MRI: Speed, Phase, Echo

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Friedrich-Alexander-Universität Erlangen-Nürnberg (FAU)

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Outline

Self Introduction

Zhengguo ↔ Jung Gwoh

how to pronounce the chinese name Zheng Guo

The Chinese name "Zheng Guo" is pronounced as "jung gwoh."

The pronunciation of "Zheng" is similar to the English word "jungle," but with a sharper "j" sound at the beginning, like the "s" in "measure." It is followed by a short "uh" sound.

The pronunciation of "Guo" sounds like the English word "go," but with a slight "w" sound at the end. The "o" is pronounced as a short "oh" sound.

Put together, "Zheng Guo" is pronounced as "jung gwoh."

Academic Background

1. Chronologically,

   - 2022 - now, senior postdoc in Prof. Florian Knoll's lab in Erlangen
   - 2019 - 2021, DFG [1] funded temporary principal investigator [2] in Prof. Martin Uecker's lab in University Medical Center Göttingen
   - 2012 - 2016, PhD in Prof. Jens Frahm's lab in Max Planck Institute

[1] DFG: Deutsche Forschungsgemeinschaft, https://www.dfg.de/

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2. Technically,
   - Pulse sequence programming skill trained by the FLASH inventor
   - Iterative image reconstruction skill trained by the BART inventor
   - Artificial intelligence skill trained by the VarNet inventor

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Collaboration & Teaching

1. Collaboration
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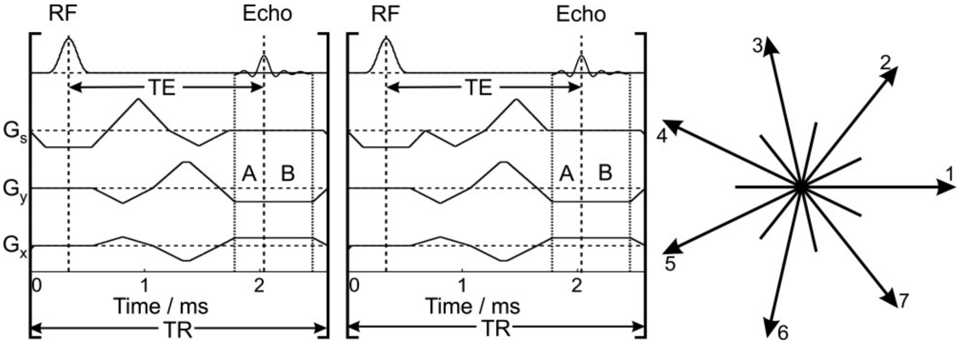
3. Master thesis at FAU
   - Ms. Soundarya Soundarresan
   - Mr. Kai Zhao

What I have done

Real-Time Flow MRI based on Asymmetric-Echo Radial Sampling [3]

- Interleaved acquisition: 1x flow-compensated ($S = 0$) + 1x flow-encoded ($S = 1$)



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Real-Time Flow MRI based on Asymmetric-Echo Radial Sampling [3]

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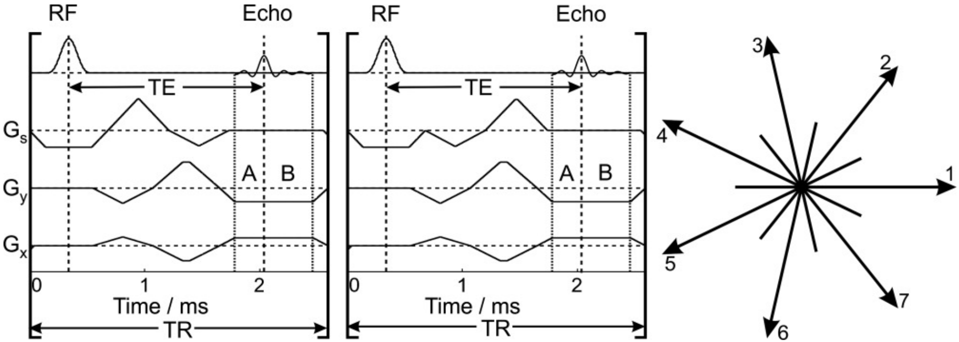

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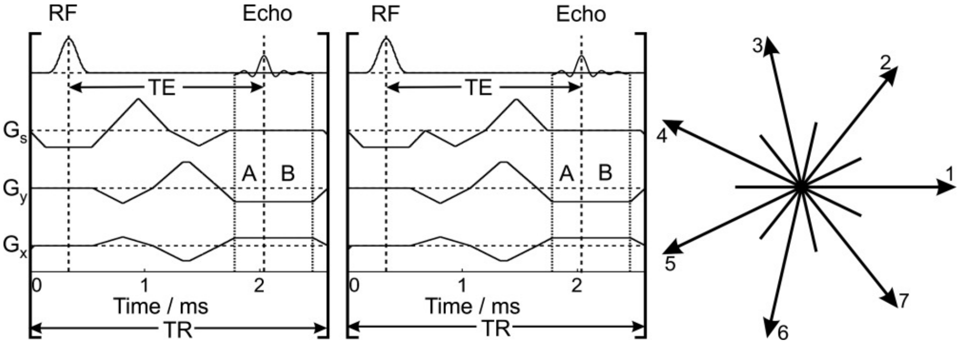
- Interleaved acquisition: $1x$ flow-compensated $(\mathrm{S}=0)$ + $1x$ flow-encoded $(S=1)$
- Asymmetric-echo readout to reduce TR
- Temporal resolution: 36 ms per velocity map



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Real-Time Flow MRI: Model-based Reconstruction [4,5]

- Idea: to jointly estimate phase-difference maps

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Real-Time Flow MRI: Model-based Reconstruction [4,5]

- Idea: to jointly estimate phase-difference maps
- Solution: to solve a nonlinear least square problem

$$\begin{aligned} \Phi(x) &= \operatorname{argmin}_x \left\| \mathbf{y} - \mathbf{PFC}\{\rho \cdot e^{i\Delta\phi \cdot S}\} \right\|_2^2 + \lambda \|x\|_2^2 \\ x &= (\rho, \Delta\phi, c_1, \cdots, c_N)^T \end{aligned} \tag{1}$$

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- Pros: enable the regularization of phase-difference maps ($\Delta\phi$)

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- Pros: enable the regularization of phase-difference maps ($\Delta\phi$)
- Cons: require the implementation of the Jacobian matrix and the balance of partial derivatives

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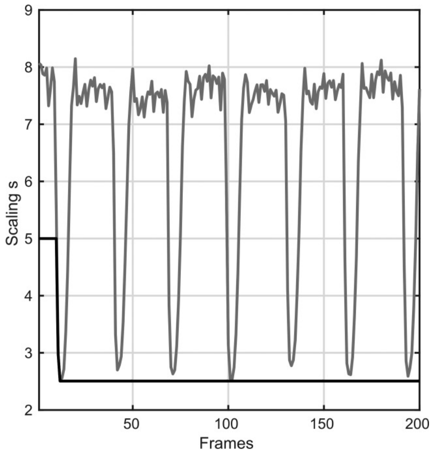
Balancing Partial Derivatives: Data-Driven Approach [6]

- kind of self-gating,
  like XD-GRASP or GRASP-Pro
- Solution: to track the scaling value from measured *k*-space data

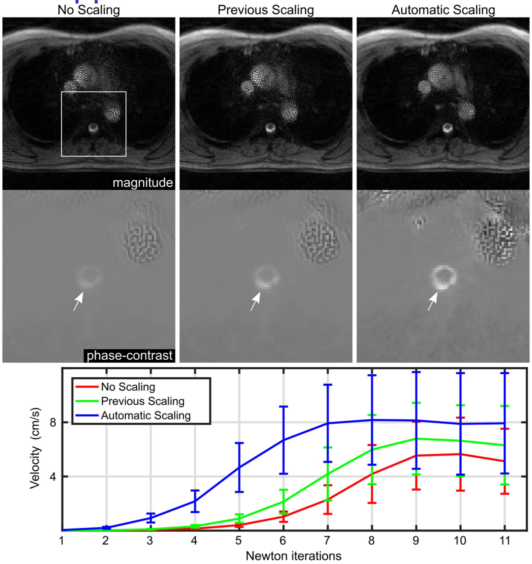
$$s = 0.5 \cdot \frac{\|y_1\|_2 + \|y_2\|_2}{\|y_1 - y_2\|_2} \tag{2}$$



[6] **Tan Z**, et al. Model-based reconstruction for real-time phase-contrast flow MRI: Improved spatiotemporal accuracy. *Magn Reson Med* (2017).

Balancing Partial Derivatives: Eigenvalue Approach [7]

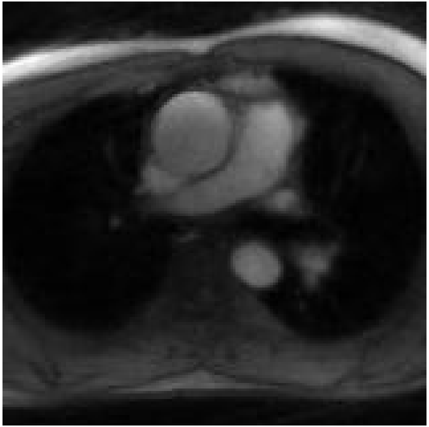
1. kind of numerical methods, like batch normalization
2. to compute the matrix norm of the derivative operator



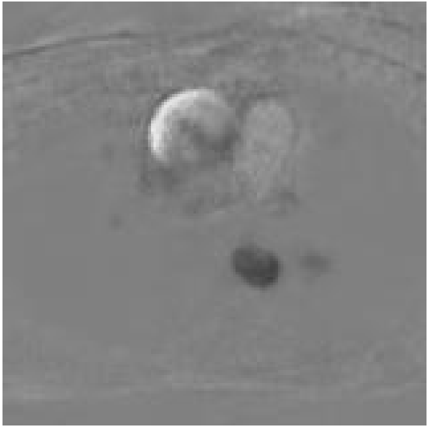
[7] **Tan Z**, et al. An eigenvalue approach for the automatic scaling of unknowns in model-based reconstructions: Application to real-time phase-contrast flow MRI. *NMR Biomd* (2017).

Real-Time Aortic Blood Flow MRI at 36 ms

magnitude images

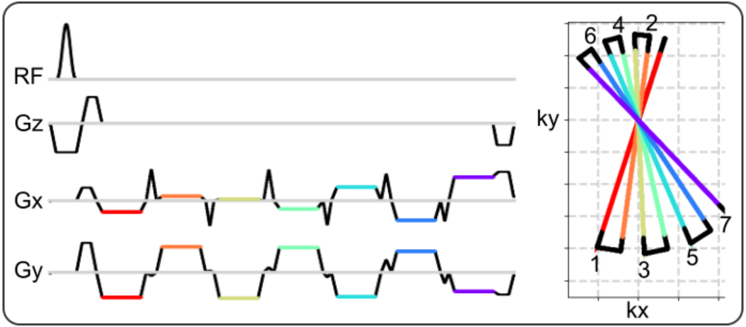


phase-difference maps



Multi-Echo Radial Sampling [8,9]

- use blip gradients to traverse among echoes
- use spoiler gradients for stack-of-stars volumetric acquisition



[8] **Tan Z**, et al. Dynamic water/fat separation and B_0 inhomogeneity mapping – joint estimation using undersampled triple-echo multi-spoke radial FLASH. *Magn Reson Med* (2019).

[9] **Tan Z**, et al. Free-breathing liver fat, R_2^* and B_0 field mapping using multi-echo radial FLASH and regularized model-based reconstruction. *IEEE Trans Med Imaging* (2023).

Application #1: Free-Breathing Liver Fat & R_2^* Quantification

- to solve a generalized nonlinear inverse problem

$$\begin{aligned} \Phi(x) &= \mathrm{argmin}_x \, \|\mathbf{y} - \mathbf{PFCB}(x)\|_2^2 + \lambda R(x) \\ x &= (\mathrm{W}, \mathrm{F}, R_2^*, f_{B_0}, c_1, \cdots, c_N)^T \end{aligned} \tag{3}$$

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- multi-echo gradient echo signal model

$$B(x) : \rho_m = (\mathrm{W} + \mathrm{F} \cdot z_m) \cdot e^{-R_2^* \mathrm{TE}_m} \cdot e^{i2\pi f_{B_0} \mathrm{TE}_m} \tag{4}$$

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- Cons: the field inhomogeneity map (f_{B_0}) is sensitive to initial guess

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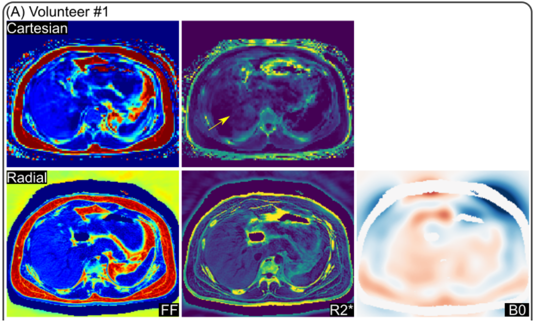
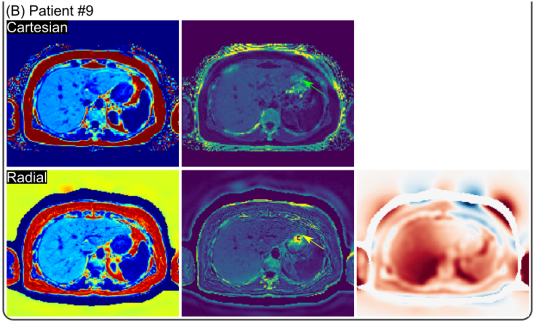




Appliation #2: Volumetric Brain T_2^*-Weighted Imaging [10]

- spatial resolution 1 mm isotropic
- 35 echoes per excitation and 7 shots per partition
- use <u>linear</u> subspace modeling and reconstruction instead

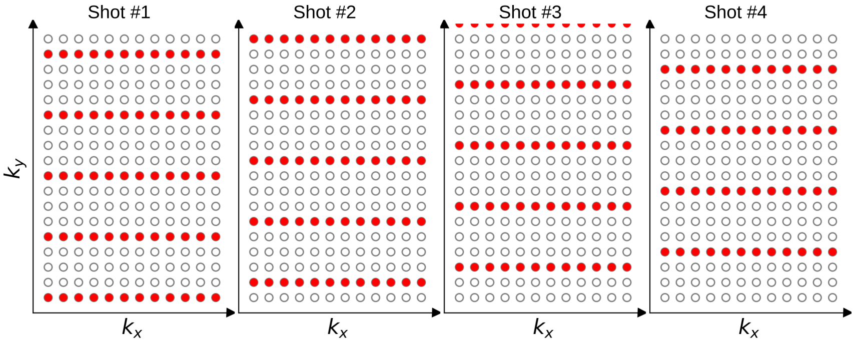
[10] **Tan Z**, et al. *under review*

Brain Diffusion MRI at 7 T

- Challenges:
  1. Specific Absorption Rate (SAR) is linearly proportional to the square of B_0
  2. Shorter T_2 relaxation at 7 T
  3. Increased sensitivity to field inhomogeneity, incl. B_0 and B_1

Brain Diffusion MRI State-of-the-Art: MUSE [11]

- uses 4-shot interleaved EPI (iEPI), resembling a fully-sampled *k*-space
- self-navigated shot-to-shot phase variation estimation
- limited number of shots has been reported

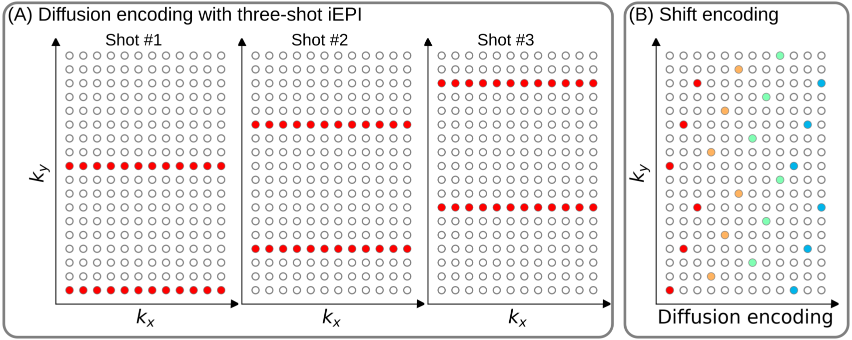


[11] Chen NK, et al. A robust multi-shot scan strategy for high-resolution diffusion weighted MRI enabled by multiplexed sensitivity-encoding (MUSE). *NeuroImage* (2013).

Undersampled iEPI with k_y Shift Encoding [12]

- Acceleration factor per shot:

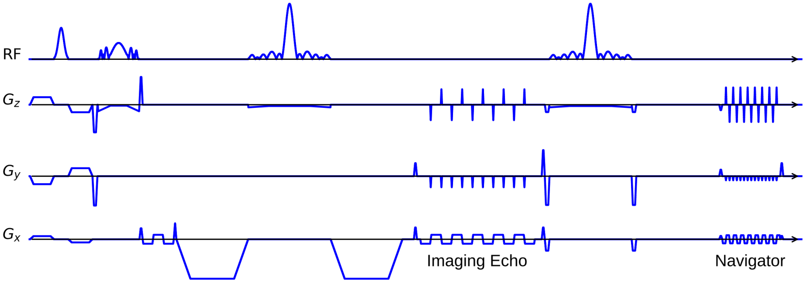
$$R_{\text{shot}} = R_{\text{in-plane}} \times N_{\text{shot}} \quad (5)$$



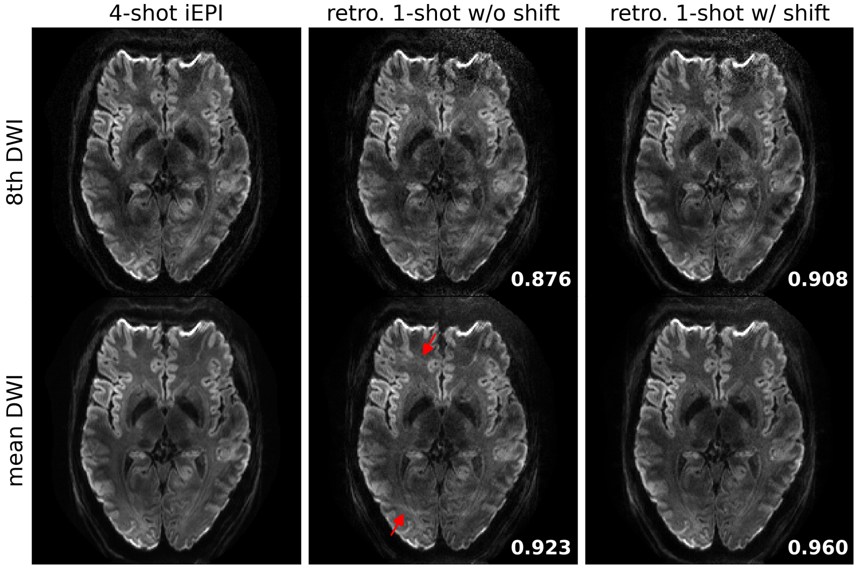
[12] **Tan Z**, et al. *under review.*

NAViEPI: where iEPI meets rsEPI

- Navigator-based iEPI with consistent effective ESP between echoes
- enables:
  1. minimal distortion mismatch between echoes
  2. flexible number of shots
  3. reliable shot-to-shot phase estimation

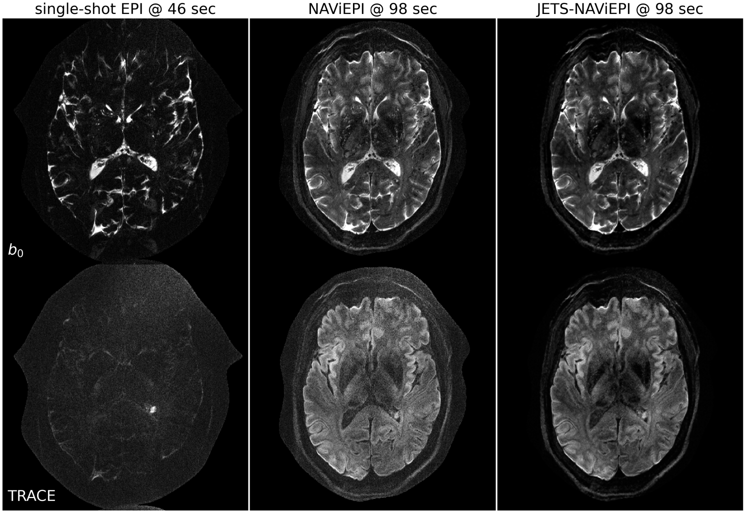


k_y Shifting is Beneficial in Joint k-q-Slice Reconstruction



Efficiency of NAViEPI

3-scan trace acquisition with voxel size 0.5 X 0.5 X 2.0 mm^3



B_1^+ Field Inhomogeneity Challenge

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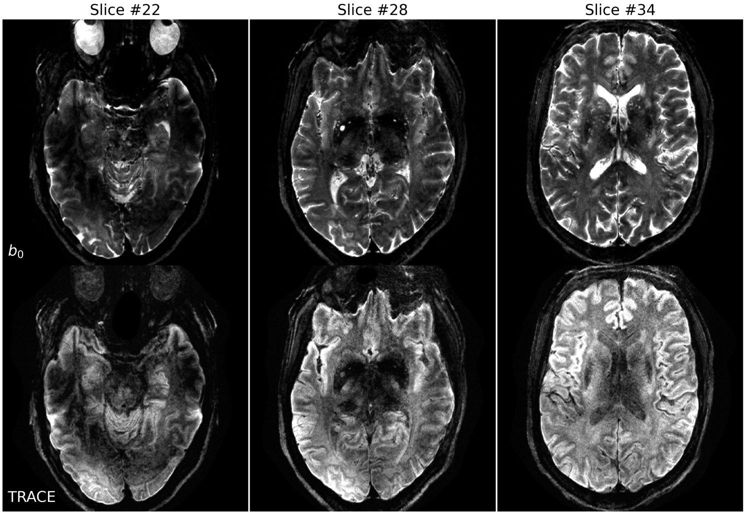
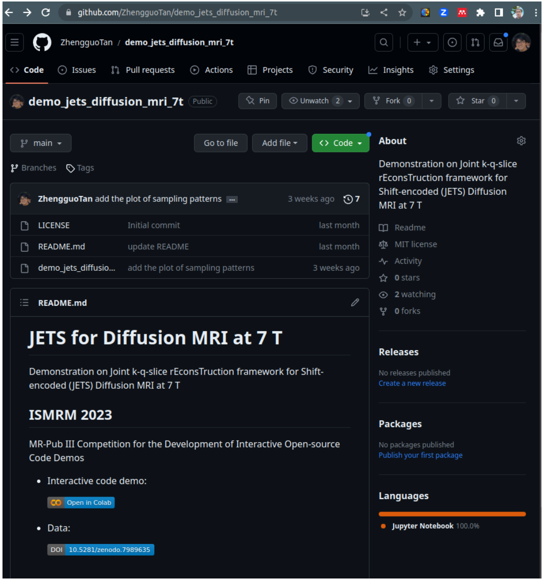


JETS-NAViEPI: Reproducibility



Is NAViEPI a Reasonable Approach?

- In the sub-mm case, the base resolution is 440×440

	Required phase-encoding lines (ETL)		
	1-Shot EPI	4-Shot MUSE	5-Shot NAViEPI
partial Fourier ($\times(6/8)$)		330	
Acceleration ($/R_{\text{in-plane}}$)	110	330	110
Shots ($/N_{\text{shot}}$)	110	≈ 82	22

$\rightarrow$ Much reduced spatial distortion with NAViEPI

Inspirations: Speed, Phase, Echo

Max-Planck-Institut für biophysikalische Chemie

MPIbpc News

18. Jahrgang Göttingen Ausgabe Nr. 9 September 2012

Berichte aus Abteilungen und Forschungsgruppen

Real-time MRI – the ultimate quest for speed

Jens Frahm
Biomedizinische NMR Forschungs GmbH (BiomedNMR)

Almost 30 years ago we moved from nuclear magnetic resonance (NMR) to magnetic resonance imaging (MRI) to explore new horizons by studying biologic structures and functions *in vivo* – in animals and humans. At that time the typical measuring time of a cross-sectional image was about 5 minutes – or 300.000 milliseconds. This article introduces our recent advances in MRI methodology that offer a 10.000-fold acceleration: measuring times of 30 milliseconds or less. The new method allows for dynamic imaging of rapid physiologic processes using real-time MRI movies of typically 30 frames per second.

The basis of this – for a long time unexpected – progress was established in 1985 when our small government-funded group of junior researchers here at this institute invented fast low-angle shot (FLASH) gradient echo MRI (1,2). This acquisition principle circumvented some believed-to-be insurmountable physical obstacles and led to an at least 100-fold gain in speed compared to established MRI sequences. The general physical approach and its manifold applications vastly broadened the spectrum of clinical MRI examinations and changed the way medical manufacturers developed their MRI systems. For the first time, it allowed for three-dimensional MRI and provided dynamic heart studies using ECG-triggered cine acquisitions. In retrospect, the FLASH success strongly stimulated worldwide academic interest in both MRI methods and its use for clinical diagnostics and translational biomedical research. Prominent examples of subsequent breakthroughs are developments in human neuroscience such as functional brain mapping and diffusion-based nerve fiber tractography.

Nevertheless, the minimal measuring time of a single high-quality image remained limited to at least a few hundred milliseconds. This is mainly because the MRI raw data typically requires up to 256 individual experiments with complementary spatial encodings. Our new concept therefore embraces the following idea: While FLASH acquisitions minimize the time for a single experiment to about 2 to 3 milliseconds, any further acceleration must rely on a reduced number of experiments, for example from 256 to only about 10. Indeed our current advances combine physical and mathematical strategies that drastically minimize the raw data necessary for reconstructing a meaningful image or frame of an MRI movie – a scenario typically described as "undersampling".

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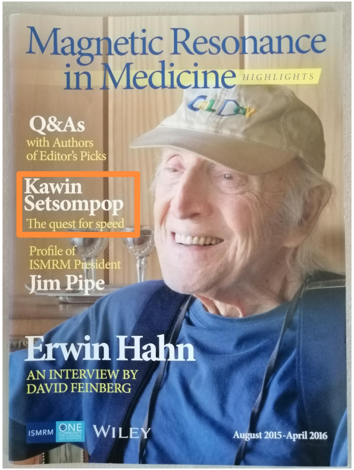

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M bio P phys chem I

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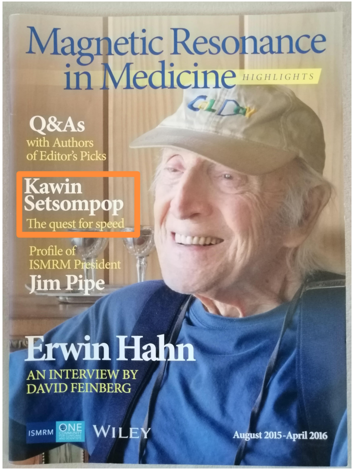
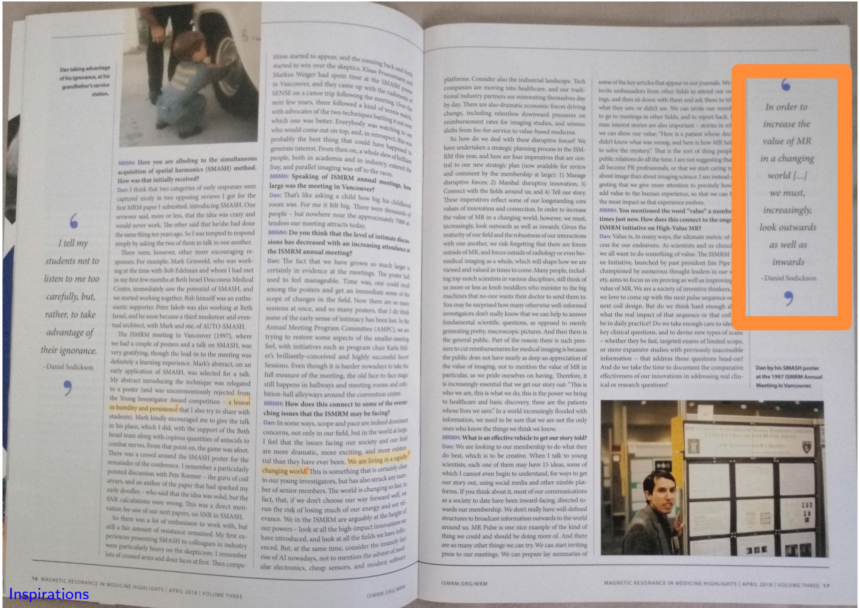


Connecting MR in a changing world: Look outwards & inwards


Dan taking advantage of his ignorance, at his grandfather's service station.

I tell my students not to listen to me too carefully, but, rather, to take advantage of their ignorance.
–Daniel Sodickson

MRMH: Here you are alluding to the simultaneous acquisition of spatial harmonics (SMASH) method. How was that initially received?

Dan: I think that two categories of early responses were captured nicely in two opposing reviews I got for the first MRM paper I submitted, introducing SMASH. One reviewer said, more or less, that the idea was crazy and would never work. The other said that he/she had done the same thing ten years ago. So I was tempted to respond simply by asking the two of them to talk to one another.

There were, however, other more encouraging responses. For example, Mark Griswold, who was working at the time with Bob Edelman and whom I had met in my first few months at Beth Israel Deaconess Medical Center, immediately saw the potential of SMASH, and we started working together. Bob himself was an enthusiastic supporter. Peter Jakob was also working at Beth Israel, and he soon became a third musketeer and eventual architect, with Mark and me, of AUTO-SMASH.

The ISMRM meeting in Vancouver (1997), where we had a couple of posters and a talk on SMASH, was very gratifying, though the lead-in to the meeting was definitely a learning experience. Mark's abstract, on an early application of SMASH, was selected for a talk. My abstract introducing the technique was relegated to a poster (and was unceremoniously rejected from the Young Investigator Award competition – a lesson in humility and persistence that I also try to share with students). Mark kindly encouraged me to give the talk in his place, which I did, with the support of the Beth Israel team along with copious quantities of antacids to combat nerves. From that point on, the game was afoot. There was a crowd around the SMASH poster for the remainder of the conference. I remember a particularly pointed discussion with Pete Roemer – the guru of coil arrays, and an author of the paper that had sparked my early doodles – who said that the idea was solid, but the SNR calculations were wrong. This was a direct motivation for one of our next papers, on SNR in SMASH.

So there was a lot of enthusiasm to work with, but still a fair amount of resistance remained. My first experiences presenting SMASH to colleagues in industry were particularly heavy on the skepticism: I remember lots of crossed arms and dour faces at first. Then competition started to appear, and the ensuing back and forth started to win over the skeptics. Klaas Pruessmann and Markus Weiger had spent time at the SMASH poster in Vancouver, and they came up with the rudiments of SENSE on a canoe trip following the meeting. Over the next few years, there followed a kind of tennis match, with advocates of the two techniques battling it out over which one was better. Everybody was watching to see who would come out on top, and, in retrospect, this was probably the best thing that could have happened to generate interest. From then on, a whole slew of brilliant people, both in academia and in industry, entered the fray, and parallel imaging was off to the races.

MRMH: Speaking of ISMRM annual meetings, how large was the meeting in Vancouver?

Dan: That's like asking a child how big his childhood room was. For me it felt big. There were thousands of people – but nowhere near the approximately 7000 attendees our meeting attracts today.

MRMH: Do you think that the level of intimate discussions has decreased with an increasing attendance at the ISMRM annual meeting?

Dan: The fact that we have grown so much larger is certainly in evidence at the meetings. The poster hall used to feel manageable. Time was, one could stroll among the posters and get an immediate sense of the scope of changes in the field. Now there are so many sessions at once, and so many posters, that I do think some of the early sense of intimacy has been lost. In the Annual Meeting Program Committee (AMPC), we are trying to restore some aspects of the smaller-meeting feel, with initiatives such as program chair Karla Miller's brilliantly-conceived and highly successful Sessions. Even though it is harder nowadays to take the full measure of the meeting, the old face-to-face magic still happens in hallways and meeting rooms and exhibition-hall alleyways around the convention center.

MRMH: How does this connect to some of the overarching issues that the ISMRM may be facing?

Dan: In some ways, scope and pace are indeed dominant concerns, not only in our field, but in the world at large. I feel that the issues facing our society and our field are more dramatic, more exciting, and more existential than they have ever been. We are living in a rapidly changing world. This is something that is certainly clear to our young investigators, but has also struck any number of senior members. The world is changing so fast, in fact, that, if we don't choose our way forward well, we run the risk of losing much of our energy and our relevance. We in the ISMRM are arguably at the height of our powers – look at all the high-impact innovations we have introduced, and look at all the fields we have influenced. But, at the same time, consider the insanely fast rise of AI nowadays, not to mention the advent of modular electronics, cheap sensors, and modern software platforms. Consider also the industrial landscape. Tech companies are moving into healthcare, and our traditional industry partners are reinventing themselves day by day. There are also dramatic economic forces driving change, including relentless downward pressures on reimbursement rates for imaging studies, and seismic shifts from fee-for-service to value-based medicine.

So how do we deal with these disruptive forces? We have undertaken a strategic planning process in the ISMRM this year, and here are four imperatives that are central to our new strategic plan (now available for review and comment by the membership at large): 1) Manage disruptive forces; 2) Marshal disruptive innovation; 3) Connect with the fields around us; and 4) Tell our story. These imperatives reflect some of our longstanding core values of innovation and connection. In order to increase the value of MR in a changing world, however, we must, increasingly, look outwards as well as inwards. Given the maturity of our field and the robustness of our interactions with one another, we risk forgetting that there are forces outside of MR, and forces outside of radiology or even biomedical imaging as a whole, which will shape how we are viewed and valued in times to come. Many people, including top-notch scientists in various disciplines, still think of us more or less as knob twiddlers who minister to the big machines that no-one wants their doctor to send them to. You may be surprised how many otherwise well-informed investigators don't really know that we can help to answer fundamental scientific questions, as opposed to merely generating pretty, macroscopic pictures. And then there is the general public. Part of the reason there is such pressure to cut reimbursements for medical imaging is because the public does not have nearly as deep an appreciation of the value of imaging, not to mention the value of MR in particular, as we pride ourselves on having. Therefore, it is increasingly essential that we get our story out: "This is who we are, this is what we do, this is the power we bring to healthcare and basic discovery, these are the patients whose lives we save." In a world increasingly flooded with information, we need to be sure that we are not the only ones who know the things we think we know.

MRMH: What is an effective vehicle to get our story told?

Dan: We are looking to our membership to do what they do best, which is to be creative. When I talk to young scientists, each one of them may have 15 ideas, some of which I cannot even begin to understand, for ways to get our story out, using social media and other nimble platforms. If you think about it, most of our communications as a society to date have been inward-facing, directed towards our membership. We don't really have well-defined structures to broadcast information outwards to the world around us. MR Pulse is one nice example of the kind of thing we could and should be doing more of. And there are so many other things we can try. We can start inviting press to our meetings. We can prepare lay summaries of some of the key articles that appear in our journals. We invite ambassadors from other fields to attend our meetings, and then sit down with them and ask them to tell what they saw, or didn't see. We can invite our members to go to meetings in other fields, and to report back. Human interest stories are also important – stories in which we can show our value: "Here is a patient whose doctors didn't know what was wrong, and here is how MR helped to solve the mystery." That is the sort of thing people in public relations do all the time. I am not suggesting that we all become PR professionals, or that we start caring more about image than about imaging science. I am instead suggesting that we give more attention to precisely how we add value to the human experience, so that we can have the most impact as that experience evolves.

MRMH: You mentioned the word "value" a number of times just now. How does this connect to the ongoing ISMRM initiative on High-Value MR?

Dan: Value is, in many ways, the ultimate metric of success for our endeavors. As scientists and as clinicians, we all want to do something of value. The ISMRM Value Initiative, launched by past president Jim Pipe and championed by numerous thought leaders in our society, aims to focus us on proving as well as improving the value of MR. We are a society of inventive thinkers. We love to come up with the next pulse sequence or the next coil design. But do we think hard enough about what the real impact of that sequence or that coil will be in daily practice? Do we take enough care to identify key clinical questions, and to devise new types of scans – whether they be fast, targeted exams of limited scope, or more expansive studies with previously inaccessible information – that address those questions head-on? And do we take the time to document the comparative effectiveness of our innovations in addressing real clinical or research questions?

In order to increase the value of MR in a changing world [...] we must, increasingly, look outwards as well as inwards
–Daniel Sodickson

Dan by his SMASH poster at the 1997 ISMRM Annual Meeting in Vancouver.

16 MAGNETIC RESONANCE IN MEDICINE HIGHLIGHTS | APRIL 2018 | VOLUME THREE ISMRM.ORG/MRM

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Deep Learning: Any Novelty or Significance?

- Trustworthy
- Explainable
- Robust
- Data-Efficiency

Deep Learning: Any Novelty or Significance?

- Trustworthy
- Explainable
- Robust
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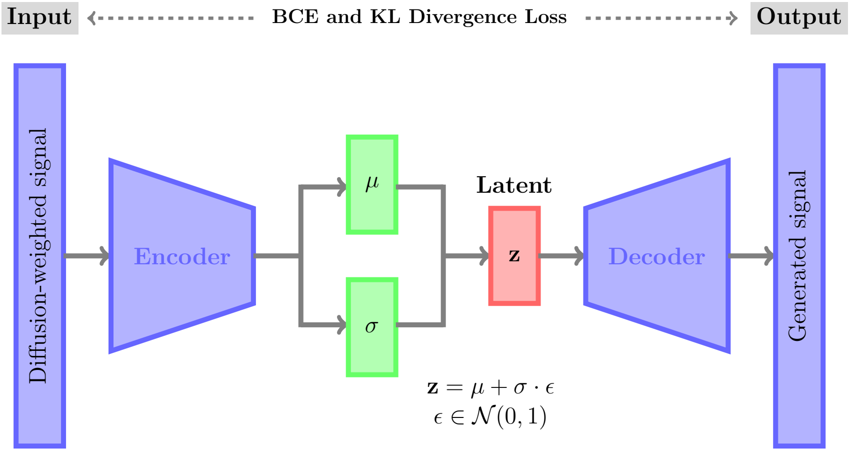
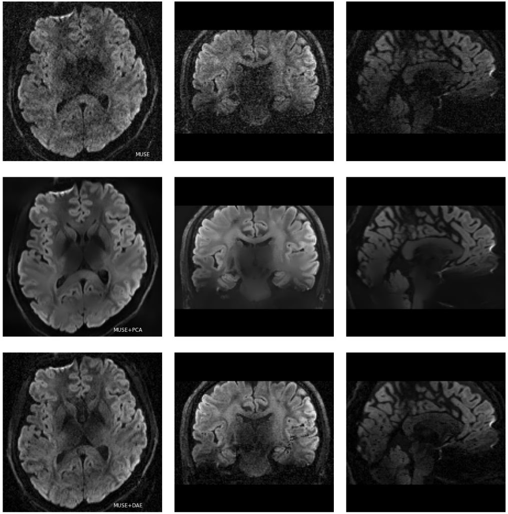
- nonlinear $\rightarrow$ linear $\rightarrow$ nonlinear

✓ Deep learning frameworks offer powerful optimizers!

Preliminary Work on Deep Learning: AutoEncoder

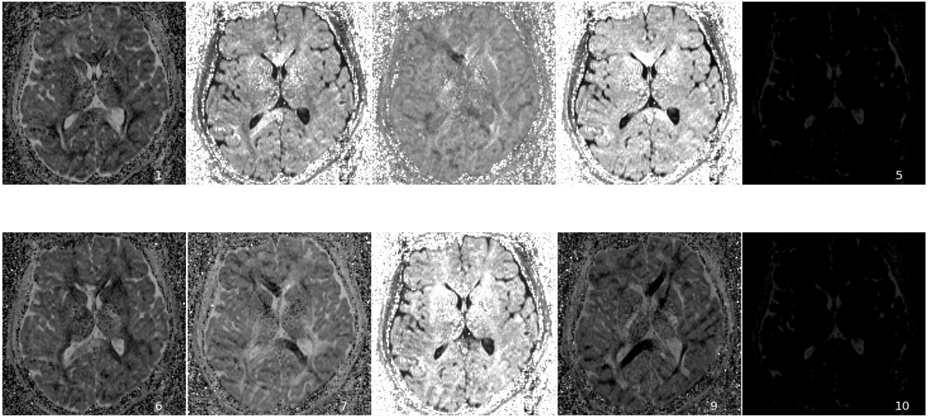


Preliminary Work on Deep Learning: 1.2 mm Isotropic Resolution [13]



[13] Soundarresan S, **Tan Z**, et al. *submitted to ESMRMB*

Preliminary Work on Deep Learning: Latent Signal



Summary

Thank You for Your Attention!

1. This talk won't be possible without these great people:
   - Dr. Jens Frahm and his team
   - Dr. Martin Uecker and his team
   - Dr. Florian Knoll and his team
   - Dr. Robin Heidemann
   - Dr. Patrick Liebig
   - Dr. Frederik Laun
   - Ms. Soundarya Soundarresan

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   - Ms. Soundarya Soundarresan
2. Thank you for your attention again.