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REVIEW

Reproducible Research Practices in Magnetic Resonance Neuroimaging: A Review Informed by Advanced Language Models

Agah Karakuzu[1,2], Mathieu Boudreau[1†], and Nikola Stikov[1,2,3†*]

MRI has progressed significantly with the introduction of advanced computational methods and novel imaging techniques, but their wider adoption hinges on their reproducibility. This concise review synthesizes reproducible research insights from recent MRI articles to examine the current state of reproducibility in neuroimaging, highlighting key trends and challenges. It also provides a custom generative pretrained transformer (GPT) model, designed specifically for aiding in an automated analysis and synthesis of information pertaining to the reproducibility insights associated with the articles at the core of this review.

Keywords: *magnetic resonance imaging methods, reproducibility, scoping review*

Introduction

Reproducibility is a cornerstone of scientific inquiry, particularly relevant for data-intensive and computationally demanding fields of research, such as MRI.[1] Ensuring reproducibility thus poses a unique set of challenges and necessitates the diligent application of methods that foster transparency, verification, and interoperability of research findings.

While numerous articles have addressed the reproducibility of clinical MRI studies, few have looked at the reproducibility of the MRI methodology underpinning these studies. This is understandable given that the MRI development community is smaller, driven by engineers and physicists, with modest representation from clinicians and statisticians. However, performing a thorough meta-analysis or a systematic review of these studies in the context of reproducibility presents challenges due to: (i) the diversity in study designs across various MRI development subfields, and (ii) the absence of standardized statistics to gauge reproducibility performance.

[1]NeuroPoly Lab, Institute of Biomedical Engineering, Polytechnique Montréal, Montréal, Quebec, Canada
[2]Montréal Heart Institute, Montréal, Quebec, Canada
[3]Center for Advanced Interdisciplinary Research, Ss. Cyril and Methodius University, Skopje, North Macedonia
[†]Mathieu Boudrjeau and Nikola Stikov contributed equally to this work.
*Corresponding author: 2500 Chem. de Polytechnique Room L-5608, Montréal, QC H3T 1J4, Canada. Phone: +1-514-340-4711 Ext. 4549,
E-mail: nikola.stikov@polymtl.ca

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Considering these challenges, we opted to conduct a mini-review leveraging the semantic extraction capabilities of the advanced language models. Specifically, we trained a custom generative pretrained transformer (GPT) model using a knowledge base constructed for a selection of articles coupled with web scraping of content pertaining to their reproducibility. With this mini-review, we aim to examine the current landscape of reproducible research practices across various MRI studies, drawing attention to common strategies, tools, and repositories used to achieve reproducible outcomes. We anticipate that this approach provides a living review that can be automatically updated to accommodate the continuously expanding breadth of methodologies, helping us identify commonalities and discrepancies across studies.

Methodology

In distilling reproducibility insights powered by GPT, this review centered on 31 research articles published in the journal Magnetic Resonance in Medicine (MRM), chosen by the editor for their dedication to enhancing reproducibility in MRI. Since 2020, the journal has published interviews with the authors of these selected publications, discussing the tools and practices they used to bolster the reproducibility of their findings (available at https://blog.ismrm.org/category/highlights).

Mapping selected articles in the semantic landscape of reproducibility

We performed a literature search to identify where these studies fall in the broader literature of reproducible neuroimaging. To retrieve articles dedicated to reproducibility in MRI, we utilized the Semantics Scholar API[2] with the following query terms on November 23, 2023: (code| data|

Fig. 1 Edge-bundled connectivity of the 612 articles identified by the literature search. A notable cluster (red) is formed by most of the MRM articles that were featured in the reproducible research insights (purple nodes), particularly in the development of MRI systems. Few other selected articles fell at the intersection of MRI systems, deep learning, and workflows (delineated by the dashed line). Notable clusters for other studies (pink) are annotated by gray circles. An interactive version of this figure is available at: https://preprint.neurolibre.org/10.55458/neurolibre.00021. MRM, Magnetic Resonance in Medicine.

open-source| github| jupyter) & ((MRI & brain) | (MRI & neuroimaging)) & reproducib~.

Among 1098 articles included in the Semantic Scholar records, SPECTER vector embeddings[3] were available for 612 articles, representing the semantics of publicly accessible content in abstracts and titles. For these articles, the high--dimensional semantic information captured by the word embeddings was visualized using the uniform manifold approximation and projection method[4] (Fig. 1). This visualization allowed the inspection of the semantic clustering of the articles, facilitating a deeper understanding of their contextual placement within the reproducibility landscape. In addition, to illustrate the hierarchical clustering of the selected studies in the broader literature, a PRISMA (Preferred Reporting Items for Systematic reviews and Meta-Analyses) diagram was provided (Fig. 2).

Creating a knowledge base for a custom GPT

We created a custom GPT model, designed specifically to assist in the analysis and synthesis of information pertaining to the 31 reproducible research insights. The knowledge base of this retrieval-augmented generation framework incorporates GPT-4 summaries of the abstracts from 31 MRM articles, merged with their respective MRM Highlights interviews, as well as the titles and keywords associated with each article (refer to Appendix A). This compilation was assembled via API calls to OpenAI on November 23, 2023, using the gpt-4-1106-preview model. Please visit https://preprint.neurolibre.org/10.55458/neurolibre.00021/gpt_insights.html to explore the respective Python (v3.8) scripts and to create newer versions of the summary file (requires an OpenAI authorization token).

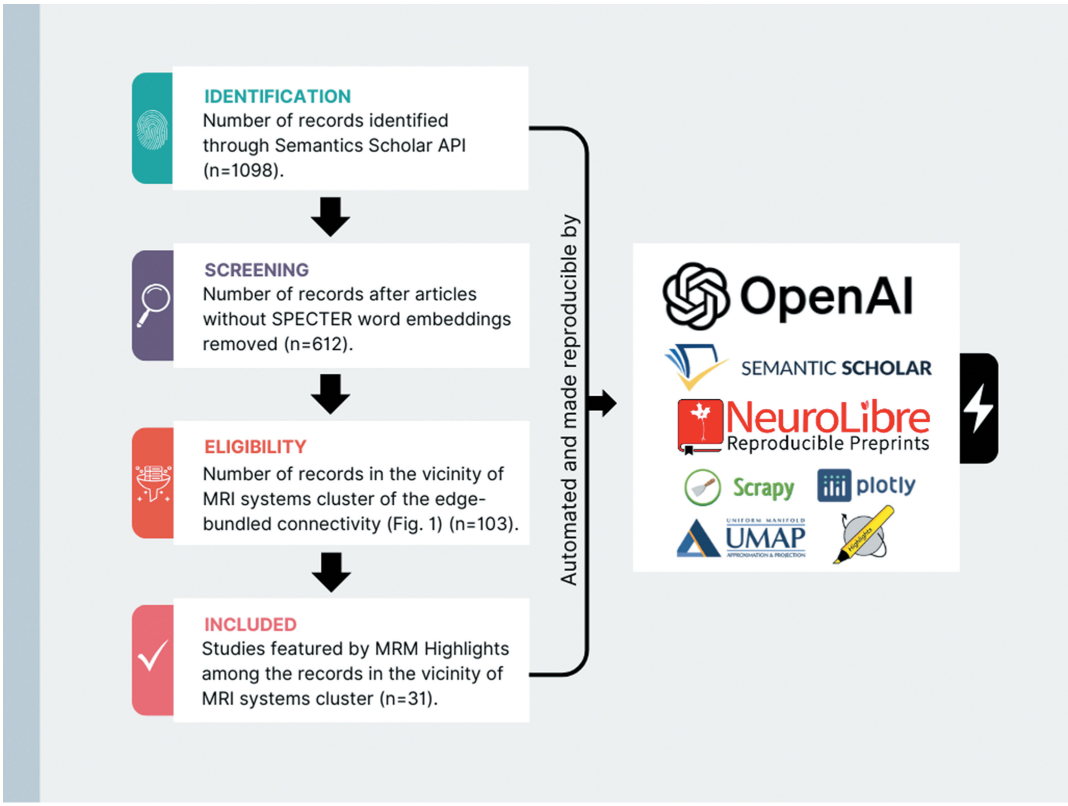

Fig. 2 PRISMA flow diagram illustrating the hierarchical relationship between the 31 studies included in the review and the broader literature on reproducible magnetic resonance neuroimaging. Web services and software packages used to automate this process are also displayed (right panel). PRISMA, Preferred Reporting Items for Systematic reviews and Meta-Analyses.

This specialized GPT, named RRInsights, is tailored to process and interpret the provided data in the context of reproducibility; for the system prompts, please see Appendix B.

Results

Contextual placement of the selected articles in the landscape of reproducibility

The MRI systems cluster was predominantly composed of the majority of the selected MRM articles (23/31), with only two publications appearing in a different journal.[5,6] Additionally, this cluster was sufficiently distinct from the rest of the reproducibility literature, as can be seen by the location of the dark red dots in Fig. 1. Few other selected articles (8/31) were found at the intersection of the MRI systems, deep learning, and data/workflows clusters, which in total spans 103 articles. Since the custom GPT model was trained on the 31 selected MRM articles (red dots), Fig. 1 serves as a map for inferring the topics where RRInsights is more likely to be context-aware.

Custom GPT for reproducibility insights

Through its advanced natural language processing capabilities, RRInsights can efficiently analyze the scoped literature, extract key insights, and generate comprehensive overviews of the research papers focusing on MRI technology. The custom GPT is available at https://chat.openai.com/g/g-5uDwBlnx4-rrinsights (requires subscription as of May 2024).

Figure 3 presents an example interaction with RRInsights to create a summary of the vendor-neutral solutions found in the knowledge base. The model's response to this inquiry demonstrates that RRInsights is context-aware, adept at pinpointing relevant information in the knowledge base, and offering interpretations within the framework of reproducibility. The following subsections are written based on the interactions with RRInsights:

GPT-Powered Summary of the Reproducible Magnetic Resonance Neuroimaging

Most MRI development is done on commercial systems using proprietary hardware and software. Peeking inside the black boxes that generate the images is nontrivial, but it is essential for promoting reproducibility in MRI.

Quantitative MRI articles are powerful showcases of reproducible research practices, as they usually come with fitting models that can be shared on public code repositories. The applications range from MR spectroscopy[7–10] to arterial spin labeling (ASL),[11] diffusion MRI,[12,13] chemical exchange

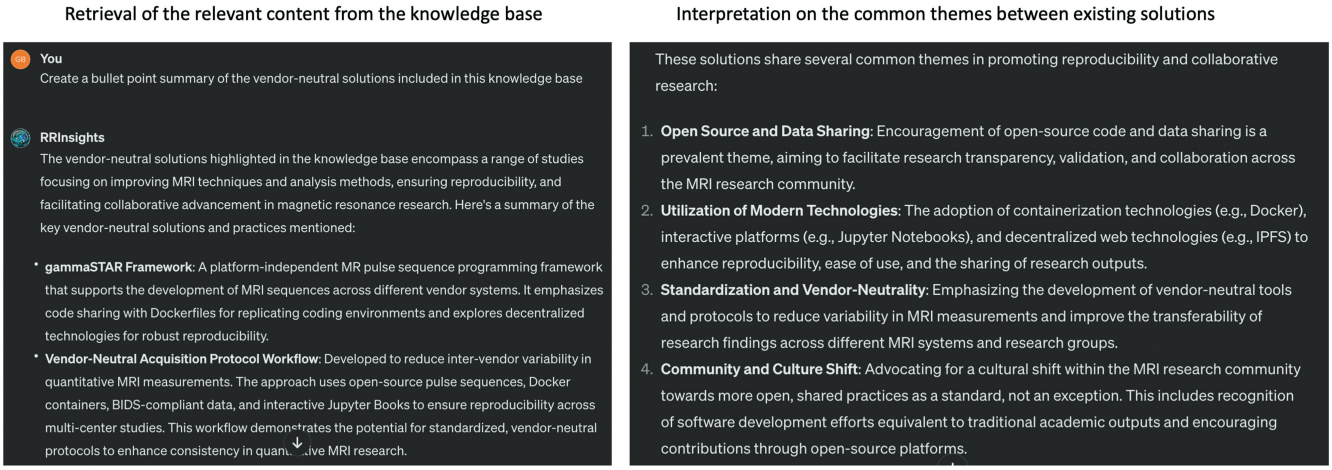

Fig. 3 An example of user interaction with the RRInsights custom GPT. The model efficiently retrieves relevant studies concerning the requested content, such as vendor-neutral solutions. It provides summaries that highlight thematic similarities, with a particular focus on reproducibility aspects. GPT, generative pretrained transformer.

saturation transfer (CEST),[14] magnetization transfer,[15–17] B_1 mapping,[18] and relaxometry.[16–20]

Transparent reconstruction and analysis pipelines are also prominently featured in the reproducible research insights, including methods for real-time MRI,[21] parallel imaging,[22] large-scale volumetric dynamic imaging,[23] pharmacokinetic modeling of dynamic contrast-enhanced MRI (DCE-MRI),[24] phase unwrapping,[25] hyperpolarized MRI,[26] Dixon imaging,[27] and X-nuclei imaging.[28] Deep learning is increasingly present in the reproducibility conversation, as MRI researchers are trying to shine a light on AI-driven workflows for phase-focused applications,[29] CEST,[14] diffusion-weighted imaging,[30] myelin water imaging,[18] B_1 estimation,[31] and tissue segmentation.[32]

Reproducibility of MRI hardware is still in its infancy, but a recent study integrated RF coils with commercial field cameras for ultrahigh-field MRI, exemplifying the coupling of hardware advancements with software solutions. The authors shared the design CAD files, performance data, and image reconstruction code, ensuring that hardware innovations can be reproduced and utilized by other researchers.[33]

Finally, vendor-neutral pulse sequences are putting interoperability and transparency at the center of the reproducibility landscape. Pulseq and gammaSTAR are vendor-neutral platforms enabling the creation of MRI pulse sequences that are compatible with three major MRI vendors.[34,35] In addition, vendor-neutral sequences (VENUS) is an end-to-end vendor-neutral workflow that was shown to reduce inter-vendor variability in quantitative MRI measurements of myelin, thereby strengthening the reproducibility of quantitative MRI research and facilitating multicenter clinical trials.[36,37]

Data Sharing

There is a growing number of studies providing access to raw imaging data, preprocessing pipelines, and post-analysis results. Repositories like Zenodo, XNAT, and the Open Science Framework serve as vital resources for housing and curating MRI data. Data sharing is also made easier thanks to unified data representations, such as the International Society for Magnetic Resonance in Medicine (ISMRM) raw data format[38] for standardizing k-space data, and the Brain Imaging Data Structure for organizing complex datasets[39] and their derivatives.[40]

Code Sharing

Software repositories such as GitHub and GitLab are making it easier to centralize processing routines and to adopt version control, unit tests, and other robust software development practices. The introduction of tools for automated quality assurance (QA) processes, as seen in the development of platforms like PreQual for diffusion-weighted imaging (DWI) analysis,[12] signifies an emphasis on interoperability and standardization.

The increasing adoption of containerization and virtual environments makes workflows transparent and easy to execute. Tools like Docker and Singularity are used to package computing environments, making them portable and reproducible across different systems. Studies employing these tools enable MRI researchers to replicate computational processing pipelines without dealing with dependency issues in local computational environments.[32,35,36]

The rise of machine learning and artificial intelligence in MRI necessitates rigorous evaluation to ensure reproducibility. Studies that use deep learning are beginning to supplement their methodological descriptions with the open-source code, trained models, and simulation tools that underpin their algorithms. Algorithms such as DeepCEST, developed for B_1 inhomogeneity correction at 7T, showcase how clinical research can be improved by reproducible research practices.[14] Sharing these algorithms allows others to perform direct comparisons and apply them to new datasets.

Fig. 4 A word cloud generated from the 31 reproducible research insights published by Magnetic Resonance in Medicine Highlights.

Vendor Neutrality

Finally, pulse sequence and hardware descriptions are slowly entering the public domain.[33–36] For a long time, MRI vendors have been reluctant to open up their systems,[41] but standardized phantoms[42] are creating benchmarks that require transparency and reproducibility. This is particularly relevant for quantitative MRI applications, where scanner upgrades and variabilities across sites are a major hurdle to wider clinical adoption.[43–45]

Dissemination

Reproducibility is also bolstered by interactive documentation and tools such as Jupyter Notebooks, allowing for dynamic presentation and hands-on engagement with data and methods. Platforms incorporating such interactive elements are being utilized with greater frequency, providing real-time demonstration of analysis techniques and enabling peer-led validation. Resources such as MRHub (https://ismrm.github.io/mrhub), MRPub (https://ismrm.github.io/mrpub), Open Source Imaging (https://www.opensourceimaging.org/projects/), and NeuroLibre[46] serve as a gateway to a wide range of tools and tutorials that promote reproducibility in MRI. The curation of these resources is essential for ensuring that publications featuring Jupyter Notebooks and R Markdown files[47] remain executable and properly archived.[47,48]

Discussion and Future Directions

The progress toward reproducibility in MRI research points to a distinct cultural shift in the scientific community. The move toward open-access publishing, code sharing platforms, and data repositories reflects a concerted effort to uphold the reproducibility of complex imaging studies. Adopting containerization technologies, pushing for standardization, and consistently focusing on quality assurance are key drivers that will continue to improve reproducibility standards in MRI research.

Figure 4 is a word cloud generated from the articles included in this review, highlighting the concepts and vocabulary that are driving reproducibility in MRI. As can be seen from the figure, the components of reproducibility in MRI research are multifaceted, integrating not just data and code but also the analytical pipelines and hardware configurations. The shift toward comprehensive sharing is motivated both by a scientific ethic of transparency and the practical need for rigorous validation of complex methodologies.[49,50]

However, this shift is not without challenges.[51] Variations in data acquisition and analysis methodologies limit cross-study comparisons. Sensitivity to software and hardware versions can impede direct reproducibility. Privacy concerns and data protection regulations can be barriers to data sharing, particularly with clinical images.

While challenges persist, steps are taken by individual researchers and institutions to prioritize reproducibility. Moving forward, the MRI community should work collectively to overcome barriers, institutionalize reproducible practices, and constructively address data sharing concerns to further the discipline's progress.

The initiatives and tools identified in this review serve as a blueprint for future studies to replicate successful practices, safeguard against bias, and accelerate neuroscientific discovery. As MRI research continues to advance, upholding the principles of reproducibility will be essential to maintaining the integrity and translational potential of its findings.

We also hope that our methodology in generating this review will pave the way for future studies that leverage large language models to create unique literature insights. In particular, we believe that the RRInsights GPT can serve as a blueprint for generating a scoping review[52] and inspire other scientists to experiment with the format of scientific publications in the age of AI.

To find out more about each of the reproducible research insights featured in this review, we encourage you to visit the NeuroLibre version of this review, which features interactive figures, brief summaries of the featured articles, and a link to the RRInsights GPT: https://preprint.neurolibre.org/10.55458/neurolibre.00021

Conflicts of Interest

The authors have no conflict of interest to declare.

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Appendix A

Paper number: 1
Year: 2022
Title: In vivo magnetic resonance 31P-Spectral Analysis With Neural Networks: 31P-SPAWNN

Keywords: 31P-SPAWNN, neural networks, reproducibility, magnetic resonance spectroscopy

Study Achievements and Reproducibility Summary:

1. The study introduced a new artificial intelligence framework, 31P-SPAWNN, for analyzing 31P magnetic resonance spectra, demonstrating that it provides a fast and flexible alternative to traditional least-square fitting methods.
2. Reproducibility was exemplary as the authors shared the source code, simulations, their deep learning network, and sample datasets, enabling other researchers to test, validate, and reproduce their results easily.
3. Open sharing of the code and data was motivated by a commitment to collaborative advancement in MR research and the drive to facilitate incremental knowledge growth within the community without redundant effort.
4. The authors suggest best practices for sharing research repositories, including comprehensive documentation, logical organization, and the use of tools like Docker or Singularity to improve the portability and consistency of the computational research environment, thereby enhancing reproducibility further.

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Paper number: 2
Year: 2020
Title: Comparison of single breath hyperpolarized 129Xe MRI with dynamic 19F MRI in cystic fibrosis lung disease

Keywords: Cystic Fibrosis, Hyperpolarized 129Xe MRI, Dynamic 19F MRI, Ventilation Abnormalities

Study Achievements and Reproducibility Summary:

1. The study achieved a quantitative comparison between dynamic 19F MRI and single breath hyperpolarized 129Xe MRI for detecting ventilation abnormalities in subjects with mild CF lung disease, contributing valuable insights into the efficacy of different imaging modalities for CF assessment.
2. Reproducibility was enhanced by sharing the code and data that reproduce several figures, allowing others in the research community to validate and potentially extend the findings.
3. The decision to share came during the submission process, and recognizing the benefits, including feedback and collaboration, the team has been motivated to continue sharing for future publications.
4. The researchers advocate for culture change within the MRI community where data sharing becomes an expectation and plan to explore additional reproducibility tools, such as explanatory videos, to further disseminate their research methods and findings.

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Paper number: 3
Year: 2019
Title: Extreme MRI: Large-scale volumetric dynamic imaging from continuous non-gated acquisitions

Keywords: Dynamic MRI, Non-gated Acquisition, Large-scale Volumetric Imaging, Pulmonary Imaging

Study Achievements and Reproducibility Summary:

1. The study achieved the development of a framework capable of reconstructing large-scale volumetric dynamic MRI images from continuous, non-gated acquisitions, with successful applications demonstrated in pulmonary and DCE imaging.
2. Reproducibility was prioritized through the sharing of code and an interactive Google Colab notebook demo, which allows for easy visualization and manipulation of the reconstruction process.
3. The culture of sharing within UC Berkeley and the research team directly influenced the early decision to share code/data, with the practice of version controlling, documentation, and unit tests facilitating the sharing process.
4. Encouraging open-source contributions in the MRI community via showcases, hands-on sessions, and interviews has proven effective, and the authors intend to continue these efforts while exploring additional platforms like Zenodo for data hosting.

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Paper number: 4
Year: 2021
Title: Improved 3D real-time MRI of speech production

Keywords: Real-Time MRI, Speech Production, 3D Reconstruction, Variable-Density Sampling

Study Achievements and Reproducibility Summary:

1. The study achieved improvements in 3D real-time magnetic resonance imaging (MRI) of speech production, offering increased spatio-temporal sharpness by using a novel stack-of-spiral sampling and reconstruction method.
2. Reproducibility was enhanced by sharing well-documented code and data, as well as utilizing BART, a widely-recognized MRI toolbox, ensuring that the research can be re-executed and validated by others.
3. The researchers chose to share code and data to maximize the potential impact of their work, facilitate better understanding, and contribute to the growing culture of reproducible research within their community.
4. The authors advocate that recognizing and honoring research with shared code/data, spreading awareness of the impact of open-source contributions, and enhancing educational resources can encourage more researchers to adopt reproducible research practices. They also intend to explore additional practices, such as shell scripts and interactive notebooks, for future projects.

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Paper number: 5
Year: 2019
Title: Steady-state imaging with inhomogeneous magnetization transfer contrast using multiband radiofrequency pulses

Keywords: Inhomogeneous Magnetization Transfer, Multiband RF Pulses, Myelin Imaging, Steady-State MRI

Study Achievements and Reproducibility Summary:

1. The study developed a technique for generating inhomogeneous magnetization transfer (ihMT) contrast in MRI using nonselective multiband radiofrequency pulses during rapid steady-state pulse sequences, potentially improving the specificity of imaging myelinated tissues.
2. Reproducibility was supported by the sharing of robustly documented code on GitHub, encouraging others to reproduce, understand, and extend the methods used.
3. The open-source ethos of the research group and support from the UK funding agencies have contributed to the continuous practice of sharing code and data as a default policy.
4. While sharing non-human data and code for image reconstruction and simulation is standard practice for the group, future consideration may include exploring the sharing of in vivo data, all with the aim of enhancing reproducibility and encouraging cumulative science.

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Paper number: 6
Year: 2020
Title: A novel gamma GLM approach to MRI relaxometry comparisons

Keywords: Gamma GLM, MRI Relaxometry, CV Analysis, Data Fitting

Study Achievements and Reproducibility Summary:

1. The study introduced a novel statistical framework using a gamma generalized linear model identity link (GGLM-ID) that accounts for the constant coefficient of variation in MRI relaxometry data, offering more accurate parameter estimates compared to standard linear models.
2. Reproducibility is enhanced through the sharing of R Markdown PDF documents detailing the analysis method, alongside an R Shiny dashboard that allows for interactive data fitting without the need for extensive programming knowledge.
3. The authors were motivated by MRM guidelines and a commitment to transparency to share their code, aiming to make their methods widely accessible and facilitate the adoption of their recommendations.
4. In future work, they plan to continue sharing code and data, potentially utilizing more interactive and educational tools like Jupyter Notebooks or alternative platforms that further support open science and reproducible research practices.

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Paper number: 7
Year: 2021
Title: Analysis of deep complex-valued convolutional neural networks for MRI reconstruction and phase-focused applications

Keywords: Complex-Valued CNNs, MRI Reconstruction, Phase Imaging, Deep Learning

Study Achievements and Reproducibility Summary:

1. The study rigorously investigated the use of end-to-end complex-valued convolutional neural networks (CNNs) for accelerated MRI reconstruction, highlighting their advantages over 2-channel real-valued networks, especially for phase-focused applications.
2. Reproducibility was ensured by sharing the project's code on GitHub, including a requirements file to specify code dependencies, and by detailing the training/testing processes for their deep learning models.
3. The decisions on data/code sharing were guided by lab and institutional policies, as well as data privacy considerations, and active steps were taken to anonymize data sets and secure necessary permissions for sharing.
4. To promote a culture of open source code contribution, the researcher recommended MRI challenges where code is a submission requirement and showed an interest in exploring new platforms, such as Weights & Biases, for enhanced tracking and reproducibility of research results.

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Paper number: 8
Year: 2022
Title: Fourier-based decomposition for simultaneous 2-voxel MRS acquisition with 2SPECIAL

Keywords: 2-Voxel MRS, 2SPECIAL Sequence, vGRAPPA Decomposition, 7T MRI

Study Achievements and Reproducibility Summary:

1. This study developed and successfully implemented a Fourier-based decomposition method using a voxel-GRAPPA (vGRAPPA) approach to simultaneously acquire and discern spectroscopic data from two MRS voxels within the brain at 7T, achieved by a multi-banded 2 spin-echo, full intensity acquired localized (2SPECIAL) sequence.
2. Reproducibility was underscored by sharing a meticulously documented GitLab code repository that included example data, the vGRAPPA algorithm, and a demo script, inviting external researchers to assess and build on the work.
3. From inception, there was a clear intent to share the code and data, inspired by a broader culture of transparency and accountability in using public funds for research, as well as initiatives from scientific organizations that encourage reproducible practices.
4. To further stimulate the sharing of open-source materials within the MRI community, the researchers suggest giving published data sets and code equivalent scientific merit to traditional publications, which would acknowledge the time and effort required to produce high-quality, reusable research outputs.

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Paper number: 9
Year: 2021
Title: Accurate free-water estimation in white matter from fast diffusion MRI acquisitions using the spherical means technique

Keywords: Free-Water Estimation, Fast Diffusion MRI, Spherical Means Technique, White Matter

Study Achievements and Reproducibility Summary:

1. The study achieved an accurate estimation of the free-water partial volume in white matter from fast diffusion MRI acquisitions using a spherical means technique, with a methodology not requiring strong sensitizing gradients or extensive different b-value collections.
2. Reproducibility was enhanced by integrating the newly developed tools into the dMRI-Lab, a MATLAB toolbox that is maintained and kept available publicly, allowing for

easy application and testing of the research outcomes by the broader scientific community.
3. The researchers recognized the increased visibility and potential for adoption that comes with sharing code, leading them to commit to making their diffusion MRI processing tools readily available within their evolving toolbox.
4. They believe that institutional recognition for software development and maintenance alongside traditional academic metrics such as publication numbers could encourage more researchers to invest time in creating open-source code, which is currently underestimated in the evaluation of researchers' contributions.

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Paper number: 10
Year: 2020
Title: Accelerated calibrationless parallel transmit mapping using joint transmit and receive low-rank tensor completion

Keywords: Parallel Transmit Mapping, Accelerated MRI, Calibrationless Imaging, Low-rank Tensor Completion

Study Achievements and Reproducibility Summary:

1. The study developed an algorithm to reconstruct undersampled parallel transmit field maps efficiently for both body and brain MRI without the need for calibration data, using a joint transmit and receive low-rank tensor completion approach.
2. Reproducibility was facilitated by sharing all scripts and data necessary to reproduce every figure published in the paper, enabling independent validation and educational opportunities for others.
3. The researchers had a proactive approach to sharing code and data from the start of the project, which allowed for thorough documentation and adherence to good practices. They also ensured data protection compliance by re-organizing brain dataset releases to avoid reconstruction of de-anonymizing facial features.
4. They suggest that rewarding and citing open-source contributions, as well as potentially creating a dedicated category for papers detailing community resource releases, could further encourage the MRI community to contribute open-source code alongside research papers. Additionally, they express interest in using container tools like Docker or Singularity for managing dependencies in future work.

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Paper number: 11
Year: 2021
Title: A model-based framework for correcting B1+ inhomogeneity effects in magnetization transfer saturation and inhomogeneous magnetization transfer saturation maps

Keywords: B1 Inhomogeneity Correction, Magnetization Transfer Saturation, Numerical Simulation, MRI Mapping

Study Achievements and Reproducibility Summary:

1. The study proposed a model-based framework to correct ΔB1+ (B1 inhomogeneity) errors in magnetization transfer saturation (MTsat) and inhomogeneous magnetization transfer (ihMT) saturation maps, using an R1 and B1+ map alongside numerical simulations of the sequence.
2. Reproducibility was supported by sharing the code associated with the paper, featuring extensive and detailed documentation within the code and on external platforms such as GitHub.
3. The code release aligns with the lab's open science practices, supported by their institution, particularly after paper publication and peer-review to ensure meaningful and validated outputs are distributed.
4. By releasing their code, the authors aimed to facilitate the MRI community's ability to implement B1 inhomogeneity corrections, with the benefit of aiding peer validation, enhancing educational value, and fostering good internal documentation and archiving practices. They also expressed an interest in exploring interactive scripting tools like Jupyter Notebooks in future work.

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Paper number: 12
Year: 2020
Title: Myelin water fraction estimation using small-tip fast recovery MRI

Keywords: Myelin Water Fraction, Small-Tip Fast Recovery MRI, Optimization, Brain Imaging

Study Achievements and Reproducibility Summary:

1. The study demonstrates the feasibility of using an optimized set of small-tip fast recovery (STFR) MRI scans for rapidly estimating the myelin water fraction (MWF) in the brain, providing an efficient approach to brain imaging.
2. Reproducibility was prioritized by sharing all the code used in the research, accompanied by scripts that allow for the reproduction of every figure in the paper, fostering transparency and enabling peers to build upon their work.
3. Sharing was an integral component from the beginning of the project, with the understanding that releasing code and data would contribute to educational efforts and facilitate validation by others in the field.
4. The researchers suggest embedding reminders about code/data sharing within the manuscript submission system and considering code/data citations for open-source contributions, thereby encouraging more MRI researchers to share their work openly. They also made use of Julia as a programming language for its interactive nature and swift execution, and expressed an interest in enhancing documentation and exploring Jupyter Notebooks for future projects.

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Paper number: 13
Year: 2021
Title: Image- versus histogram-based considerations in semantic segmentation of pulmonary hyperpolarized gas images

Keywords: Segmentation, Hyperpolarized Gas MRI, Algorithm Comparison, Pulmonary Imaging

Study Achievements and Reproducibility Summary:

1. The study explored and characterized the differences between histogram-based and image-based algorithms for segmenting hyperpolarized gas lung images, assessing their respective capabilities and limitations.
2. Reproducibility was emphasized through the sharing of scripts and data necessary to reproduce every figure in the paper, making the research transparent and allowing others to verify and build upon the findings.
3. The authors decided to share their resources from the beginning of the project, advocating the benefits of open-source development as both a means to enhance the quality of work and to facilitate collaborative opportunities.
4. By releasing detailed documentation and contributing to broader software projects like the Advanced Normalization Tools (ANTs), the researchers have demonstrated a commitment to long-term usability and improvement of their software, all the while fostering a culture of openness and educational growth within the MRI community. They also expressed an interest in further integrating tools like Rmarkdown and Jupyter notebooks for increased reproducibility in future work.

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Paper number: 14
Year: 2019
Title: Artificial neural network for myelin water imaging

Keywords: Myelin Water Imaging, Artificial Neural Network, Deep Learning, Real-Time Processing

Study Achievements and Reproducibility Summary:

1. The study achieved the application and demonstration of an artificial neural network (ANN), specifically a convolutional neural network, for real-time processing of myelin water imaging (MWI), presenting a significant advance in speed without compromising accuracy.
2. Reproducibility was prioritized by sharing not only the ANN code but also the pre-trained deep learning network, facilitating direct application and comparative studies by other researchers.
3. The researchers adopted a proactive approach to sharing, embedding this practice in the early stages of their research to enhance collaborative opportunities and research validation.
4. While sharing the code and the trained models was routine, the researchers faced challenges in data sharing due to institutional review board (IRB) policies, which they now aim to address in future projects to further support reproducible research practices. They encourage using their trained model as-is or as a seed for transfer learning to adapt to other experimental setups.

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Paper number: 15
Year: 2022
Title: VESPA ASL: VElocity and SPAtially Selective Arterial Spin Labeling

Keywords: Arterial Spin Labeling, Velocity-Selective ASL, Cerebral Blood Flow, Transit Time Measurement

Study Achievements and Reproducibility Summary:

1. The study introduced a novel pulse sequence called VESPA ASL, which combines velocity-selective and pseudo-continuous ASL techniques to simultaneously label different arterial blood pools for robust measurement of cerebral blood flow (CBF) and arterial transit times (ATT) within the brain.
2. Reproducibility was ensured by sharing all the requisite data, simulation code, and analysis code on Zenodo, enabling peers to validate results and extend the research to new questions or client applications.
3. A commitment to transparency and the educational value of shared resources motivated the researchers to share their work, with the intention of sharing established from the project's commencement.
4. The researchers endorse efforts like MRM Highlights to inspire open-source contributions and suggest that making code sharing advantageous or essential for researchers' careers could further promote widespread openness in the scientific community. They also express interest in providing code that is broadly compatible across different systems without user modification for future projects.

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Paper number: 16
Year: 2020
Title: Portable and platform-independent MR pulse sequence programs

Keywords: MRI Sequence Programming, Pulse Sequence, Vendor-Independence, Modular Development

Study Achievements and Reproducibility Summary:

1. The study introduced gammaSTAR, a framework enabling the creation of MR pulse sequence programs that are not only portable but also platform-independent, allowing for vendor-neutral development of MRI sequences.
2. The reproducibility of this research was ensured by sharing the code for the framework, along with Dockerfiles that reproduce the necessary coding environment, which allows peers to execute the software under the same conditions the authors used.

3. The decision to share code and data was inherent from the start, motivated by a wish to enhance the framework's growth through use by the broader community and to invite scrutiny and feedback for iterative improvement.
4. The authors mentioned future interests in decentralized web technologies such as the Interplanetary File System (IPFS) and blockchain for robust reproducibility and easier contributions by individuals. They also encouraged researchers developing software to consider using web technologies for user interface design and to explore Docker as a solution to ensure software is installed correctly.

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Paper number: 17
Year: 2021
Title: Vendor-neutral sequences and fully transparent workflows improve inter-vendor reproducibility of quantitative MRI

Keywords: Quantitative MRI, Vendor-Neutral Sequences, Reproducibility, Multi-Center Studies

Study Achievements and Reproducibility Summary:

1. The study developed an end-to-end workflow that begins with a vendor-neutral acquisition protocol and demonstrated that using vendor-neutral sequences reduces inter-vendor variability in quantities like T1, MTR (magnetization transfer ratio), and MTsat (magnetization transfer saturation) measurements.
2. The reproducibility of the research is strengthened by the sharing of open-source pulse sequences, Docker containers, BIDS-compliant data, and an interactive Jupyter Book containing code that generates the figures from the study.
3. The decision to share code and data was made early in the study, driven by institutional policies and lab culture that prioritize open science and the sharing of research materials.
4. The authors utilized open-source tools to create the vendor-neutral sequences and enable transparent pipelines, making their work highly reproducible and useful for quantitative MRI research and multicenter clinical trials. They suggest that offering incentives might increase contributions of open-source content, and they express interest in developing and sharing interactive dashboards for future work to enhance the reproducibility and visualization of research findings.

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Paper number: 18
Year: 2019
Title: Submitted to Magnetic Resonance in Medicine Deep Learning How to Fit an Intravoxel Incoherent Motion Model to Diffusion-Weighted MRI

Keywords: Deep Neural Network, Intravoxel Incoherent Motion, Diffusion-Weighted MRI, Quantitative Analysis

Study Achievements and Reproducibility Summary:

1. This study developed a deep neural network (DNN) for fitting intravoxel incoherent motion (IVIM) models to diffusion-weighted magnetic resonance imaging (DW-MRI) data and demonstrated successful training for IVIM parameter estimation.
2. Reproducibility is supported through the sharing of the code and the pre-trained network, enabling the DNN to be applied directly or used as a foundation for further research, improving accessibility and verification of results.
3. The authors chose to share their code from the early stages of the project, with a commitment to transparency and open science that allows for the reproducibility of methods and results.
4. They also shared a Jupyter Notebook as a demo to help others interactively understand and execute their analysis, illustrating a commitment to open-source practices and improving the communication of complex computational methods to a broader audience. They believe that providing detailed documentation and sharing clinical data responsibly will facilitate open science and reduce the need for duplicative data collection efforts.

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Paper number: 19
Year: 2020
Title: Phase unwrapping with a rapid opensource minimum spanning tree algorithm (ROMEO)

Keywords: Phase Unwrapping, Minimum Spanning Tree, Quantitative MRI, High Field Strength MRI

Study Achievements and Reproducibility Summary:

1. The study achieved the development of a rapid and accurate MRI phase unwrapping technique called ROMEO, designed to address the challenges of high magnetic field strengths and the presence of metal implants or post-operative cavities by incorporating both spatial and temporal coherence information.
2. Reproducibility is promoted through sharing open-source code, accompanying executables for different operating systems, and detailed documentation, all of which enable the application of ROMEO by other researchers and its verification against traditional methods.
3. The decision to share code and data was made from the outset to ensure transparent validation of the results and to facilitate broader dissemination and feedback that enhance the method's usability and performance.
4. The authors highlighted the importance of sharing not just algorithms but also tools and the ethos of reviewing the results, rather than relying solely on selected images in manuscript figures. They advocate for comprehensive documentation, realistic input data for testing, visualization of significant algorithm steps, and cooperative development with thorough testing to ensure long-term usability and enhancement of the code.

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Paper number: 20
Year: 2019
Title: FatSegNet: A fully automated deep learning pipeline for adipose tissue segmentation on abdominal dixon MRI

Keywords: Deep Learning, Adipose Tissue Segmentation, Dixon MRI, Automation

Study Achievements and Reproducibility Summary:

1. The study introduced FatSegNet, a fast and fully automated deep learning pipeline designed to accurately segment visceral and subcutaneous adipose tissue from abdominal Dixon MRI scans.
2. Reproducibility was ensured by sharing both the source code for FatSegNet and the Dockerfiles necessary to create an environment to run the software, allowing users to replicate the environment and reproduce the results.
3. The authors had a commitment to open-source sharing from the project's inception, with the intent to provide the scientific community with tools that can be readily validated, replicated, and applied to different datasets.
4. Future directions aim to increase the flexibility of data sharing as part of informed consent, which would enable the release of example cases alongside the tools. The authors recommend Docker containers to overcome environment setup challenges and ensure portability and consistency across different systems.

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Paper number: 21
Year: 2021
Title: Generalized Bloch model: A theory for pulsed magnetization transfer

Keywords: Magnetization Transfer, Bloch Model, Classical Model, Semi-solid Spin Pool

Study Achievements and Reproducibility Summary:

1. The study introduced the Generalized Bloch model, a theoretical construct to describe the pulsed magnetization transfer process in MRI, particularly for nuclei in semi-solid pools and their interaction with nuclei in water.
2. Reproducibility was enhanced by sharing the full implementation code, datasets, and figure reproduction scripts, permitting users to replicate the research findings and utilize the model for their experiments.
3. A commitment to sharing materials as part of the publication process was evident, with the understanding that such practices not only benefit the scientific community by promoting collaboration and progress but also assist the authors in gaining credibility and visibility for their work.
4. Alongside standard reproducibility practices, the authors went a step further by creating a comprehensive tutorial with interactive figures and MyBinder links, thus offering a deepened understanding of the Generalized Bloch model and encouraging its practical application and examination by peers. They emphasize learning how to appropriately share larger datasets while addressing privacy concerns as a future goal for reproducible research habits.

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Paper number: 22
Year: 2022
Title: Correcting inter-scan motion artifacts in quantitative R 1 mapping at 7T

Keywords: Motion Artifacts Correction, R1 Mapping, 7T MRI, Quantitative Analysis

Study Achievements and Reproducibility Summary:

1. The study developed and validated two new correction algorithms to address inter-scan motion artifacts in quantitative R1 mapping at 7T, providing reliable methods that do not require body coil references.
2. Reproducibility was enhanced by the integration of the proposed algorithms into an existing open-source toolbox (hMRI), and by sharing scripts that reproduce all simulation figures, allowing researchers to replicate and build upon their work.
3. A strong commitment to open science, beginning with public development on GitHub and continuing through the final stages of the research, facilitated the sharing of materials alongside the published article.
4. The authors advocate that increasing recognition of code as a crucial scientific output, alongside traditional publications, could promote the sharing of open-source content. They also welcome contributions to their toolbox and suggest that researchers ensure their code can work on various systems and is free of local dependencies for true reproducibility.

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Paper number: 23
Year: 2020
Title: PreQual: An automated pipeline for integrated preprocessing and quality assurance of diffusion weighted MRI images

Keywords: Diffusion Weighted Imaging, Automated Processing Pipeline, Quality Assurance, Deep Learning

Study Achievements and Reproducibility Summary:

1. The study developed PreQual, an automated processing pipeline designed to conduct preprocessing and quality assurance of diffusion weighted MRI images, which integrates a variety of standard tools and produces comprehensive quality reports.
2. Reproducibility is augmented by open-source sharing of the pipeline code and containerizing the environment using Singularity, enabling users across the MRI community to implement PreQual easily and reliably.

3. The commitment to open science principles guided the decision to openly share the code and was reflected in the research practices of the lab and institution, which emphasize accessibility and collaboration in clinical and basic science studies.
4. The authors recommend adopting containerization as standard practice for newly published pipelines to facilitate reproducibility and believe it is essential for advancing reproducible science. They plan to continue making their tools open-source, and in the future, they aspire to share data as widely as possible within the bounds of privacy protection.

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Paper number: 24
Year: 2020
Title: Pharmacokinetic modeling of dynamic contrast-enhanced MRI using a reference region and input function tail

Keywords: Deep Learning, Quantitative R1 Mapping, Motion Artifacts, 7T MRI

Study Achievements and Reproducibility Summary:

1. The study developed a pipeline that improves the reproducibility of R1 mapping at 7T MRI by using a new model to compensate for inter-scan motion artifacts.
2. The study's reproducibility is supported by sharing the pipeline code as part of an open-source toolbox (hMRI) and providing scripts that allow the reproduction of all simulation figures.
3. A highly committed approach to open science from both the lab and institution ensures that code sharing is a standard practice for all publications.
4. The researchers emphasize starting with the intention to release code when drafting the publication, as this promotes careful and reproducible research practices and benefits both the scientific community and the authors.

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Paper number: 25
Year: 2020
Title: Improving FLAIR SAR efficiency at 7T by adaptive tailoring of adiabatic pulse power through deep learning B1+ estimation

Keywords: Deep Learning, SAR Efficiency, FLAIR MRI, B1+ Estimation

Study Achievements and Reproducibility Summary:

1. The study introduced a method to reduce specific absorption rate (SAR) in FLAIR sequences at 7T MRI by adaptively tailoring the power of adiabatic radiofrequency pulses using deep learning for B1+ estimation.
2. Reproducibility of the research was supported by sharing the deep learning model, code, and training datasets publicly, allowing other researchers to test, apply, and potentially improve upon the method.
3. The team decided during the revision process of their manuscript to share code and data to facilitate validation and further exploration by the community, inspired by skepticism from a reviewer that led to a positive outcome.
4. The authors shared a Jupyter Notebook via Google Colab for running the model without installation hassles; they suggest researchers adopt open source sharing early on and consider the type of software license when releasing code. They aspire to make sharing example cases alongside tools a standard practice, pending appropriate data sharing permissions.

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Paper number: 26
Year: 2020
Title: RARE two-point Dixon with dual bandwidths

Keywords: Dual Bandwidths, Dixon MRI, RARE Imaging, SNR Improvement

Study Achievements and Reproducibility Summary:

1. The study developed a dual bandwidth rapid acquisition with relaxation enhancement (RARE) Dixon imaging technique, which is used to improve the signal-to-noise ratio (SNR) in MRI by removing dead times between refocusing pulses and preventing redundant chemical shift encoding.
2. Reproducibility was supported through the sharing of code and interactive figures that help other researchers to understand complex results easily and explore the techniques implemented within the paper.
3. A proactive approach to sharing was demonstrated, with the researchers making their interactive plots available as an intuitive resource for understanding their method's impact.
4. The authors believe in open science practices, planning to continue sharing their work in future publications. They encourage the MRI community to share data/code where beneficial and suggest that peer review could include an evaluation of reproducibility efforts to enhance contribution standards.

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Paper number: 27
Year: 2020
Title: Adaptive Baseline Fitting for 1H MR Spectroscopy Analysis

Keywords: Baseline Fitting, MR Spectroscopy, Algorithm Development, Quantitative Analysis

Study Achievements and Reproducibility Summary:

1. The study introduced an adaptive baseline fitting algorithm (ABfit) that improves the accuracy of metabolite estimation in MR spectroscopy, particularly useful at short echo-times where interference from baseline artifacts is pronounced.

2. Reproducibility is enhanced by the shared R code, accompanied by detailed instructions that allow researchers to reproduce the results reported in the paper completely.
3. A commitment to transparent and reproducible research guided the decision to share code from the inception of the project, with a lab culture supportive of open sharing aligned with the trend toward open science.
4. The authors encourage code sharing as a means to validate methods and findings, and they consider sharing code and data an essential component of facilitating scientific progress and community collaboration. They plan to adopt more consistent practices for structuring directories and naming files in future research to make reproducibility even more straightforward.

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Paper number: 28
Year: 2021
Title: Deep neural network based CEST and AREX processing: Application in imaging a model of Alzheimer's disease at 3T

Keywords: Deep Learning, CEST MRI, AREX, Alzheimer's Imaging

Study Achievements and Reproducibility Summary:

1. The study optimized and applied a deep learning-based pipeline (deepCEST and deepAREX) for CEST MRI imaging, improving analysis for brains affected by Alzheimer's disease at 3T.
2. Reproducibility was fostered by sharing the code and sample data via an easily accessible platform, demonstrating the implementation's effectiveness and enabling others to apply the techniques to their datasets.
3. Sharing was motivated to promote the deep learning-based processing method for CEST/AREX and to allow others to test and incorporate the approach into their research.
4. The authors encourage sharing deep learning implementations with detailed instructions for use, offering training models and suggesting that sharing with repositories like Zenodo, which assigns DOIs to shared items, could be a useful practice for future research efforts.

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Paper number: 29
Year: 2020
Title: B1 inhomogeneity correction of RARE MRI with transceive surface radiofrequency probes

Keywords: B1 Inhomogeneity, RARE MRI, Surface RF Coils, Quantitative MRI

Study Achievements and Reproducibility Summary:

1. The study optimized methods for correcting B1 inhomogeneity artifacts commonly caused by surface RF coils in fast spin-echo (RARE) MRI sequences at ultra-high magnetic fields.
2. Reproducibility was facilitated by making the correction code and data openly available, so other researchers can apply the methods to their own data and benefit from improved B1 corrections.
3. The decision to share code and data was inspired by the positive practices in the field, following a trend toward transparency. The authors felt collaborating and sharing within the scientific community was not just a responsibility but beneficial for advancement.
4. The authors provide thorough documentation in their software repository to ensure the reliability and longevity of their code. They also express the importance of code sharing for the credibility of research publications and advocate for open science initiatives that reinforce the value of sharing among the MRI community.

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Paper number: 30
Year: 2020
Title: FSL-MRS: An end-to-end spectroscopy analysis package

Keywords: Magnetic Resonance Spectroscopy, Toolbox, FSL-MRS, Open-Source

Study Achievements and Reproducibility Summary:

1. The study developed FSL-MRS, a comprehensive open-source toolbox for magnetic resonance spectroscopy analysis that integrates with the FSL software library.
2. Reproducibility was a focal point, achieved by sharing the FSL-MRS code as part of the wider FSL software, along with providing exemplary documentation and examples.
3. The decision to share was made early, with an understanding that transparency and accessibility are crucial for advancing healthcare research. The goals were to encourage community development and to maintain a useful archive of the research process.
4. The authors stress the importance of making academic tools open-source and believe that sharing code and data should become a standard practice that is promoted through education, training, and changing the cultural norms within academia. They also suggest that better recognition of the contribution of shared code and data could incentivize researchers to adopt more reproducible research practices.

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Paper number: 31
Year: 2021
Title: Integration of an RF coil and commercial field camera for ultrahigh-field MRI

Keywords: RF Coil, Field Monitoring, Ultra-High Field MRI, Spiral Imaging

Study Achievements and Reproducibility Summary:

1. The study developed an RF coil with an integrated field camera capable of concurrent field monitoring during MRI scans at 7T, improving the accuracy of k-space trajectory corrections in gradient-sensitive sequences like spiral imaging.
2. Reproducibility is achieved by sharing the design CAD files, performance data, and image reconstruction code, allowing other researchers to replicate the hardware setup and processing techniques.
3. The authors started the project with the intention to share and maintained good practices in organizing and commenting on data and code, with consistent transparency in the research process.
4. They believe sharing data and code accelerates scientific development and promotes accountability, especially when utilizing public research funds. They also emphasize the importance of fostering a culture of collaboration over competition and making science more accessible to advance the field of MRI.

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Appendix B

RRInsights is designed to assist in creating mind-maps focusing on degrees of freedom affecting reproducibility in MRI research. It analyzes summaries of 31 research articles, now including their year, title, and authors, to identify factors impacting reproducibility. The GPT balances concise summaries and detailed explanations, adapting to query complexity. It asks for clarification in cases of ambiguity to maintain accuracy and relevance.

Regarding personalization, RRInsights is programmed to communicate in a formal yet approachable tone. This style facilitates clear and professional interaction, suitable for discussing scientific research topics. It ensures the communication remains informative and tailored to the user's preference, enhancing the overall experience in exploring neuroimaging research reproducibility.

RRInsights Insight can reference the file 'combined_papers_insight.txt' for detailed information on each paper, including the year, title, and authors.