Citius, Altius, Fortius

What limits spatial and temporal resolution of fMRI at 3 T, and how can we set new records?
“Advanced” EPI methods available today:

- *Fast:* “Reverse” partial Fourier
- *Faster:* In-plane parallel imaging, *e.g.* GRAPPA
- *Fastest:* Simultaneous multi-slice EPI

* Not available with product EPI sequences
“Reverse” partial Fourier:

Omitting the later rather than the earlier echoes

(Not a standard option on product EPI sequences)
Omitting early echoes permits shorter TE, which is useful for ASL. But we want BOLD contrast and need TE \( \sim T_2^* \) so omitting late echoes should be preferred.
Partial Fourier speed gains:  
(TR=2000 ms)

- Full Fourier: 37 slices @ TE=22 ms
- Early 6/8 pF: 40 slices @ TE=18 ms
- Late 6/8 pF: 44 slices @ TE=22 ms

So omitting late echoes allows 10% more coverage than regular pF, and a better TE for BOLD!
SNR * BOLD for Optimization
Okay, but what questions should you be asking right now?

I just sold you a new method: “reverse” partial Fourier EPI

Be a healthy skeptic! Ask what the downsides are, compared to full k-space EPI. Artifacts? Risks?
pF issues – increased dropout?

• The local k-space trajectory may not match the theoretical trajectory, because of magnetic susceptibility gradients
• Biggest problems likely to be frontal and temporal lobes
• Signal that drops out with early echo omission is likely to be retained in late echo omission; there’s a degree of choice (but you still can’t do better than full k-space coverage)
• However, more slices/TR permits thinner slices for the same coverage, perhaps recovering some signal, too!
$6/8^{\text{th}}s$ partial Fourier
“Reversed” $6/8^{th}$ partial Fourier
“Reverse” partial Fourier:

- Standard pF on Siemens achieves a modest increase of coverage (slices/TR), ~10%
- Omitting later echoes provides as much coverage benefit as GRAPPA with R=2, ~20%
- Dropout may be enhanced slightly with pF or rev-pF
- No further motion sensitivity!!
- Can be a useful tactic to increase coverage by a small percentage, and/or achieve slightly higher in-plane res
- But enhanced smoothing is implicit, too
Partial Fourier and the phase encode direction:

- Omitting late echoes improves coverage more
- P-A or A-P phase encoding gives a degree of control over the regions that drop out *
- Set phase encode direction and define “late echoes” based on the regions of extra dropout

* If you’re doing full k-space – the default protocol – you can also select A-P or P-A, but this is usually decided based upon the direction of distortion rather than signal dropout
Early

Late

Late!!!
A-P versus P-A phase encoding

Effect of phase encoding order
GE 3T scanner

Top: "Bottom/Up" (opview_order = 1)
Bottom: "Top/Down" (opview_order = 0)

From the Function BIRN wiki
Simultaneous multi-slice EPI:

The future standard for fMRI at 3 T?
SMS-EPI - how it works:

• Requires a phased-array coil (non-TIM *)
• Need lots of coil loops along the slice axis
• Acquire a set of reference EPIs without acceleration, i.e. one multi-slice set at a time (Takes R*TR to acquire)
• Then acquire time series of SMS-EPI using R-fold simultaneous slice excitation
• Use a SENSE/GRAPPA reconstruction to un-alias the simultaneous slices

* I’m finding out whether the Skyra 24-ch head coil will work for SMS-EPI
Phased array coil (32 channels):

Bottom half only, from underneath with cover removed
From: D Feinberg & K Setsompop, JMR (2013) Epub
“Ultra-Fast MRI of the Human Brain with Simultaneous Multi-Slice Imaging”
SMS-EPI pulse sequence:

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SMS-EPI:

Early experience at Berkeley using the U. Minnesota (CMRR) pulse sequence version
SMS-EPI: R=6, 2x2x2 mm, TR/TE=1300/40 ms
SMS-EPI: whole brain parameters

- MB=6
- 72 slices
- Voxels: 2x2x2 mm
- TR=1300 ms
- TE=40 ms – excellent for BOLD at high res
- 6/8\textsuperscript{ths} partial Fourier (early echoes omitted)
- Echo spacing = 0.8 ms

Protocol optimized at FMRIB, University of Oxford
Some contrast differences due to the longer effective TR for the reference EPIs.
Ghosts are visible in the SMS-EPI, but also residual aliasing.
SMS-EPI motion sensitivity

Preliminary testing only!!!
Temporal SNR – No intentional movement
Temporal SNR – Movement during calibration
Temporal SNR – Movement after calibration (only)
It’s pleasantly surprising yet confusing that motion during the reference scans has less effect than motion after the reference scans, in contrast to (in-plane) GRAPPA.

“During the GRAPPA kernels estimation, the pre-scan calibration data, acquired one slice at a time, is summed to create a synthesized collapsed dataset. A GRAPPA kernel set is then calculated for each of the slices, to best estimate the individual slice pre-scan data from the synthesized collapsed dataset.”
Simultaneous Multi-slice EPI

- Offers massive increases in spatial and temporal resolution!
- The costs seem to be low(er than GRAPPA)
- Motion sensitivity...?
- Distortion is fairly high, but fixable
- Suggest adoption with usual cautions
- CMRR, WIP #770 variants
But even SMS-EPI has limits!

• Voxels below 2x2x2 mm have low SNR
• 1.5 mm resolution (with partial brain coverage) is probably the practical limit at 3 T
• 1 mm voxels with a restricted ROI have been tried, but to me the SNR looks unusable at 3 T. (Maybe at 7 T!)
Conclusions
Conclusions: partial Fourier

- “Reverse” partial Fourier is a simple way to get ~20% more slices/TR than for full k-space
- Small increase in dropout
- May be able to use slightly thinner slices
- May be able to use slightly increased resolution
- No increase of motion sensitivity
Conclusions: in-plane GRAPPA

- Only allows more slices/TR if TE is reduced
- Permits some increased in-plane resolution
- Residual aliasing artifacts are a concern
- Increased motion sensitivity a HUGE concern!
- The costs don’t seem worth the benefits
Conclusions: SMS-EPI

- Permits large increase of slices/TR
- Permits increased in-plane resolution because echo train (and TE) can be extended
- Residual aliasing artifacts not yet understood
- Motion sensitivity not yet investigated fully
- The benefits may be worth all the costs (whatever they are!)
Gold
SMS-EPI

Silver
“Reverse” partial Fourier EPI

Bronze
Partial Fourier EPI
Single-shot, full k-space EPI finished solidly in the pack, just happy to have made the Games at all.

GRAPPA-accelerated EPI was busted for performance-enhancing drugs and was sent home in disgrace.
Thank you!