints require significant averaging, why bother scanning rapidly (e.g. spiral CSI)?

Answer: increased flexibility!

Spiral MRSI
• Allows “independent” selection of imaging time, voxel size, and FOV
• Allows “smart” averaging
  – Interleaving to increase FOV and/or spectral bandwidth
  – RF phase cycling
• Other applications
  – Water referencing
  – Spatially-resolved 2D NMR
  – $k$-space filtering
Spatially Resolved 2-D Spectroscopy

- Spiral gradients allow collection of 2 spectral and up to 3 spatial axes
- Suitable for variety of 2D MRS methods: e.g. J-resolved, COSY.

Example: J-Resolved Spiral MRSI (1.5 T)

Spiral readout
18×18×128×256 (k_x, k_y, t_1, t_2) data set
1 cc voxels
17 min acquisition
Variable-Density Sampling

- Problem: MRSI suffers from significant Gibbs ringing. Increased k-space coverage can reduce ringing, however post-acquisition windowing reduces SNR (see Problem Set 1).

- Solution: use a k-space sampling density proportional to desired window (Mareci 84, Parker 87, Star-Lack 95, Boada 97)

Examples: Fixed Voxel Size & Imaging Time

![Diagram showing sampling density, reconstruction weighting, impulse response, and noise variance](image)
Variable-Density Spiral MRSI

**k-space Coverage**

- Constant density
- Variable density

**Impulse Response**

- Fixed nominal voxel size and FOV

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In practice, slew rate constraints produce additional weighting.
Variable-Density Spiral MRSI

Water Reference

Lipids

Metabolites
$^{1}$H volumetric vd-spiral MRSI

1.5 T, 7 yo male, TE=144ms, 1 cc voxels, 15 min acq.

Pro: lots of data!

Con: lots of data!
(also poorer shim vs single voxel)
Fast $^1$H MRSI at 3T

Spiral MRSI
TR/TI/TE=2000/180/144 ms
1.2 cc voxels
3.6 min acquisition

Metabolite maps

Representative spectrum
In Vivo MRI/MRS

• Three: most important factors for a successful in vivo MRSI exam:
  – Homogeneity, homogeneity, and homogeneity (SNR should probably be somewhere in this list)
• Hence, shimming is extremely important.
• MRI scanners typically compensated with passive and supercon shims to very high orders (e.g. 14th order zonal shims).
  – Typical homogeneity = 1ppm over 30 cm sphere.
• Magnets also equipped with linear gradients for shimming as well as higher order resistive shims such as $z^2$, $xy$, etc

Question: If supercon shims already adjusted to maximize field uniformity, why do we need additional resistive shims?

Answer: Any object placed within the main magnet changes the magnetic field!
Magnetic Susceptibility

- All materials are magnetized to some degree.

\[ B = \mu_0 (1 + \chi_m) H \]

\( \mu_0 \) is the magnetic permeability of free space, \( \chi \) is the magnetic susceptibility.

Susceptibility:
- air = 0.000004
- water = -0.000002

Max shift about ±10 ppm
Susceptibility and $B_0$ orientation

Parallel (0.5T)  Orthogonal (0.5T)
High Field Magnets (≥3T)

- Pros
  - SNR linear with $B_0$
  - Spectral separation increases

- Cons
  - Susceptibility scales with $B_0$
  - If linewidths dominated by $T_2^*$, SNR goes only as $\sqrt{B_0}$

Example:

- Good: $3T$ $T_2$ dominated
- Bad: $3T$ $T_2^*$ dominated
- Ugly: $1.5T$
Summary

• $^1$H MRS is best viewed as an adjunct to MRI, currently in widespread clinical use.
• Technical difficulties addressed with large voxels, water/lipid suppression, in vivo shimming
• Clinical neuro applications available today, body applications under development.
• Ongoing technical development:
  – Improved Shimming: homogeneity is key to a successful study!!
  – Automated processing and quantification
  – Phased-array coils, SENSE/SMASH
  – Motion-insensitive sequences
  – High field MRSI: other nuclei, improved spectral editing
Next Lecture: Clinical MRS I