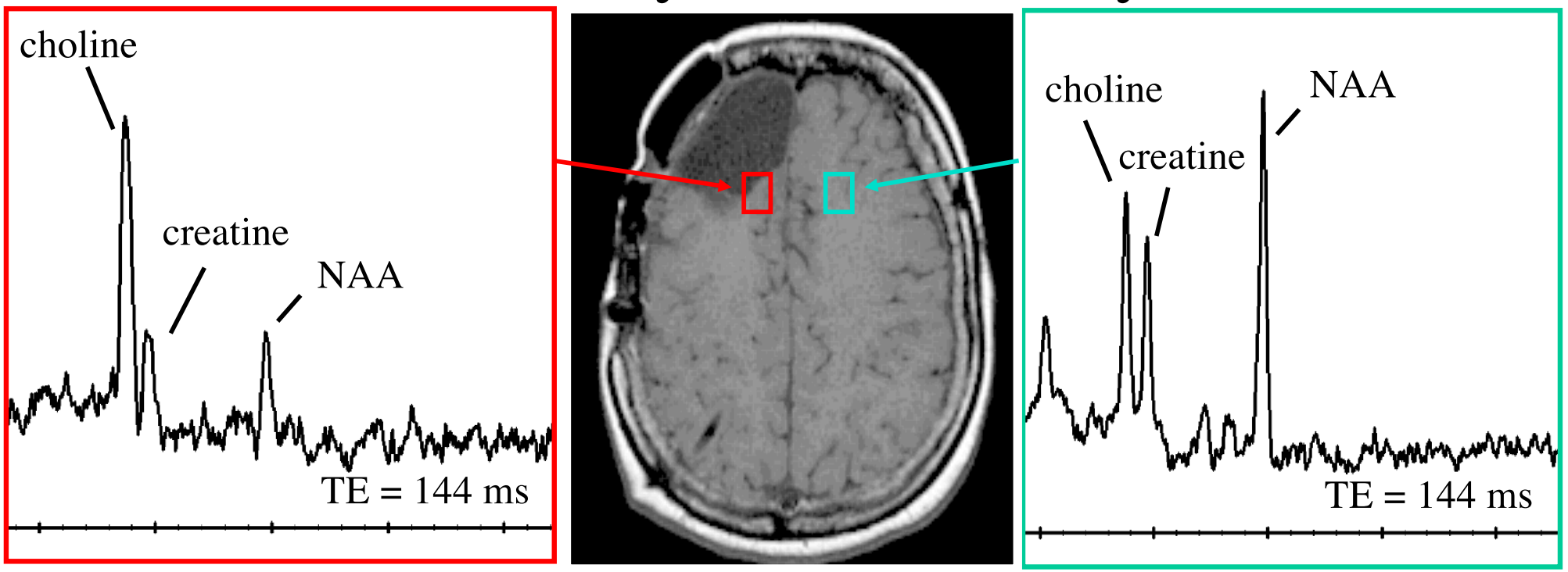
Lecture #15
^{1}H MRS: Single-voxel and Spectroscopic Imaging Studies

- 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



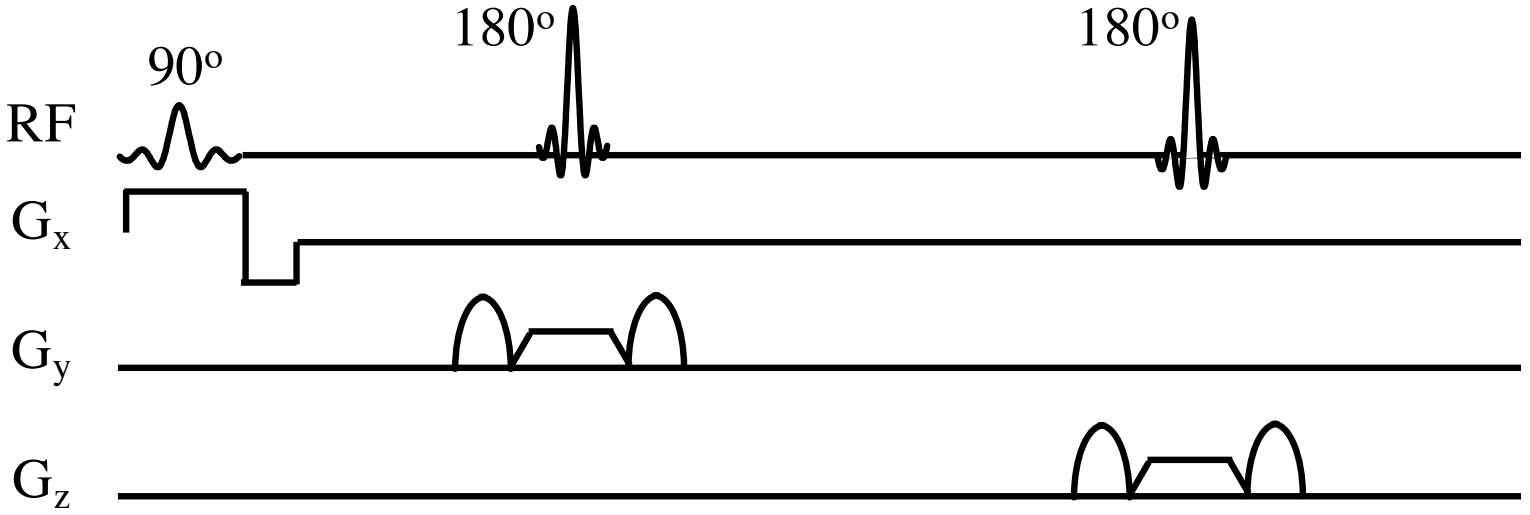
Technical requirements

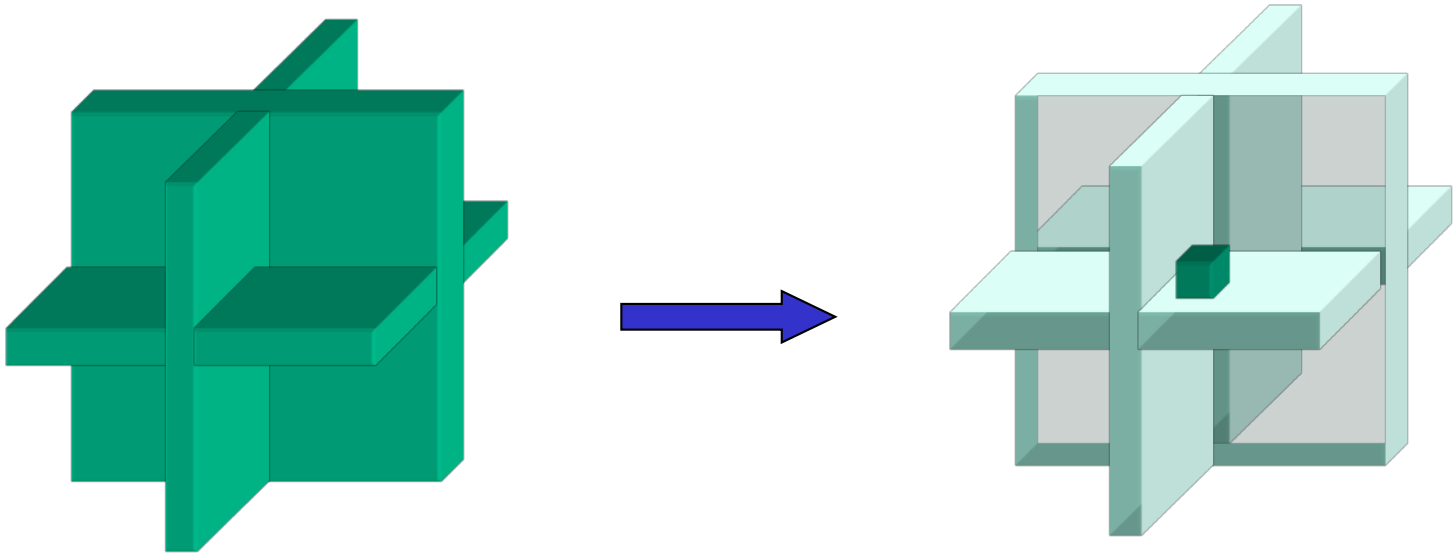
- Spatial localization
- Water suppression
- Lipid suppression
- B_0 homogeneity

→ Spectral quantitation

Position Resolved Spectroscopy (PRESS)

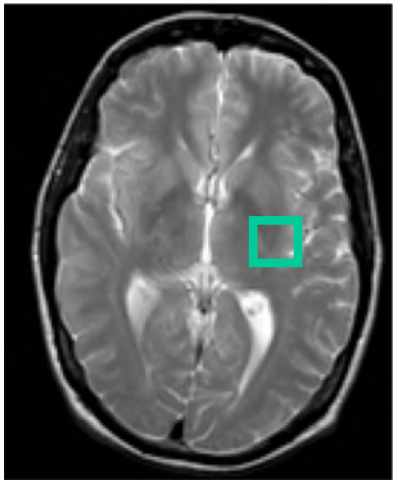
- 90º- 180º- 180º

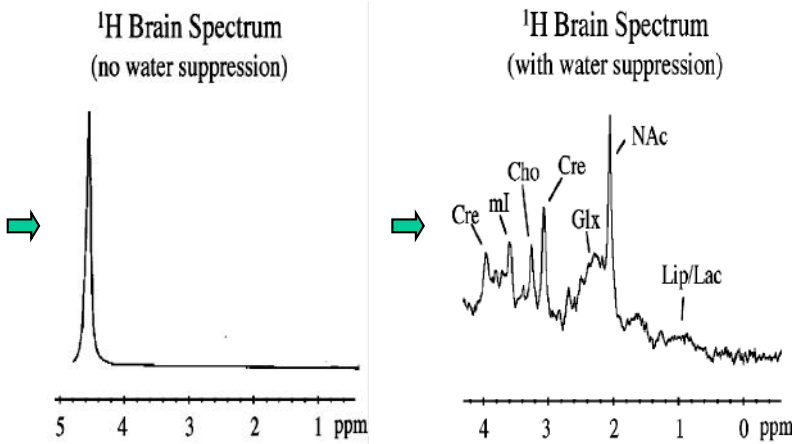


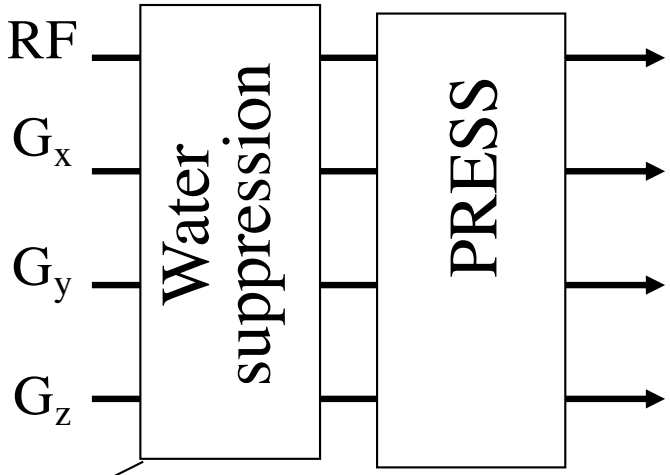


- STEAM: alternative sequence using three 90º to localize via a stimulated echo (1/2 the signal but shorter minimum TE)

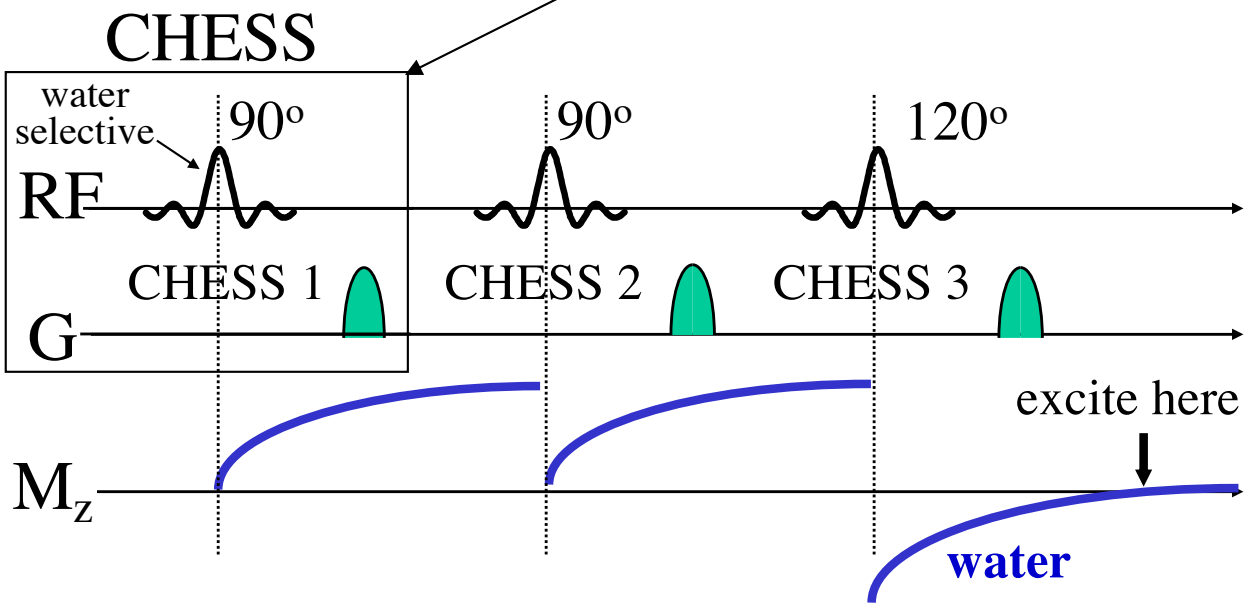
Water Suppression







Flip angle on last CHESS pulse adjusted to minimize water signal: typically 110°-120°

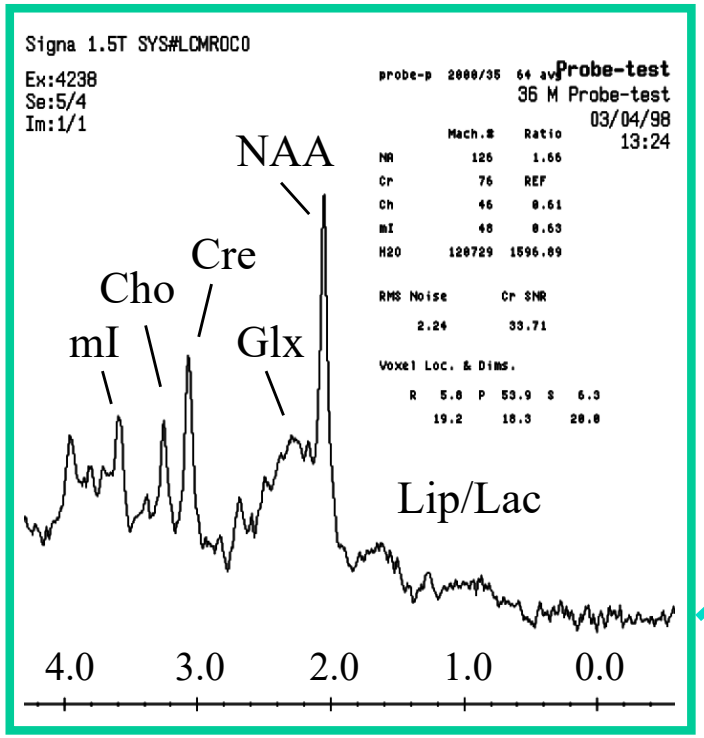


Single Voxel ^{1}H MRS

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

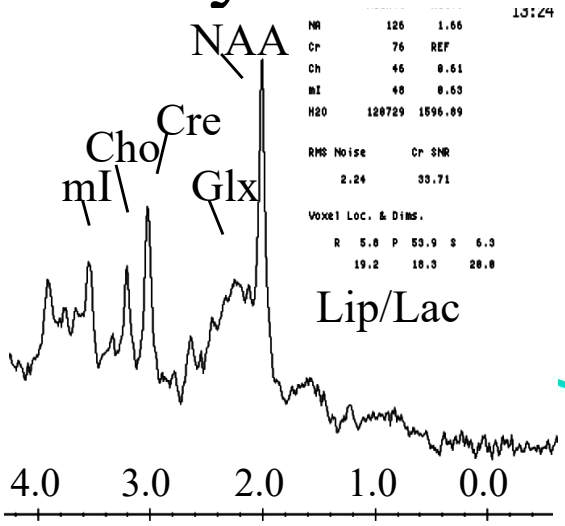


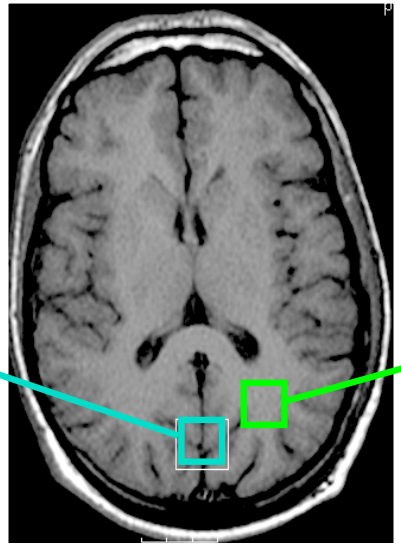
TR/TE=2000/35 ms
64 averages
PRESS

- Applications:
  - focal ROIs
  - diffuse diseases
- Reliability high, but still some technical challenges:
  - homogeneity
  - SNR

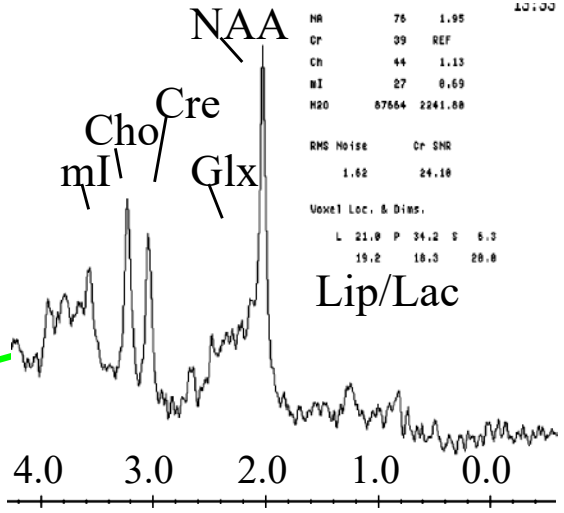
Tissue Composition

Gray Matter

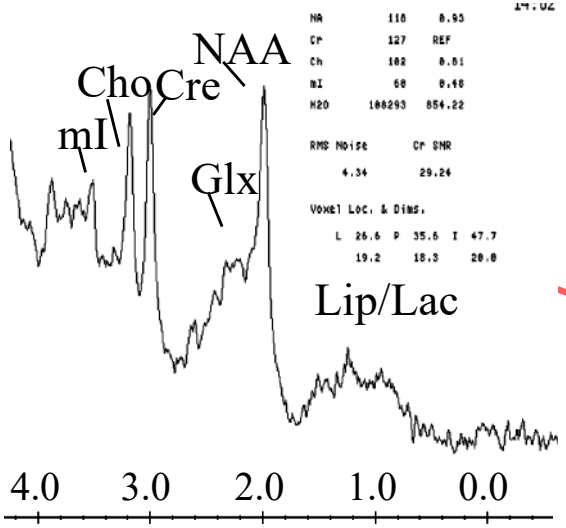


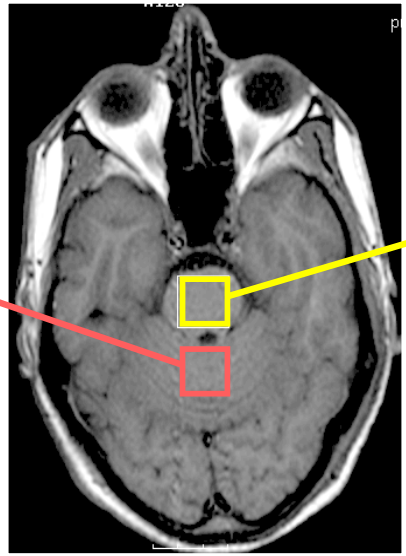


White Matter

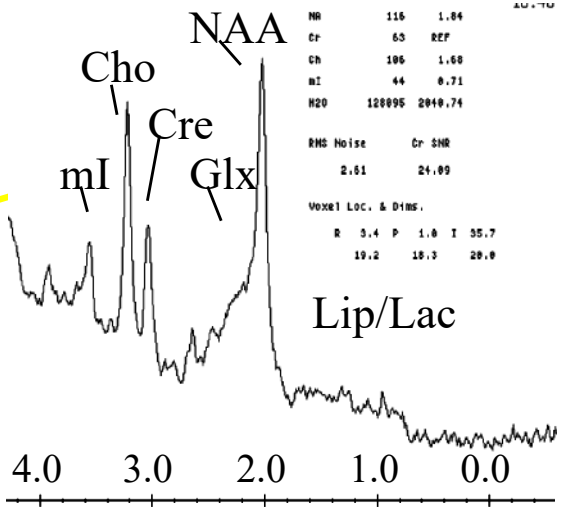


Cerebellum



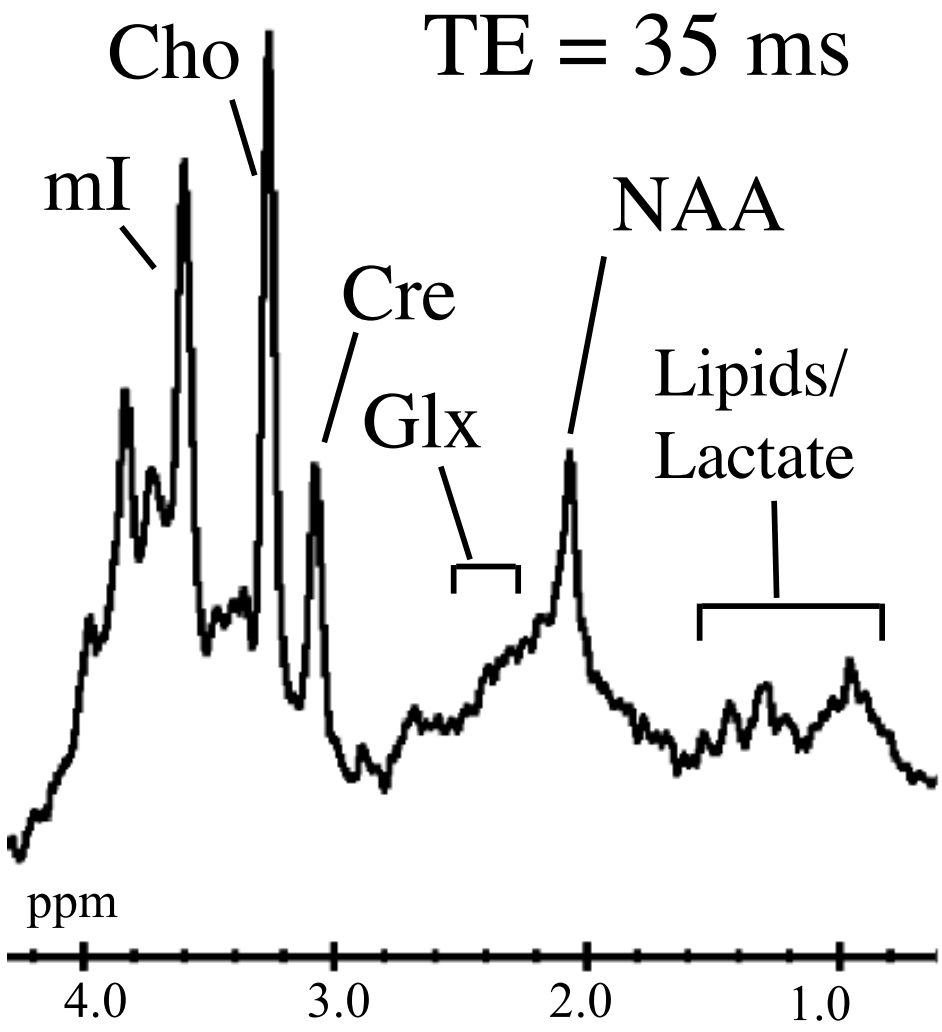


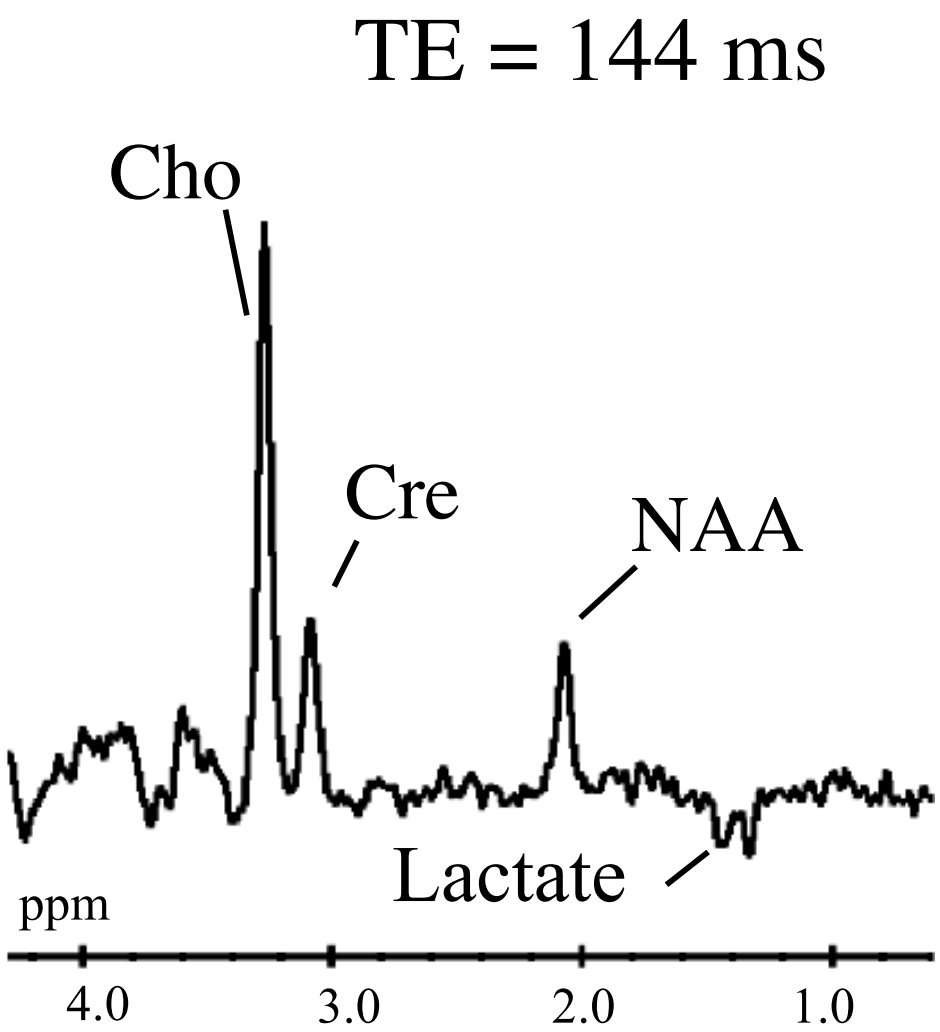
Pons



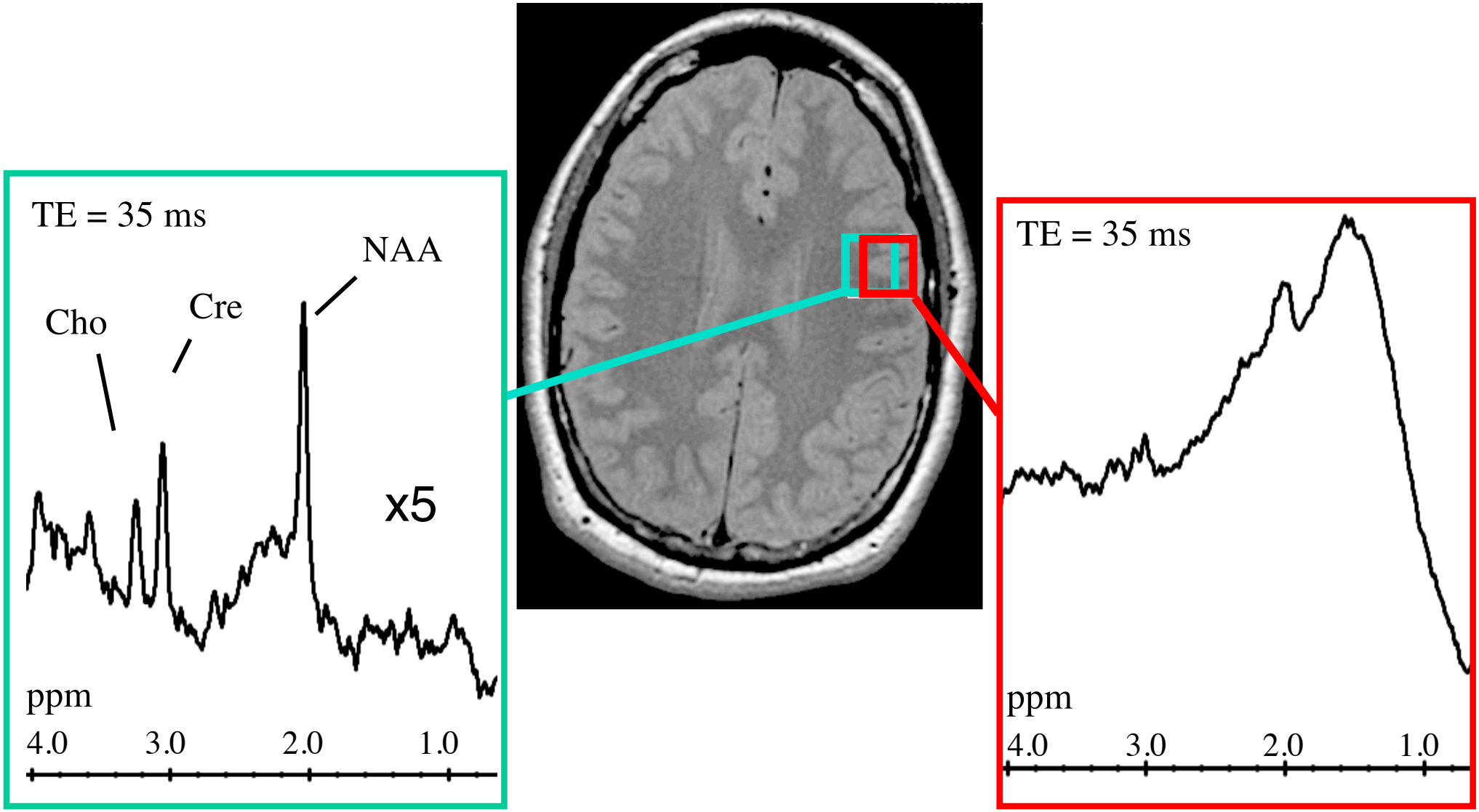
TR/TE=2000/35 ms

Echo Time Considerations
1 month old infant

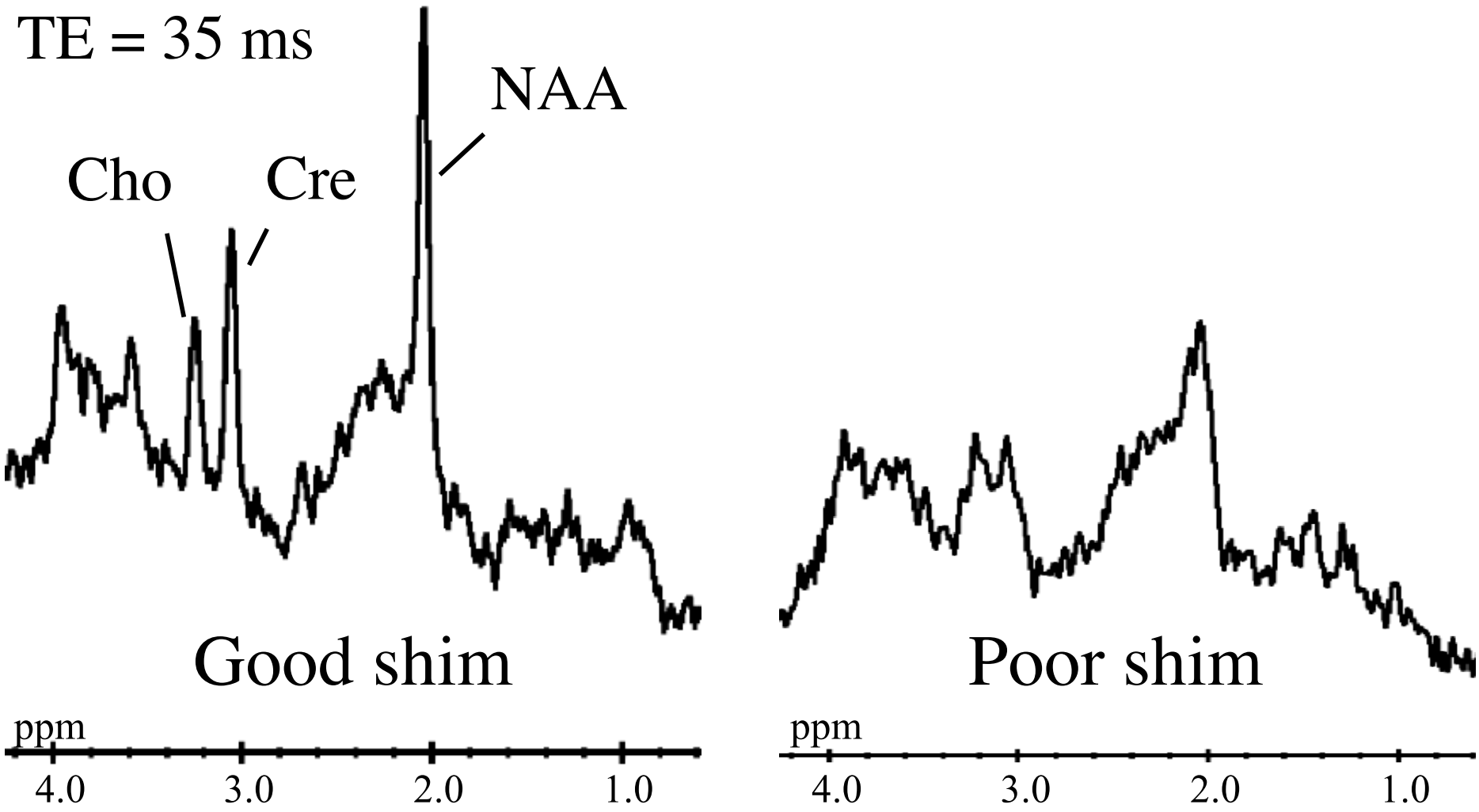




Difficulties: Lipid Contamination

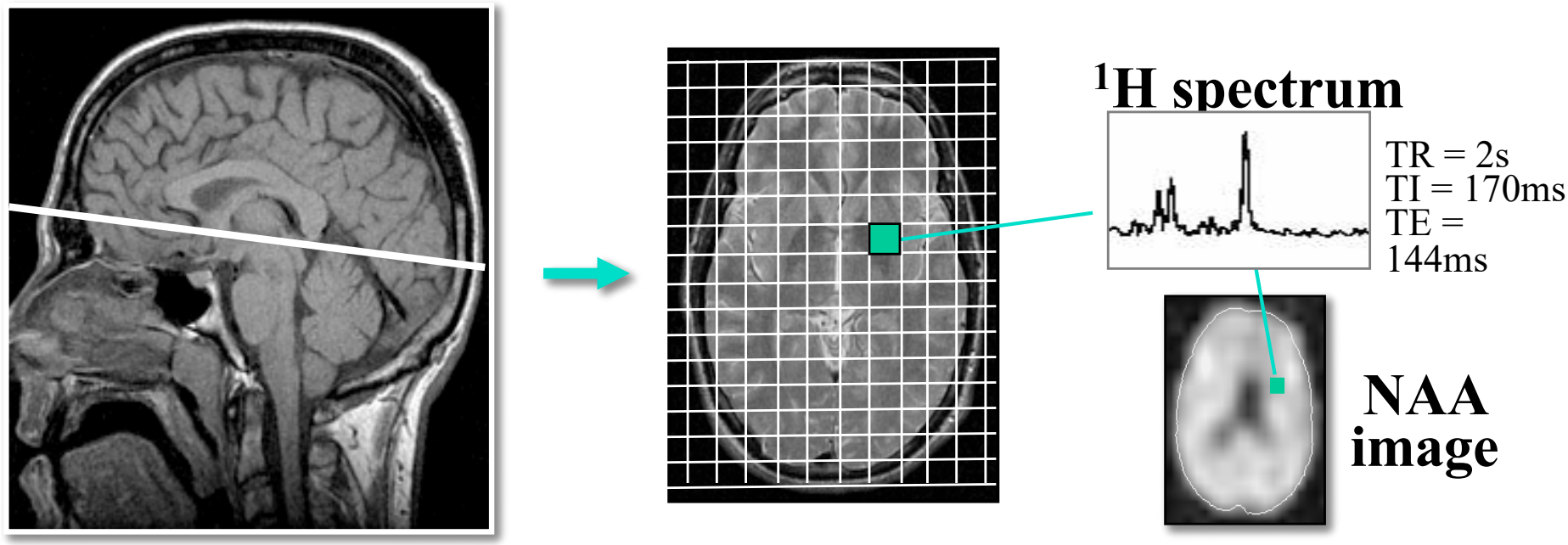


Difficulties: B_0 Inhomogeneity

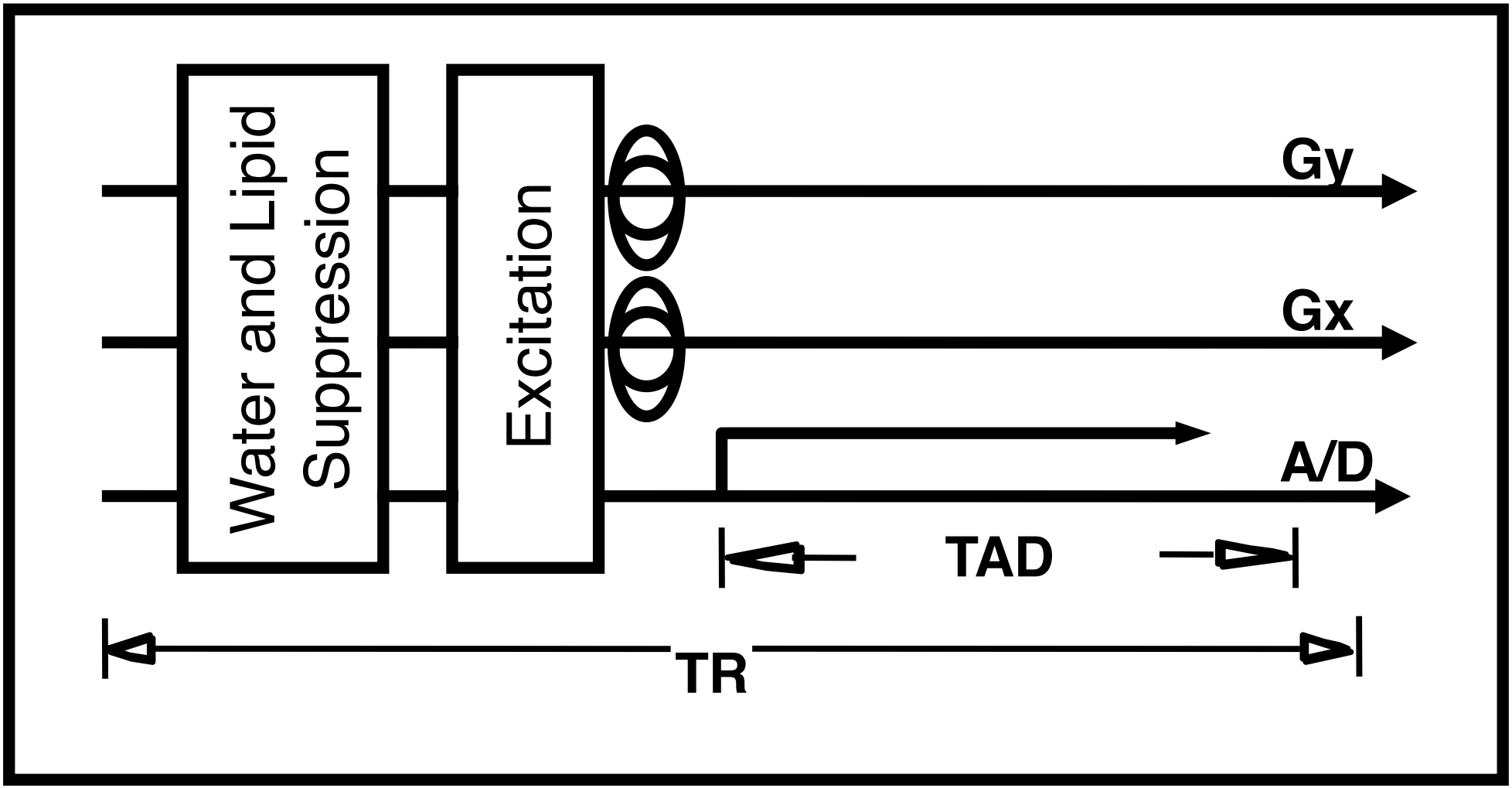


Spectroscopic Imaging

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

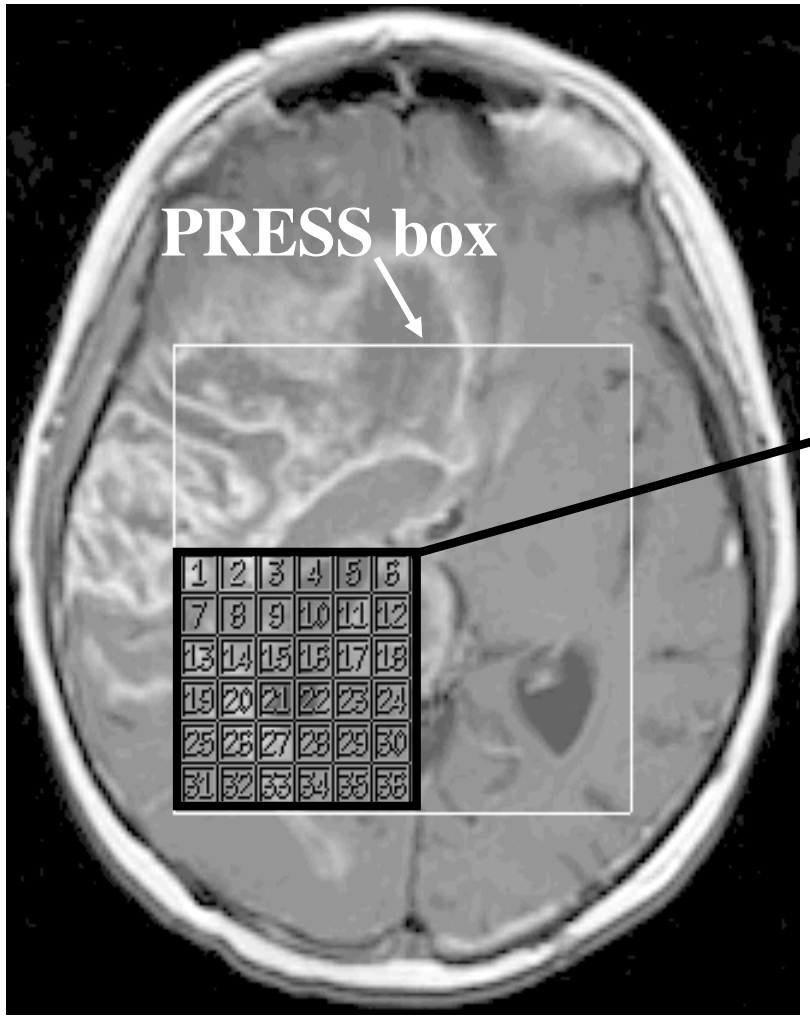


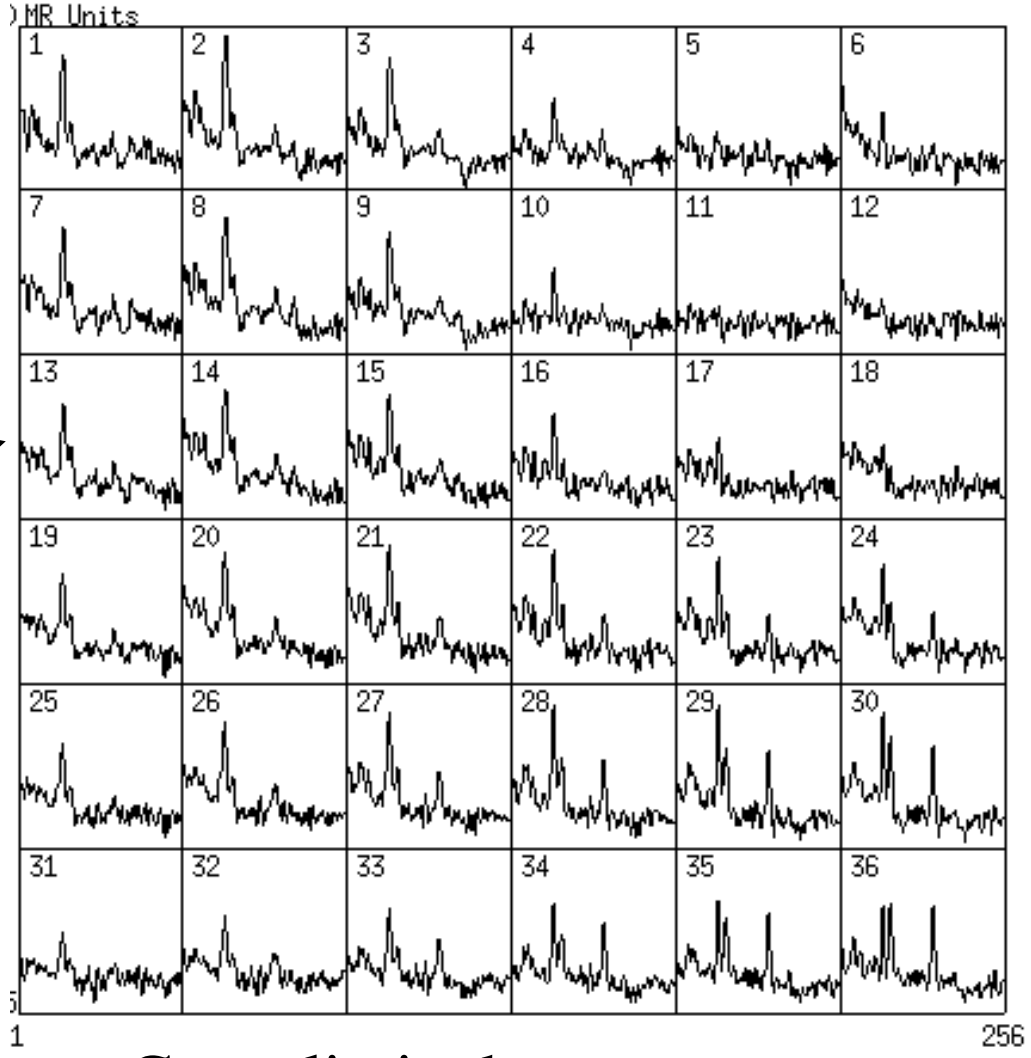
Traditional ^{1}H CSI



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

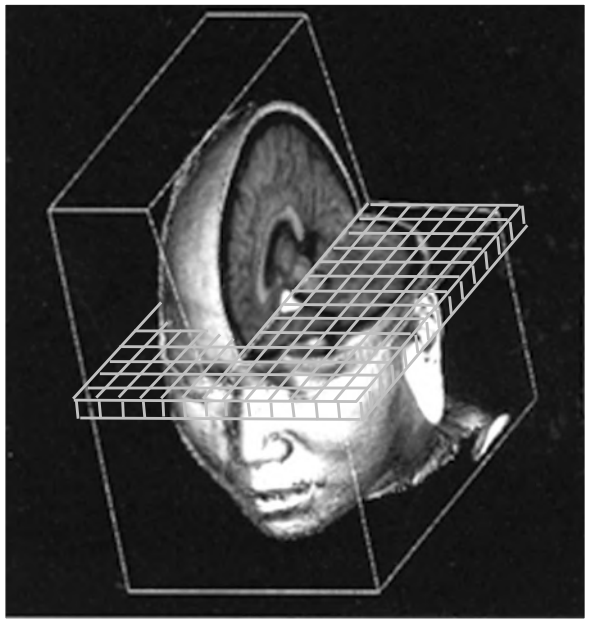
- Technical developments:
  - Volumetric spectroscopic imaging
  - Robust measurement of additional metabolites such as mI, Glu, Gln, GABA, etc
  - Spectral quantification
  - ^{1}H MRS in non-brain tissues (primary problems due to motion and lipids)
- Biological/medical questions: better understanding of the roles of these metabolites under normal and pathological conditions.

Motivation for MRSI

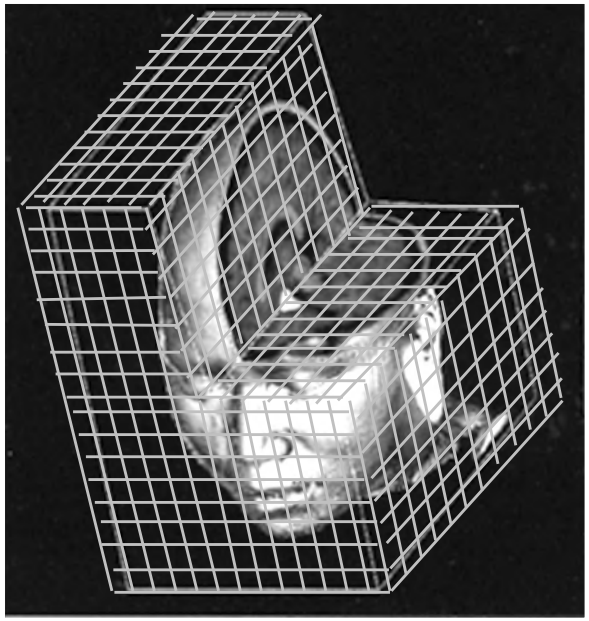
SNR considerations should dominate, and SNR is independent of the number of voxels.

$$SNR \propto V\sqrt{T_{AD}}$$

single voxel



single slice



volumetric

Increasing Spatial-coverage:
k-space view of MRSI

MRI vs MRSI

(k_x, k_y, k_z) (k_x, k_y, k_z, k_f)

k_f = time

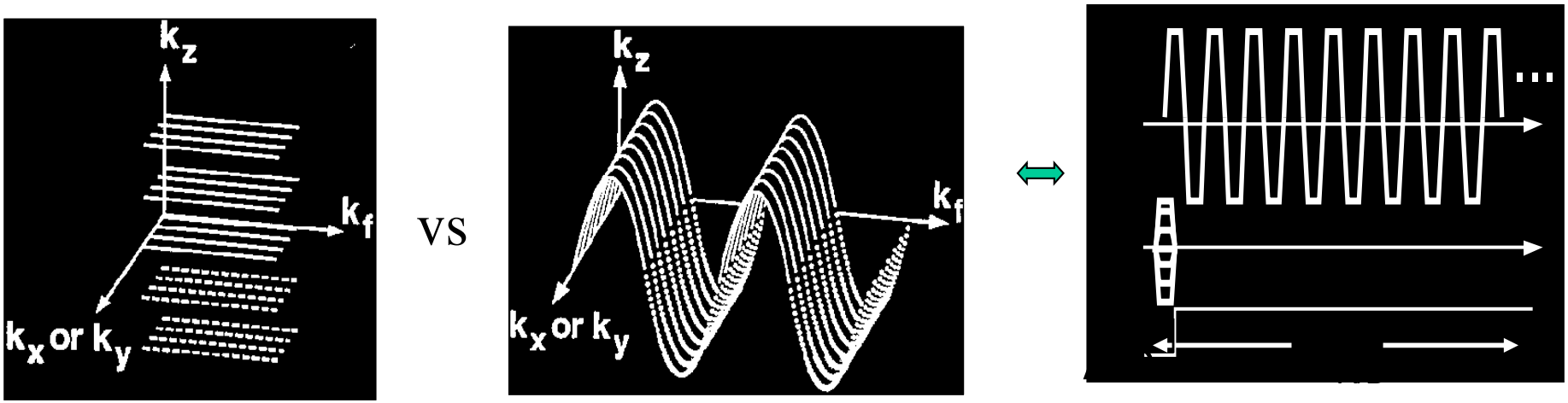
Strategy: use time-varying readout gradients to cover *k*-space

⇒ EPI, EPSI, spiral-MRSI

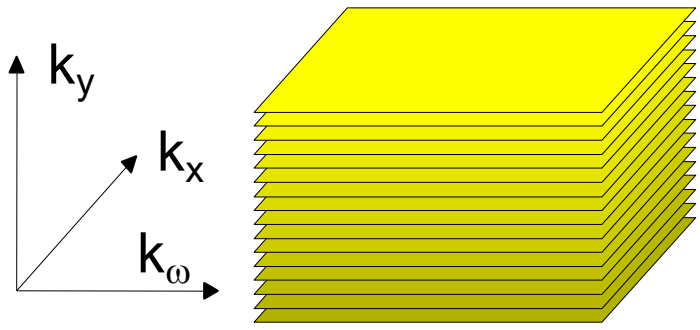
k-space view of MRSI

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

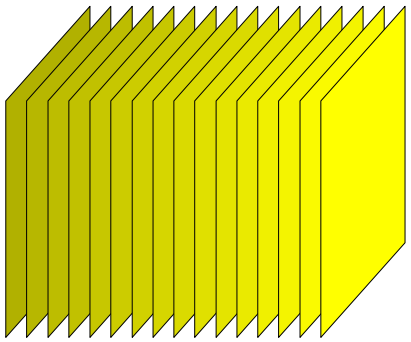
3DFT MRSI with an oscillating readout gradient



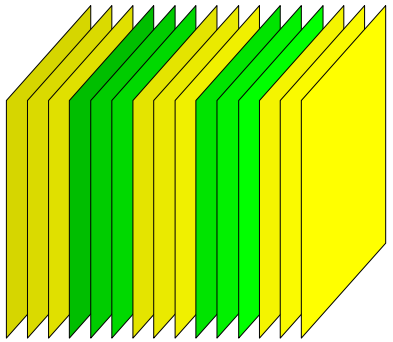
Echo Planar CSI



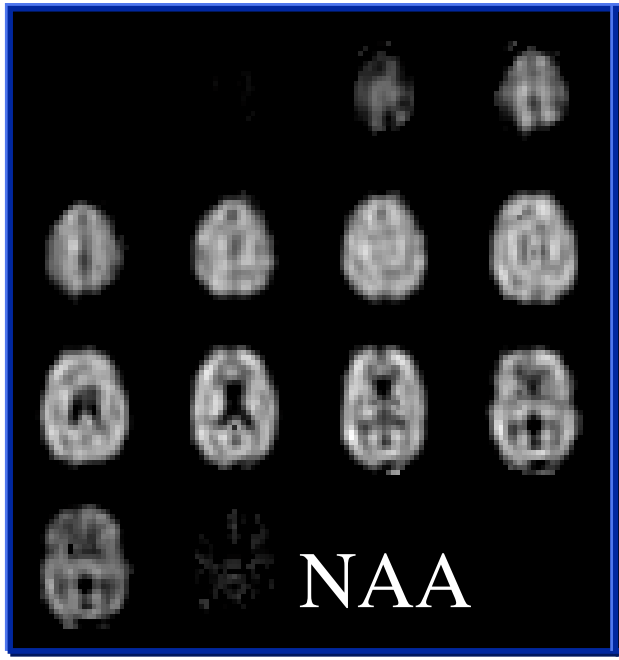
Spectroscopic U-FLARE
(Dreher, MRM 44:668-72 [2000])

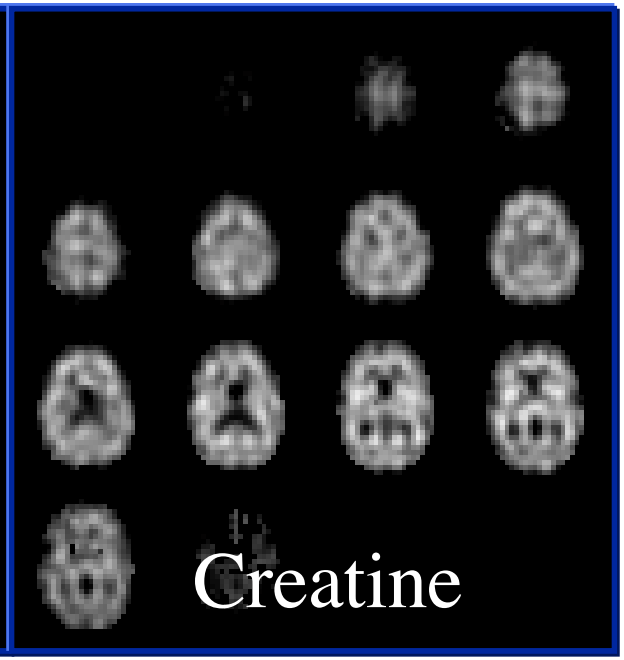


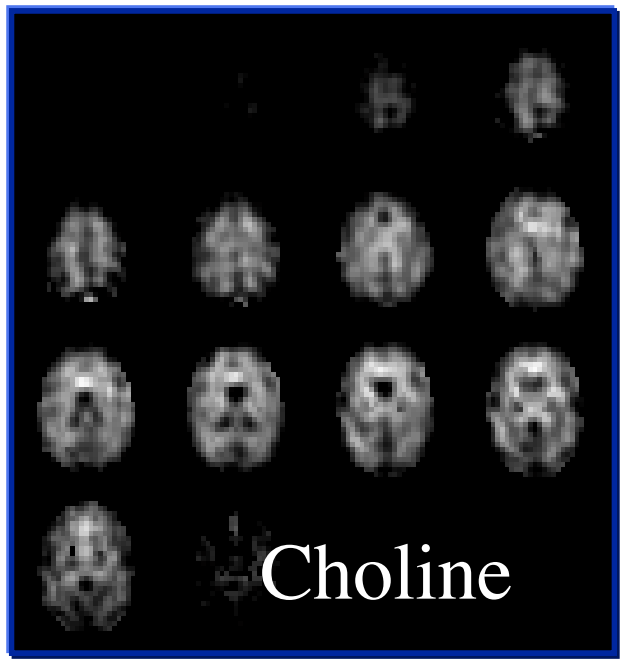
Spectroscopic GRASE
(Dreher, MRI 17:611-21 [1999])



Volumetric Echo-Planar MRSI



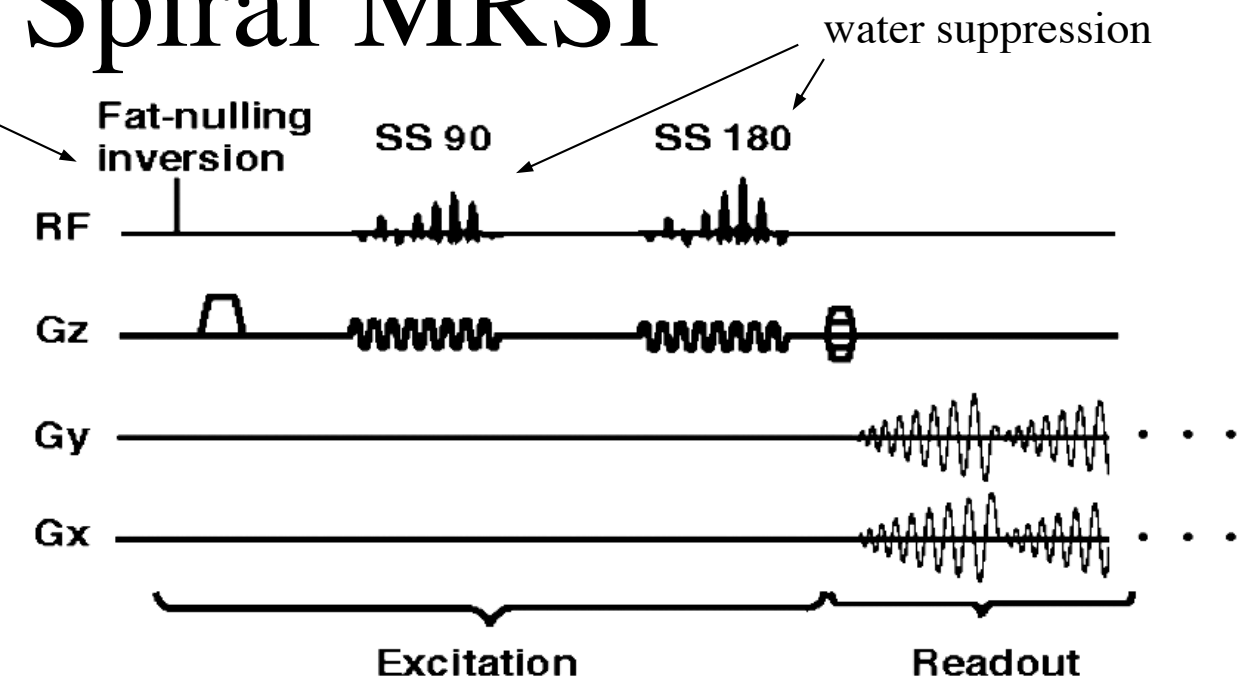


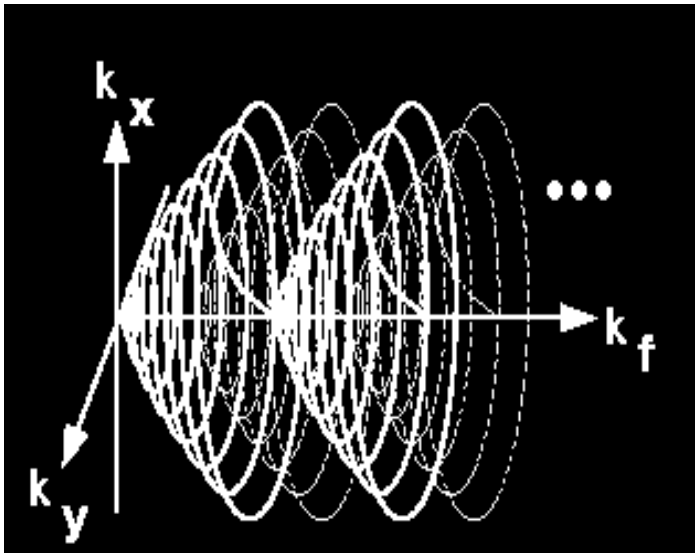


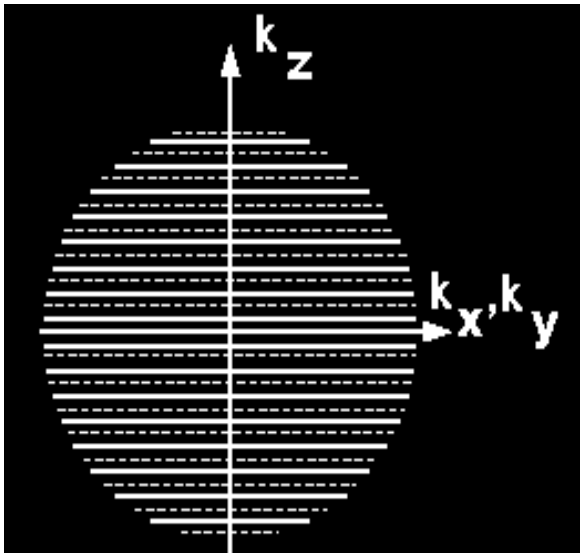
16 slices
1.1 cc voxels
TR/TI/TE = 2000/170/144 ms
17 min acquisition
Gridding reconstruction

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

spherical coverage in k_x, k_y, k_z

Fast MRSI

Given that SNR constraints require significant averaging, why bother scanning rapidly (e.g. spiral CSI)?

Answer: increased flexibility!

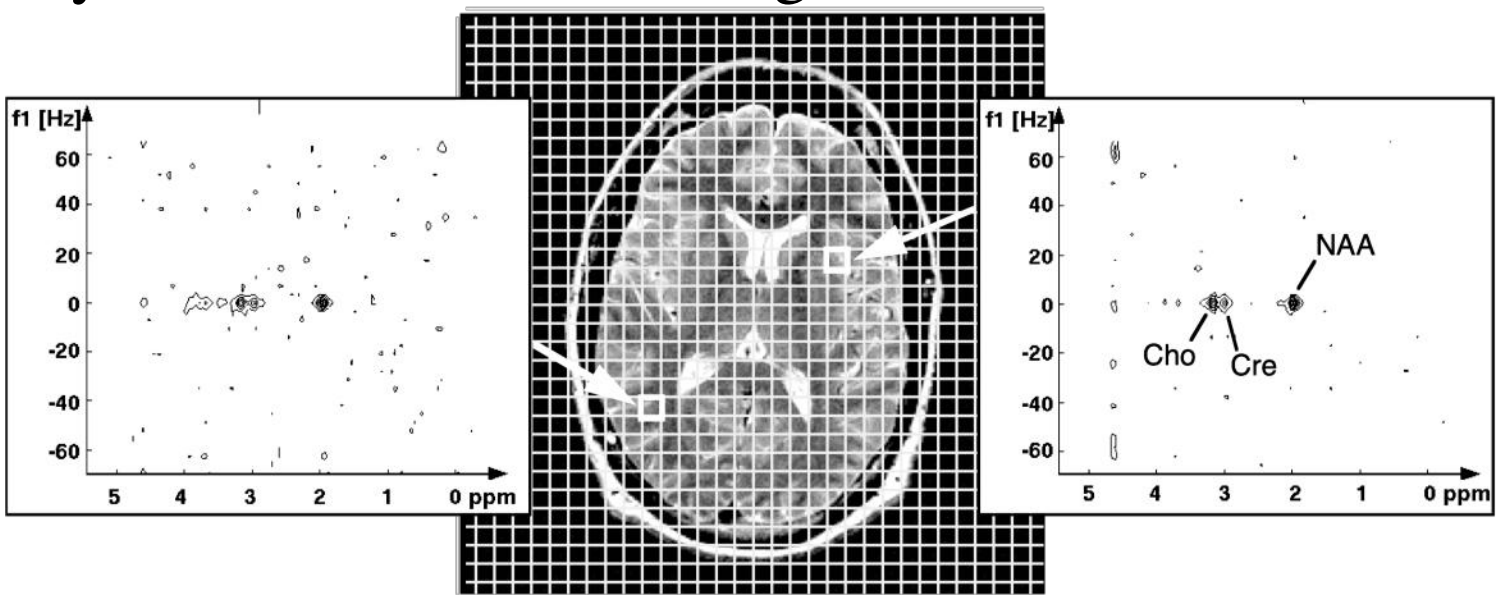
Spiral MRSI

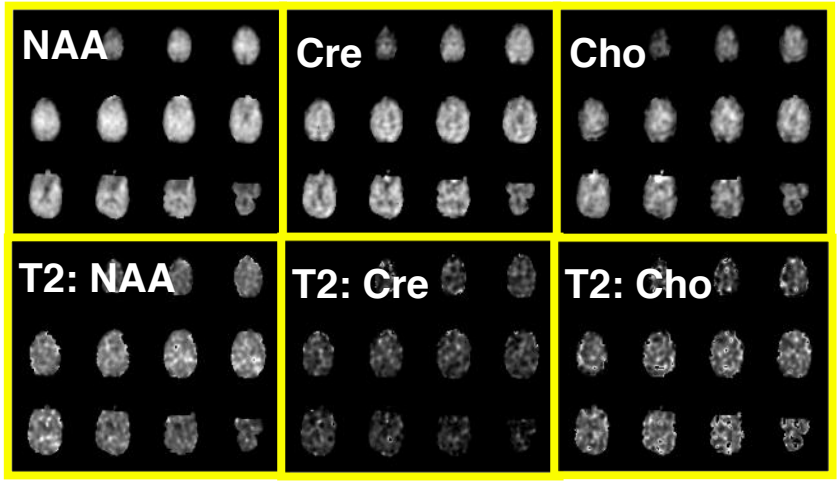
- Allows "independent" selection of imaging time, voxel size, and FOV
- Allows "smart" averaging
  - Interleaving to increase FOV and/or spectral bandwidth
  - RF phase cycling
- Other applications
  - Water referencing
  - Spatially-resolved 2D NMR
  - *k*-space filtering

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)



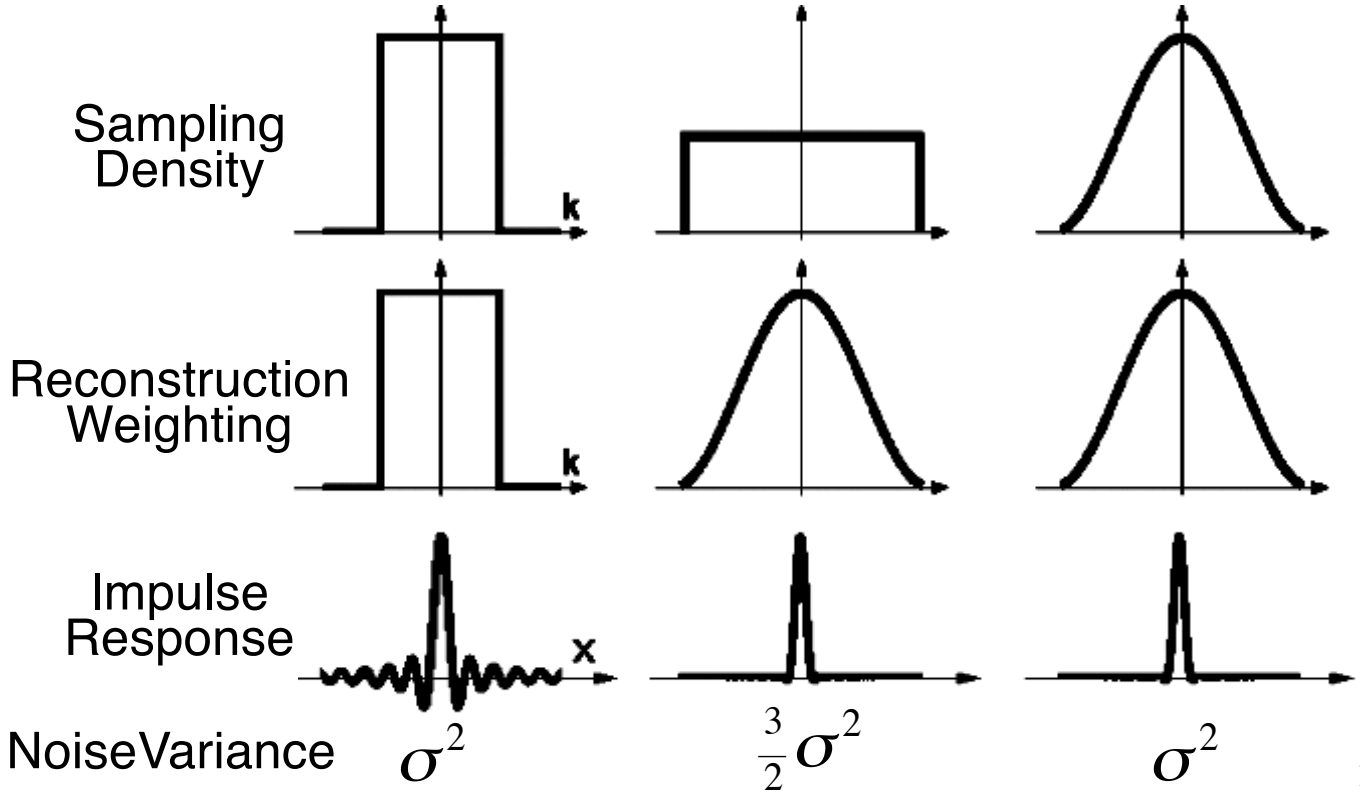


Spiral readout
18×18×128×256
(k_x, k_y, t_1, t_2) data set
1 cc voxels
17 min acquisition

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)

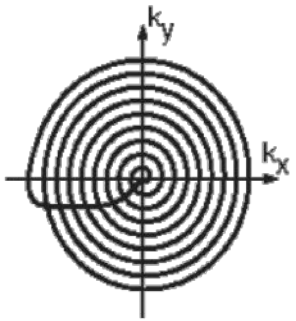
Examples: Fixed Voxel Size & Imaging Time



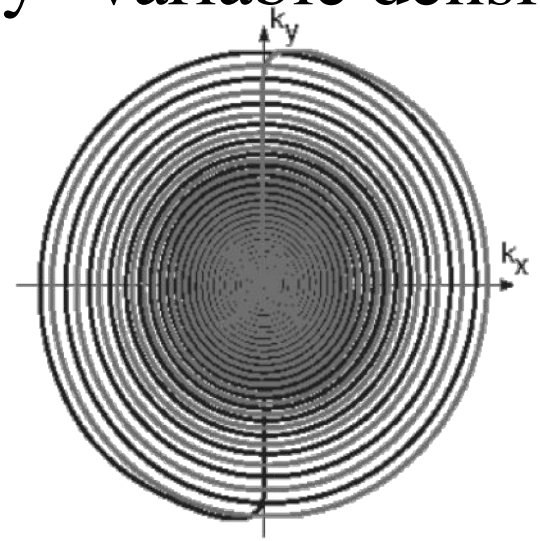
Variable-Density Spiral MRSI

k-space Coverage

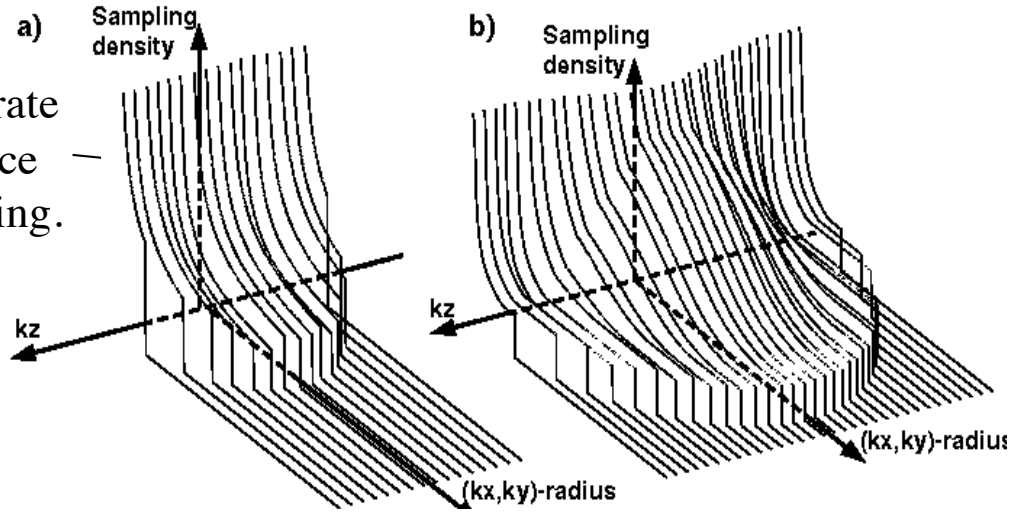
Constant density



Variable density

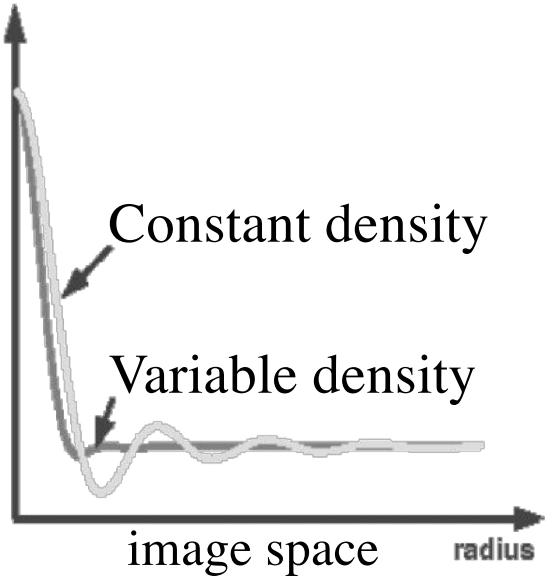


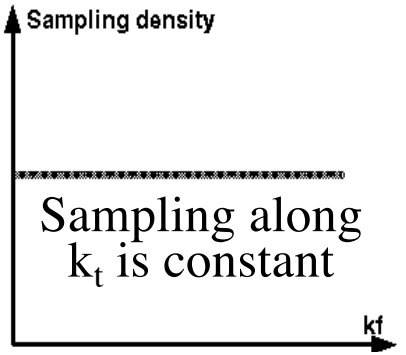
In practice, slew rate contraints produce additional weighting.



Impulse Response

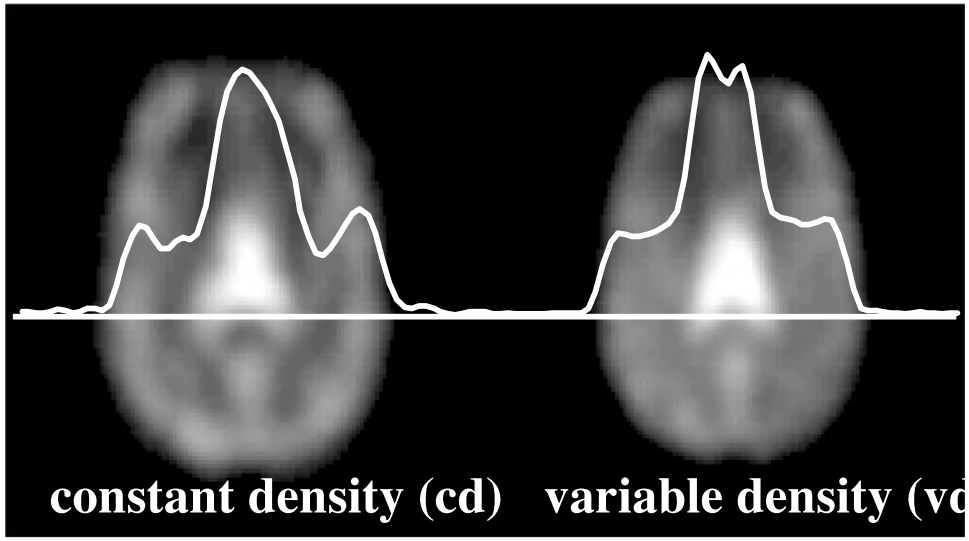
Fixed nominal voxel size and FOV



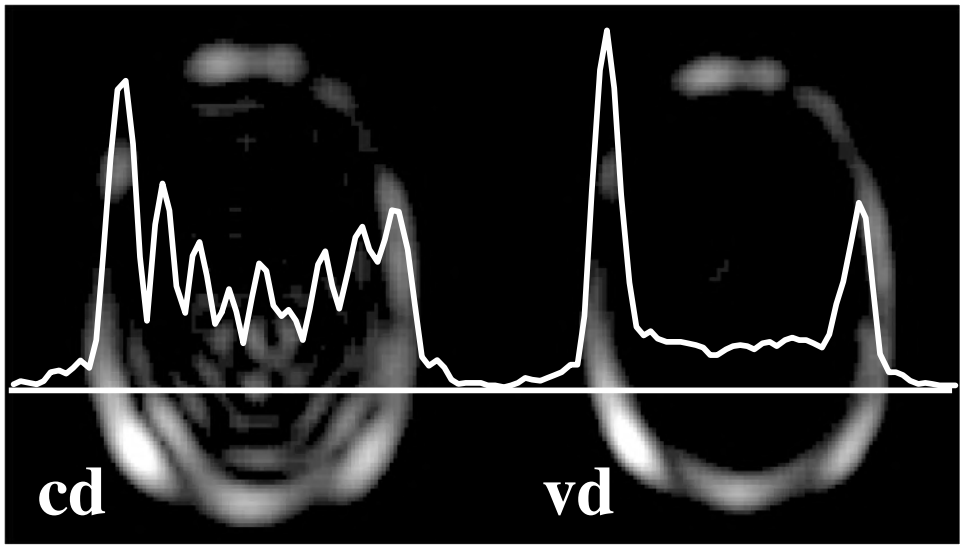


Variable-Density Spiral MRSI

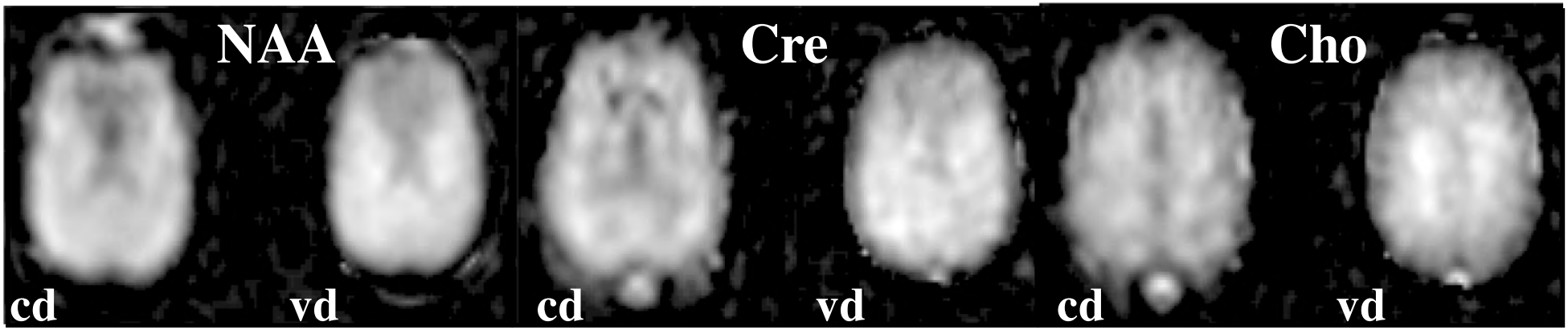
Water Reference



Lipids

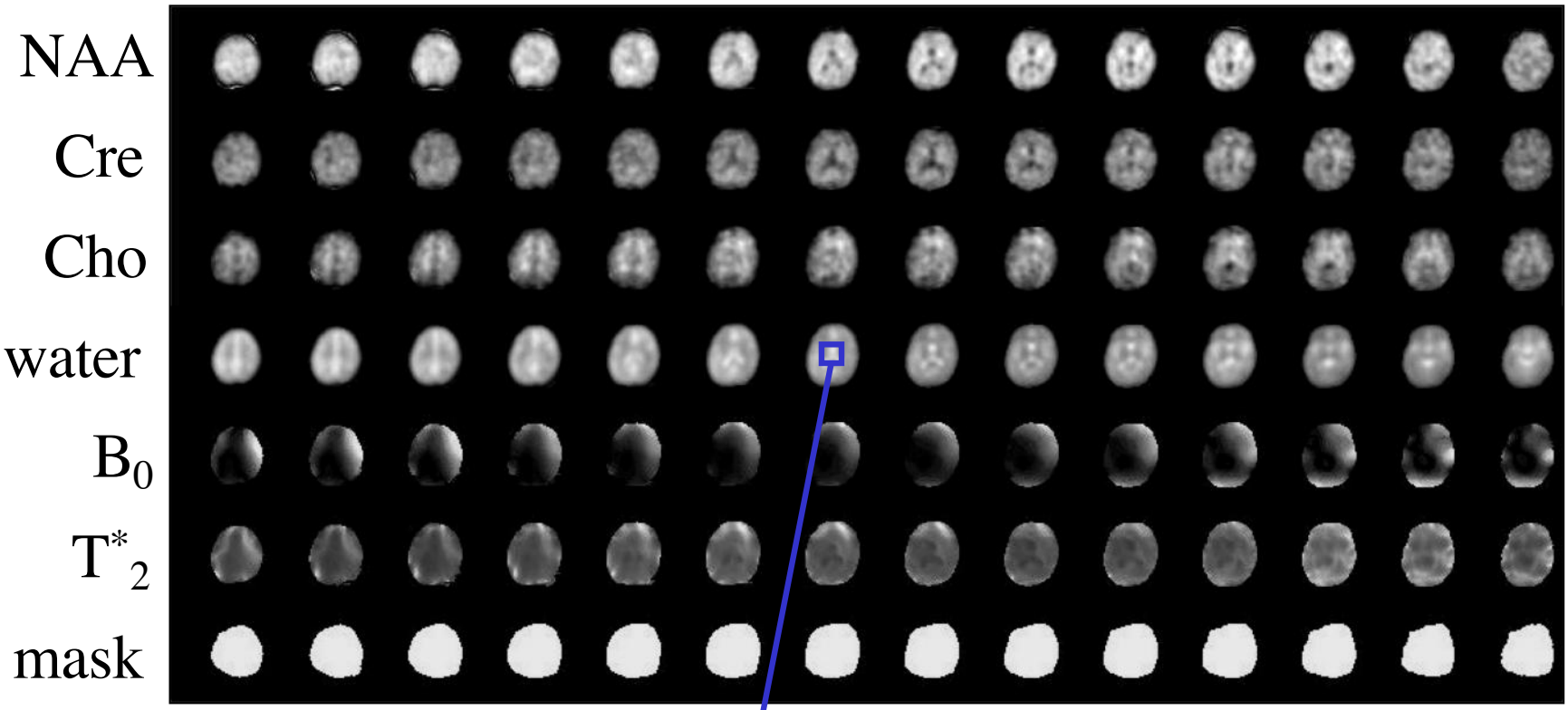


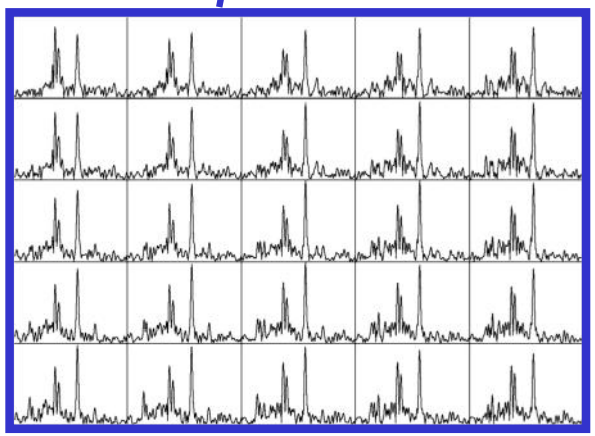
Metabolites



^{1}H volumetric vd-spiral MRSI

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

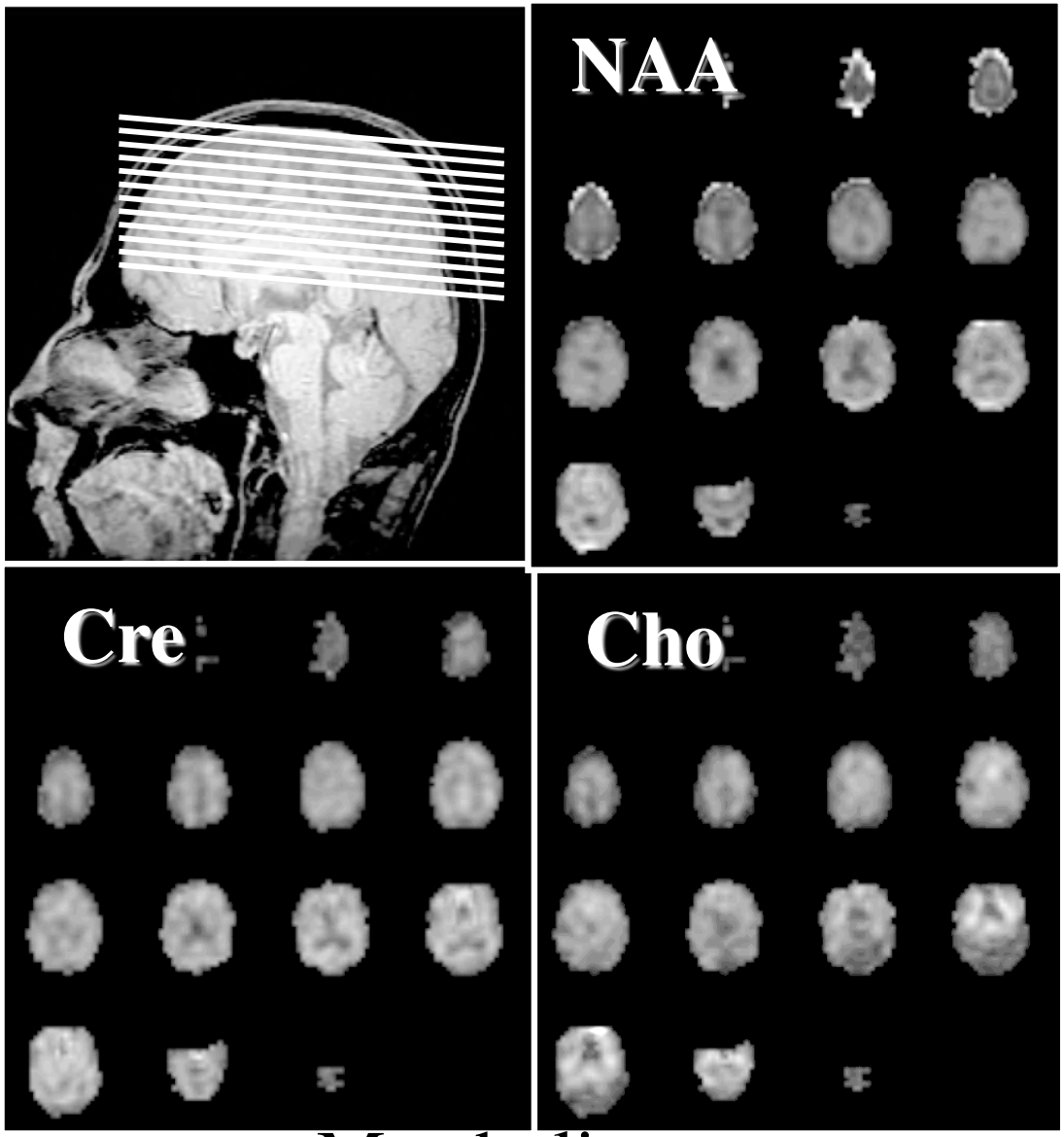




Pro: lots of data!

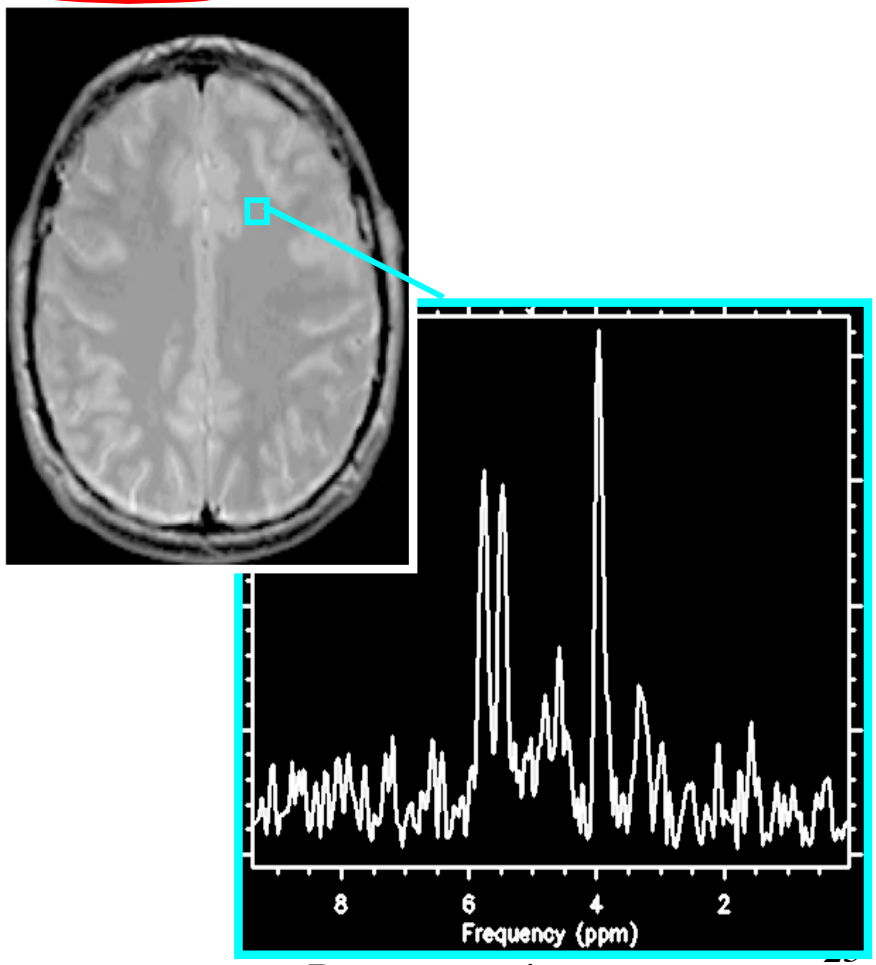
Con: lots of data!
(also poorer shim vs single voxel)

Fast ^{1}H MRSI at 3T



Metabolite maps

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



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?

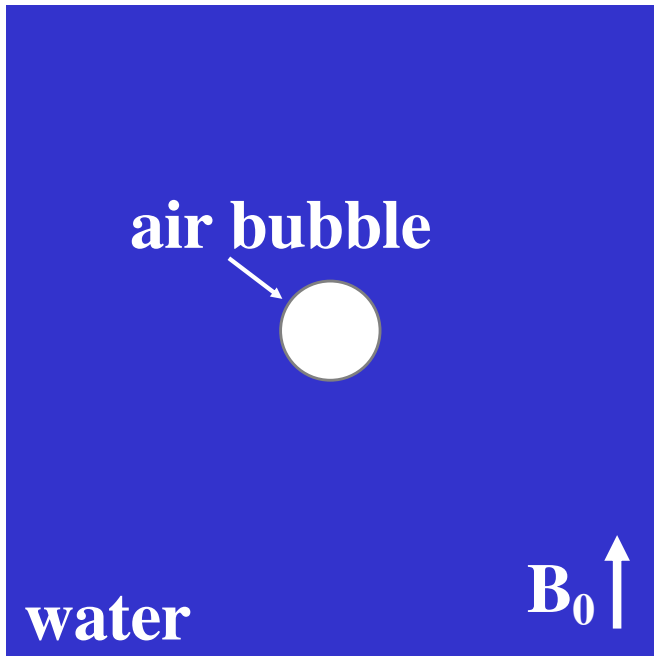
Answer: Any object placed within the main magnet changes the magnetic field!

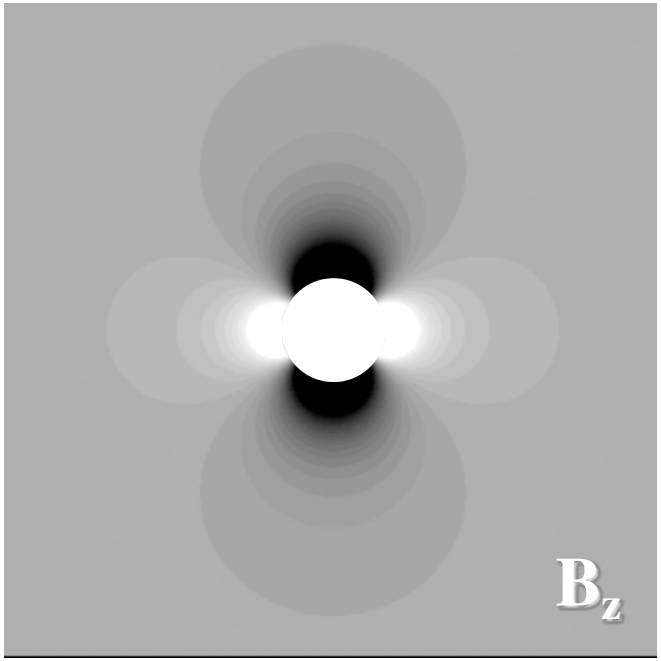
Magnetic Susceptibility

- All materials are magnetized to some degree.

$$B=\mu_0(1+\chi_m)H$$

χ_m: magnetic susceptibility



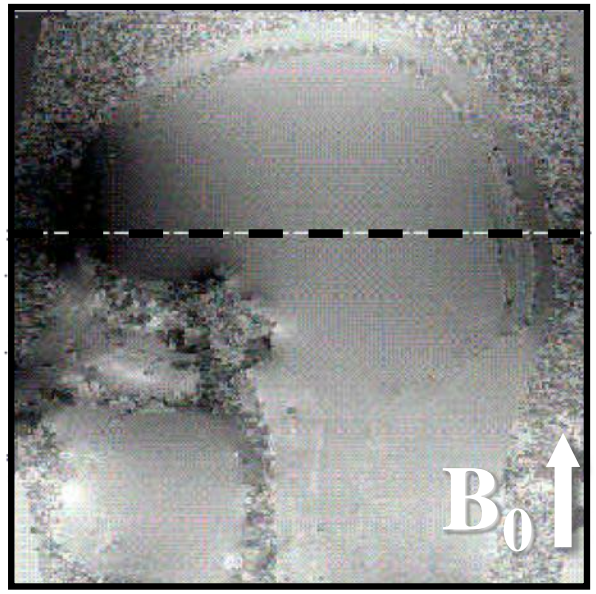


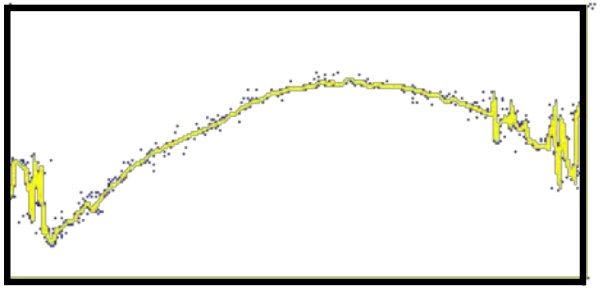
Susceptibility: air = 0.000004, water = -0.000002

max shift about ±10 ppm

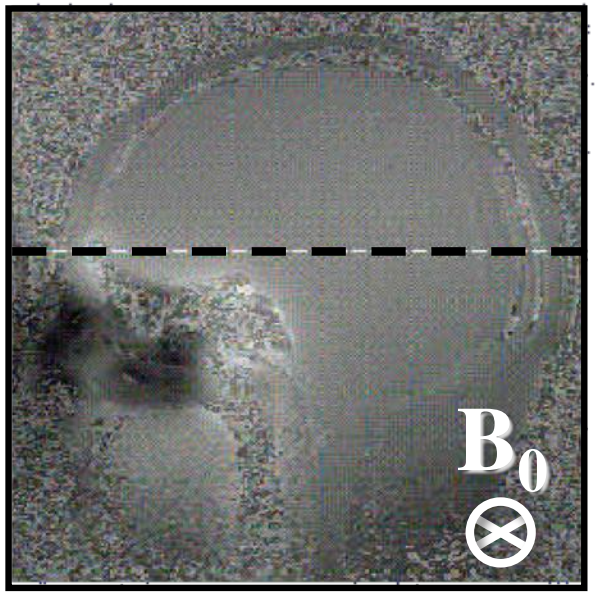
Susceptibility and B_0 orientation

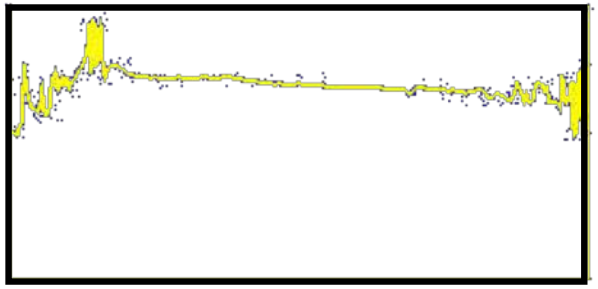
Parallel (0.5T)





Orthogonal (0.5T)

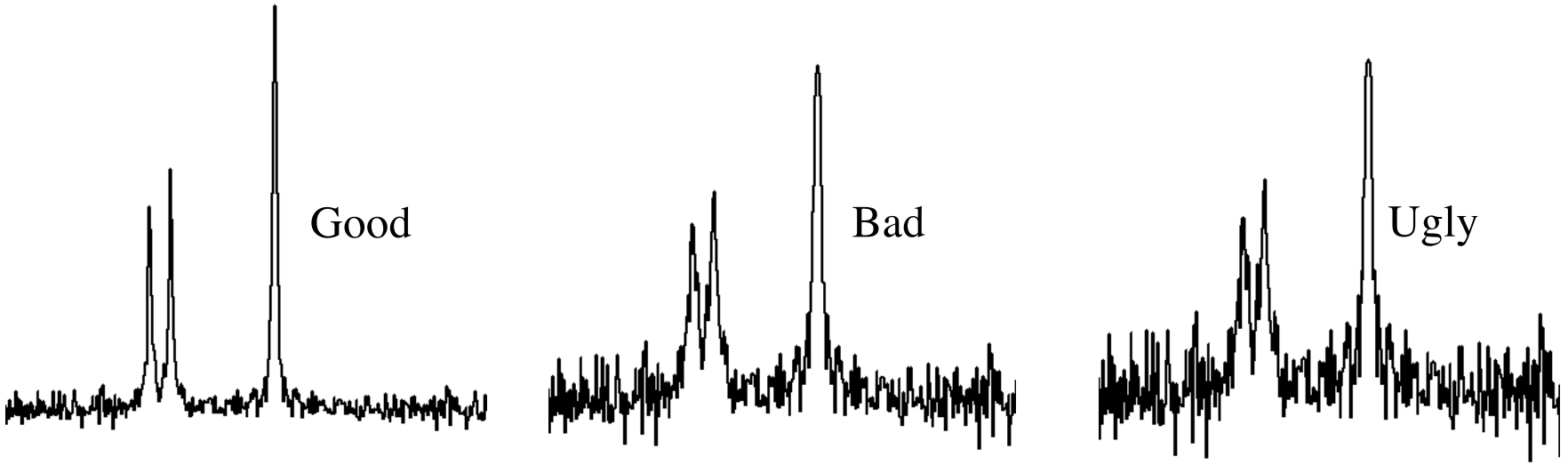




High Field Magnets (≥3T)

- 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:



3T T_2 dominated 3T T_2^* dominated 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-insenitive sequences
  - High field MRSI: other nuclei, improved spectral editing

Next Lecture: Clinical MRS I