Advanced MRI in the Clinic: MR Spectroscopy

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Information Encoding

Larmor equation

\[ \omega = \gamma B \]

Extrinsic factors
- \( B_0 \)
- Magnetic field gradients
- Magnetic field inhomogeneity

Intrinsic factors
- Electron shielding
- J-coupling

Magnetic information specific
encoded in frequency, \( ^{13}\text{C} \), etc.)
Information Encoding

Larmor frequency
\[ \omega = \gamma B \]

Electron shielding
\[ B_i = \sigma B_0 \]
\[ \sigma \text{- shielding constant} \]
\[ \delta = B_0 - B_i \]
\[ B = B_0 (1 - \sigma) \]
\[ \omega = \gamma B_0 (1 - \sigma) \]

Scalar spin-spin interaction (\( J \)-coupling)
Interaction between spins mediated through chemical bonds

Chemical Shift

\[ \omega_i = \gamma B_0 (1 - \sigma_i) \]
\[ \nu_i = \gamma B_0 (1 - \sigma_i)/2\pi \]

\[ \delta_i = (\nu_i - \nu_{\text{ref}})/\nu_0 \]

Chemical shift reference
Tetramethysilylamine (TMS)

- independent of \( B_0 \)
- units: ppm

increased proton shielding

Chemical Encoding

Information Encoding

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increased proton shielding
180° RF pulse does NOT re-phase evolution due to J-coupling.

Choice of TE affects spectral peak appearance of coupled nuclei.
4 Requirements for Successful MRS

1. Incredibly homogeneous magnetic field
2. Effective water/fat suppression
3. High-quality localization
4. Robust analysis

Magnetic Field Homogeneity

- MRI requires a homogeneous magnetic field. MRS requires an incredibly homogeneous field.
- FWHM \( \propto \frac{1}{T_2^*} \) so better homogeneity \( \rightarrow \) narrower peaks (i.e. better spectral resolution).
- Narrow peaks are also required for good water suppression.
- Good shimming is critical
  - Figure out which technique works best on your scanner.
  - Repeat the shim and/or re-position the patient if necessary.
  - Use a system with at least 2nd-order shims.
Water suppression

- Water signal (55M) must be suppressed to accurately visualize metabolite signals (0.5-10mM), even with high-quality digital ADCs.
- Our goal is to suppress the water signal by >98%.
- Relaxation-based methods (e.g. IR prep) are problematic so most clinical techniques use chemically-selective saturation (i.e. FatSat tuned to water).
- CHESS is the most common in the clinic.
- As a general rule, the longer and stronger (i.e. more time and/or SAR), the better the water suppression.
Water suppression

3x CHESS

Courtesy of Allen D. Elster, MRIquestions.com

VAPOR


Water suppression

STEAM
TE = 2 ms

gain x 3000

Courtesy of Ivan Tkáč
Localization

- For a spectrum to aid clinical diagnosis, the location from which it was obtained must be known accurately.
- Surface coil localization was originally used for superficial lesions and cardiac studies, but is no longer common.
- Single voxel spectroscopy (SVS) and multi-voxel spectroscopy (MVS, a.k.a. spectroscopic imaging [SI]) are currently used in the clinic.

Single voxel spectroscopy (SVS)

- Most common technique.
- Simple to acquire and interpret.
- Excellent SNR efficiency.
- Single, localized voxel allows for excellent shimming and, therefore, high-quality spectra.
- Many sequences clinically available.
Stimulated Echo Acquisition Mode (STEAM)

Point Resolved Spectroscopy (PRESS)
Localization by Adiabatic Selective Refocusing (LASER)


semi-LASER

semi-LASER

Mitigates most of the problems with LASER, while keeping most of the benefits of using adiabatic pulses.

Sequence Recommendation

For routine clinical use:

1. Try semi-LASER if you have it.
2. If not available, try PRESS (3 T and lower) or STEAM (7 T).

Multi-Voxel Spectroscopy (MVS)

- A larger total coverage area takes the guesswork out of SVS voxel placement and permits “mapping” of metabolite distribution.
- Smaller individual voxels are possible, which leads to higher spatial resolution, but lower SNR and potential spectral contamination from adjacent voxels.
- Acquisition times are usually long, though acceleration techniques are clinically available.
- Difficulties obtaining a good shim/water suppression over the entire region often results in reduced quality.
- MVS sequences are usually just SVS sequences with phase encoding.
MRS Analysis

- Goal is to quantify different metabolites and several software packages are available.
- Spectra are processed (baseline correction, phase correction, apodization, Fourier transform, etc.) and then quantified.
- Some software programs are significantly more advanced than others.

MRS Analysis Software

<table>
<thead>
<tr>
<th>Vendor Basic</th>
<th>Vendor Agnostic</th>
<th>Vendor Advanced</th>
</tr>
</thead>
<tbody>
<tr>
<td>Comes with the vendor MRS package.</td>
<td>e.g. LCModel, Tarquin</td>
<td>e.g. Syngo, IntelliSpace, READYView</td>
</tr>
<tr>
<td>Often automatic.</td>
<td>Very advanced software with sophisticated fitting algorithms.</td>
<td>Best of both worlds.</td>
</tr>
<tr>
<td>Very simple peak height or integral quantification.</td>
<td>Fully customizable (basis sets, metabolites, processing, etc.).</td>
<td>Rapidly approaching vendor agnostic software in terms advanced features.</td>
</tr>
<tr>
<td>Only a few metabolites can be quantified.</td>
<td>Provide estimates of quantification errors and metrics of spectral quality.</td>
<td>Allows for sophisticated processing, custom metabolites, error estimation, etc.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Not FDA approved.</td>
</tr>
</tbody>
</table>
MRS Artifacts

- Artifacts in MRS appear very different from artifacts in MRI and are often less conspicuous.

Motion artifact
Susceptibility Artifact

- Poor shimming results in wide, short (low SNR), and poorly-separated peaks.
- Strong susceptibility artifacts may arise from air-tissue interfaces, blood products, etc.
- The presence of strong susceptibility gradients may prevent a good shim and, therefore, the acquisition of high-quality spectra.

Poor Water Suppression

- Poor water suppression is usually evidenced by non-linear baselines and low peak SNR, especially above 3.5 ppm.
- Often due to poor shim and more common in MVS (where getting a good shim over the entire volume is challenging).
Signal Bleed

- Typically evidenced by the phase difference and broadness of the peak.
- This particular voxel was located very near the skull and sequence/pulse imperfections (and, possibly, patient motion) acquired some signal from the scalp.
- OVS is important.

CNS

- MRS is indicated for a variety of neurological conditions
- The most common uses include:
  - Primary diagnosis of brain lesions.
  - Distinguishing recurrent brain tumor from radiation necrosis.
  - Diagnosis of inborn errors of metabolism affecting the CNS.
CNS

- **Primary peaks:**
  - Total NAA (2.0 ppm)
    - N-acetylaspartate and N-acetylaspartylglutamate
    - Neuronal marker
  - Total Cr (3.0 ppm)
    - Creatine and phosphocreatine
    - Energy buffer
  - Total Ch (3.2 ppm)
    - Choline, glycerophosphorylcholine and phosphorylcholine
    - Membrane turnover

- **Other peaks:**
  - Glx (glutamine, glutamate)
  - γ-Aminobutyric acid
  - Lactate
  - Lipids
  - Myo- and scyllo-inositol
  - Citrate
  - (D)-2-hydroxyglutarate (2HG)
  - Taurine
  - Glucose
  - Ethanol
  - Mannitol
  - Acetate and succinate
  - Branched-chain amino acids

** Courtesy of R. Jason Stafford **

MRS QA

- AAPM Report 100 (2010) details recommended MRS acceptance testing using a phantom.
- I personally argue that phantom-based MRS QA alone is insufficient since the phantom poorly emulates both the biochemical milieu and electromagnetic environment found in vivo.
- I would argue that every spectrum from every scan from every patient be verified for quality before being sent to a radiologist.

Reimbursement

- CPT code 76390
Thank you!