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Community-organized Resources for Reproducible MRS Data Analysis

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In 2021, the de-facto gold-standard *in-vivo* magnetic resonance spectroscopy (MRS) analysis software, LCModel[1], transitioned from proprietary/paid to an open-source/free model. For 29 years, this software has fulfilled the demand for robust analysis workflows, while at the same time restricting access and dissuading continued development. We argue that this moment represents a golden opportunity for MRS developers and users to transition towards collaborative community-sourced workflows and datasets.

NMR spectroscopy preceded MR medical imaging by decades and offers unique potential to non-invasively extract biochemical information. However, the clinical impact of in-vivo MRS is modest compared to functional, diffusion, perfusion, or magnetization transfer imaging. One particular reason is comparably low replicability and comparability of metabolite estimates across MRS groups, which is exacerbated by heterogeneous analysis approaches and poor validation[2–5]. This hardly comes as a surprise, as MRS spans several highly specialized sub-fields (X-nuclei, spectral editing, spectroscopic imaging), all operating under low-signal-to-noise conditions relative to conventional MRI. Like any inherently quantitative technique, MRS estimates depend on decisions made during preprocessing, modeling, and quantification[2,3]. Historically, MRS groups tend to use local data analysis infrastructure, often matured over years of research. However, local operational continuity comes at the expense of

comparability, reproducibility and repeatability of metabolite estimates across sites, vendor ecosystems, and software environments. Expert consensus recommendations on data acquisition[6–8], processing and modeling[9], macromolecule handling[10], nomenclature[11], and reporting[12] have recently been published, recognizing the need for methodological harmonization. These recommendations need to be widely adopted. But shifting established lab-specific workflows to consensus practices requires effort with little incentive (or funding) to individual labs.

We propose a more efficient way of implementing consensus: pooling resources to create community-organized deliverables like software tools, databases, continued support, and educational material. This paradigm is applicable for single-voxel MRS (where substantial consensus exists), and can serve as a template for spectroscopic imaging, which is methodologically more diverse and consensus formation is less mature. There is precedent in the magnetic resonance community: the fMRI field has been able to build around collaborative open-source platforms (AFNI[13], SPM[14], FSL[15]) from its earliest days. This allowed the community and software developers to identify weaknesses, integrate new methods into mainstream workflows, and boost standardization.

As consensus recommendations emerge, a shift in the MRS field towards community organization has already occurred. Four authors of this article served as inaugural members of the Code & Data Sharing Committee of the ISMRM MR Spectroscopy Study Group, creating community resources and efforts to harmonize spectroscopic data storage into the NIfTI-MRS format[16] and a BIDS[17] MRS extension proposal. Open-source end-to-end analysis software[18–22] has emerged for a variety of environments (Python, MATLAB, and R), including modular consensus-based preprocessing routines and customizable linear-combination-modeling algorithms. The coalescence of these initiatives occurred at an auspicious moment: the transition of the LCModel software to open-source and free availability.

We challenge the community to look upon this convergence of events as an opportunity for MRS developers and users alike to transition towards community-organized resource building. The ultimate endpoint is an ecosystem of interoperable analysis tools and datasets, created and maintained through community projects and connected by standardized data storage specifications. This will:

- encourage consensus adoption,
- facilitate development and validation of new MRS methods,
- accelerate integration into mainstream usage,
- offer long-term accessibility and maintenance,
- reduce duplicate efforts.

This new generation of analysis software and harmonized data storage can evolve continuously to disseminate consensus, distribute new methods, safeguard accessibility and longevity, and promote critical evaluation. In tandem with increasingly ”open data” (in-vivo and synthetic-realistic), validation and benchmarking will become easier and more accessible, providing training and validation data for emerging neural-network-based approaches as a welcome side effect. Importantly, new methods encoding additional information into an MRS acquisition are maturing, for example diffusion-weighted[23–25], functional[26,27], and multi-parametric MRS[28], unlocking access to cell-type-specific microstructure, dynamic metabolism, and individual relaxometry. This new generation of experiments needs a new, innovative generation of multi-spectrum tools, allowing to incorporate physical relationships between spectra and break the barriers of traditional single-spectrum modeling.

The enduring popularity of the LCModel application is proof that the MRS field demands well-structured analysis methods. Its transition to open-source paves the way for collective resource building in

the MRS field. The MRSHub (https://www.mrshub.org) is a free online gathering place for the MRS community to share resources and contribute solutions. We call upon MRS developers to contribute their new methods into this community ecosystem that increases availability and accelerates uptake and validation. We encourage MRS users to take advantage of the modular, consensus-based, open-source pipelines in MRSHub to drive access to reproducible state-of-the-art analysis. This approach will improve access to advanced methods for users at a broader range of institutions and foster adoption of consensus recommendations by researchers and scanner manufacturers alike, ultimately removing barriers to the adoption of MRS in the clinic.

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