BOLD fMRI:
signal source, data acquisition, and interpretation

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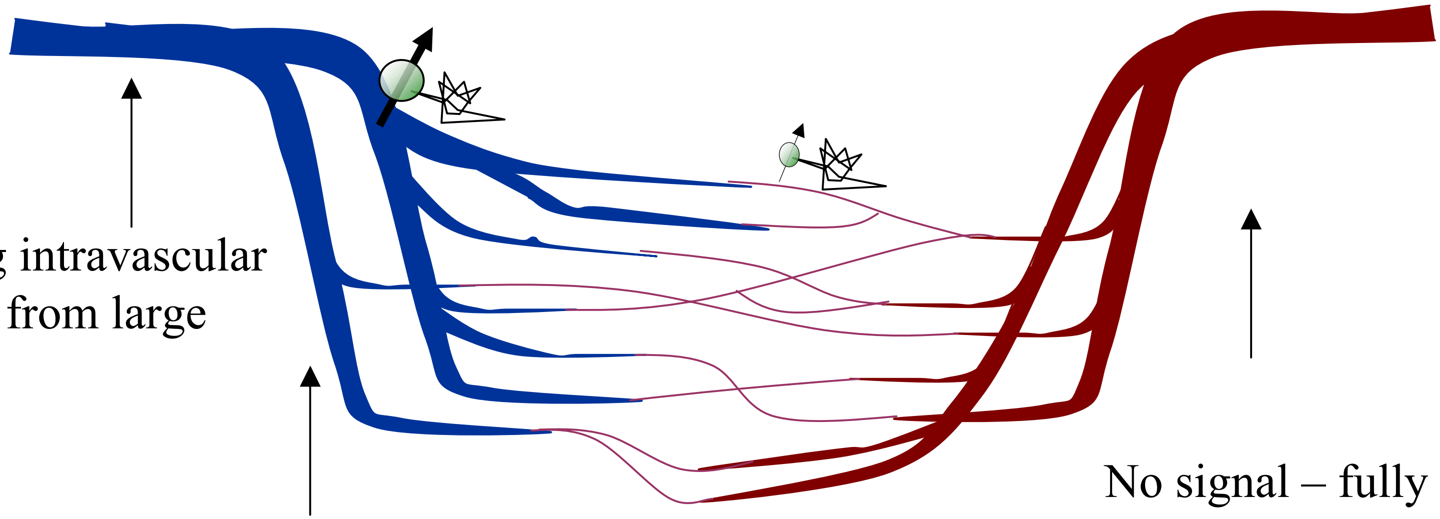
Discussion series

- Week 1: Biological basis: where’s the signal coming from?
- Week 2: Physical basis: what is the signal, how is it measured?
- Week 3: Imaging basics: image formation, noise, and artifacts.
- **Week 4: The specific case of BOLD fMRI.**
- Week 5: BOLD analysis: what’s significant and what’s not?
- Week 6: Spikes vs. BOLD: neural activity in visual areas

BOLD fMRI

- The signal around veins and capillaries
- BOLD and CBF measurements
- Modeling the BOLD response
- Optimizing imaging for BOLD (flip angle, TE)
- Distortion (continued from last week)
- Motion correction – prospective routines
- Sample BOLD experiment

Arteries, Capillaries, and Veins



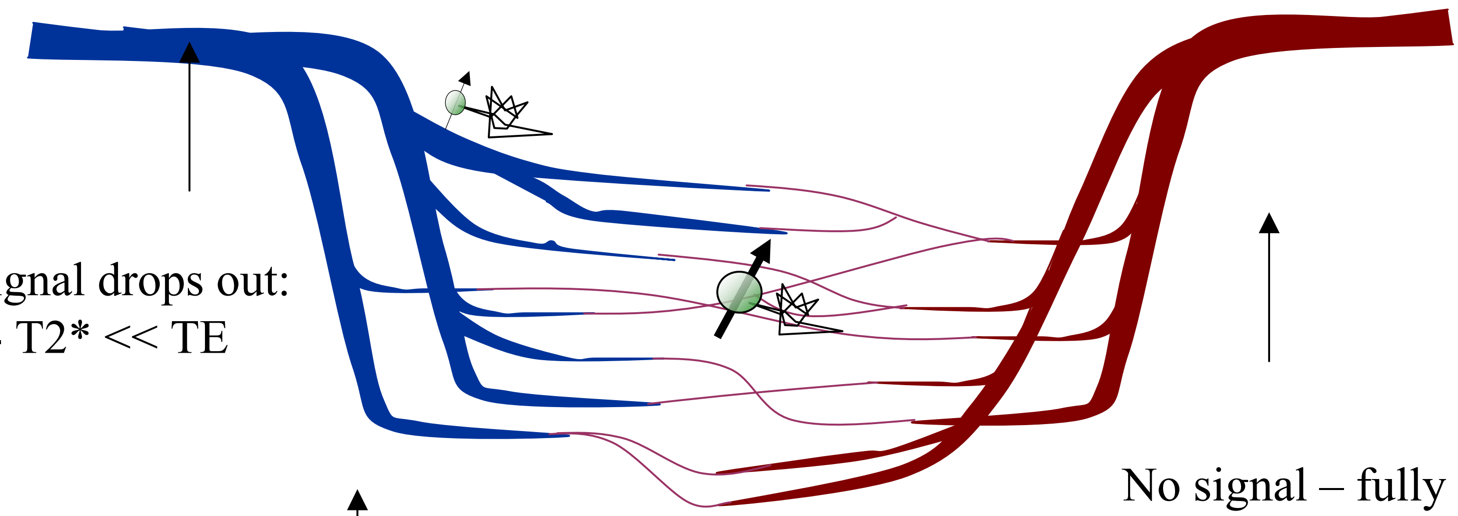
Strong intravascular signal from large veins

Strong extravascular signal:
- highest [dHb] (60%)
- large diameter means less dynamic averaging during diffusion of water molecules

Weak extravascular signal:
- Relatively high [dHb] (70 – 80%)
- Dynamic averaging from diffusion reduces effect of field inhomogeneities even further

No signal – fully oxygenated

Field Dependence



Signal drops out:
- T2* << TE

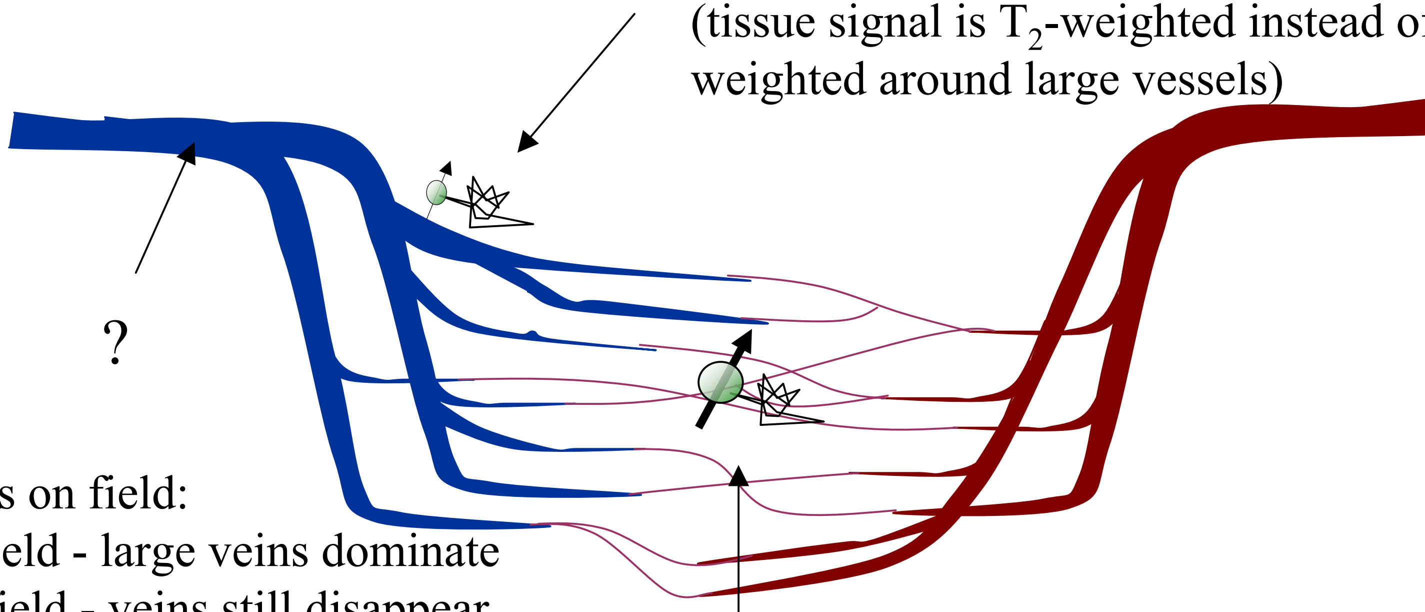
No signal – fully oxygenated

Strong signal:
- T2* ~ TE
- static averaging

Signal increases:
- Higher field means bigger effect from [dHb]-induced inhomogeneities
- Less time for dynamic averaging

What does Spin Echo do?

Protons experiencing static dephasing are refocused, but BOLD effect is eliminated (tissue signal is T_2-weighted instead of T_2^*-weighted around large vessels)



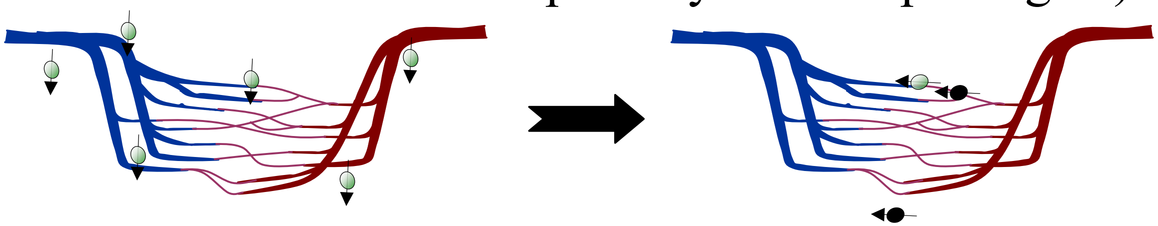
Depends on field:
Low field - large veins dominate
High field - veins still disappear

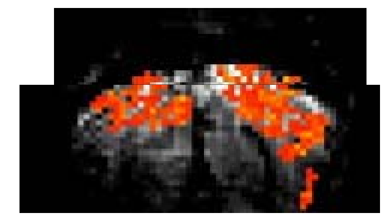
Tissue protons experiencing dynamic dephasing see residual BOLD signal.

Perfusion imaging (FAIR technique)

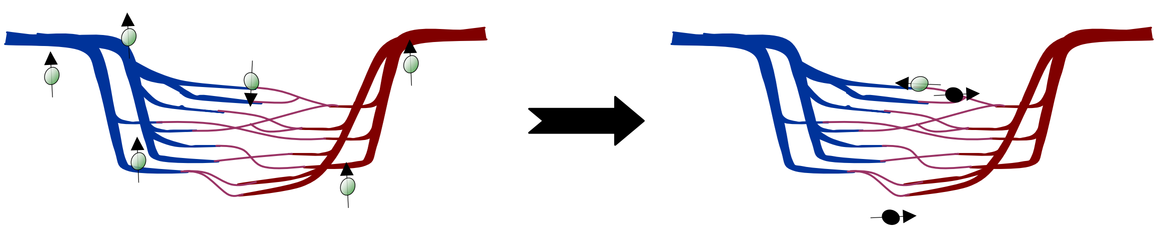
1) Non-selective inversion pulse before acquisition

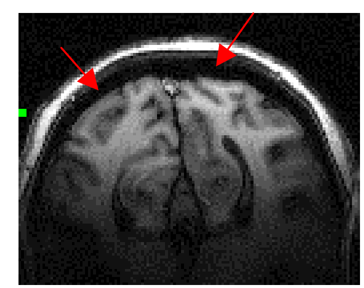
(free bonus BOLD data in specially marked packages!)





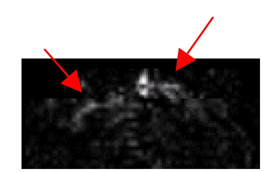
2) Slice-selective inversion pulse before acquisition





3) Difference image produces perfusion map

$$\Delta S \propto 2M_{0A}$$



Modeling the BOLD response

Relaxation rates are proportional to blood volume and [dHb]:

$R_2^* \sim V\,[dHb]^\beta$, with $\beta > 1$ because of diffusion, and the fact that increasing blood volume displaces tissue water

…

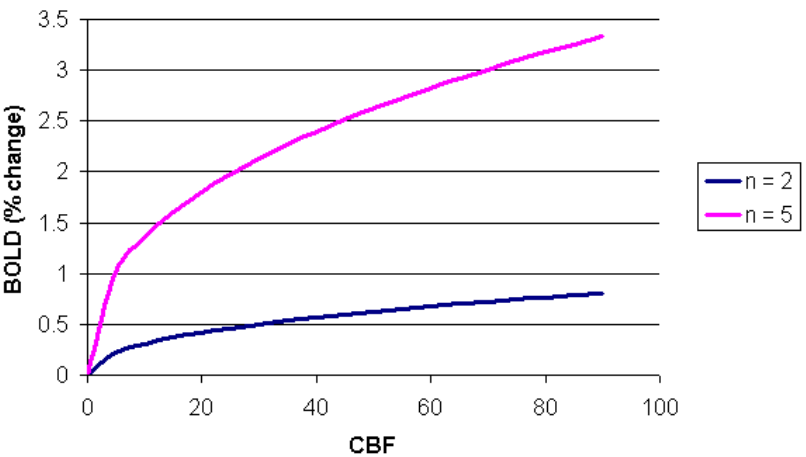
$$dS/S = S_{max}(1 - vc^{\beta})$$

where v is relative blood volume, and c is relative [dHb].

Using

$c = m/f$ (where m is relative $CMRO_2$, and f is relative CBF)

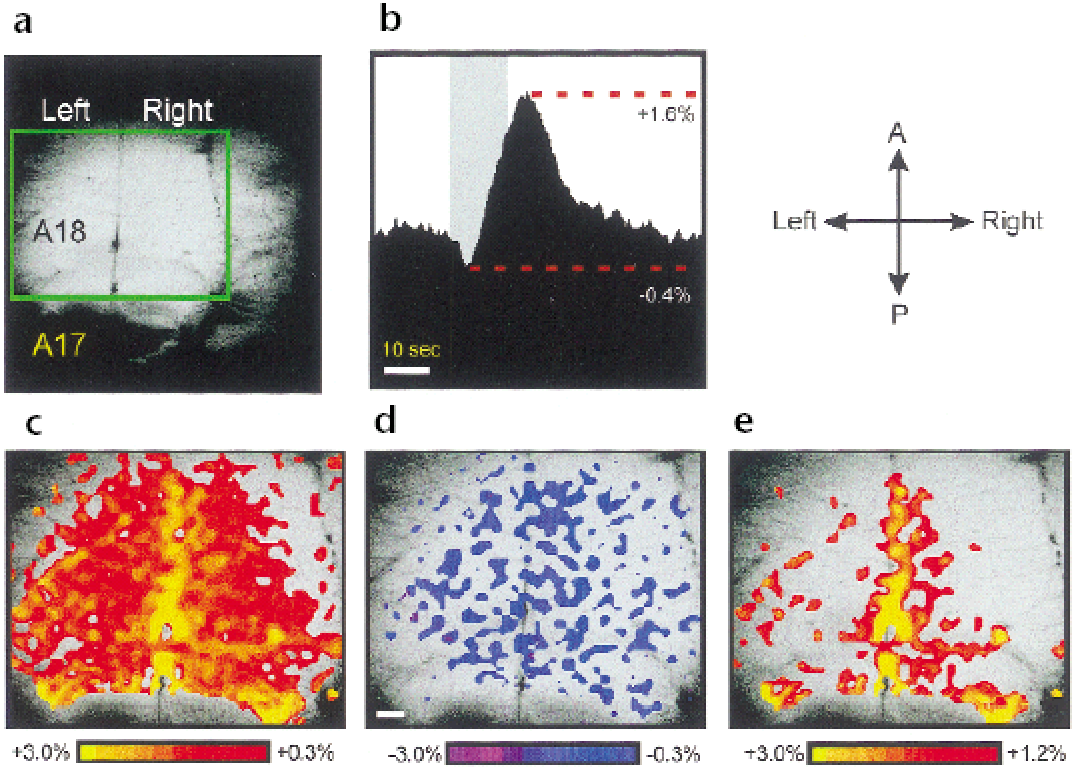
$v = f^{\alpha}$ ($\alpha \sim 0.4$, from animal studies)

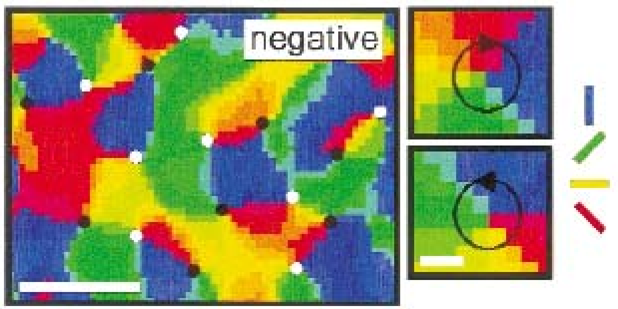


(this represents just a partial understanding of Box 16 in the Buxton book … the goal would be to use this to model the temporal dynamics of the response to neural activity … the hemodynamic response)

Early Dip

Buxton sums it up well: controversial and important



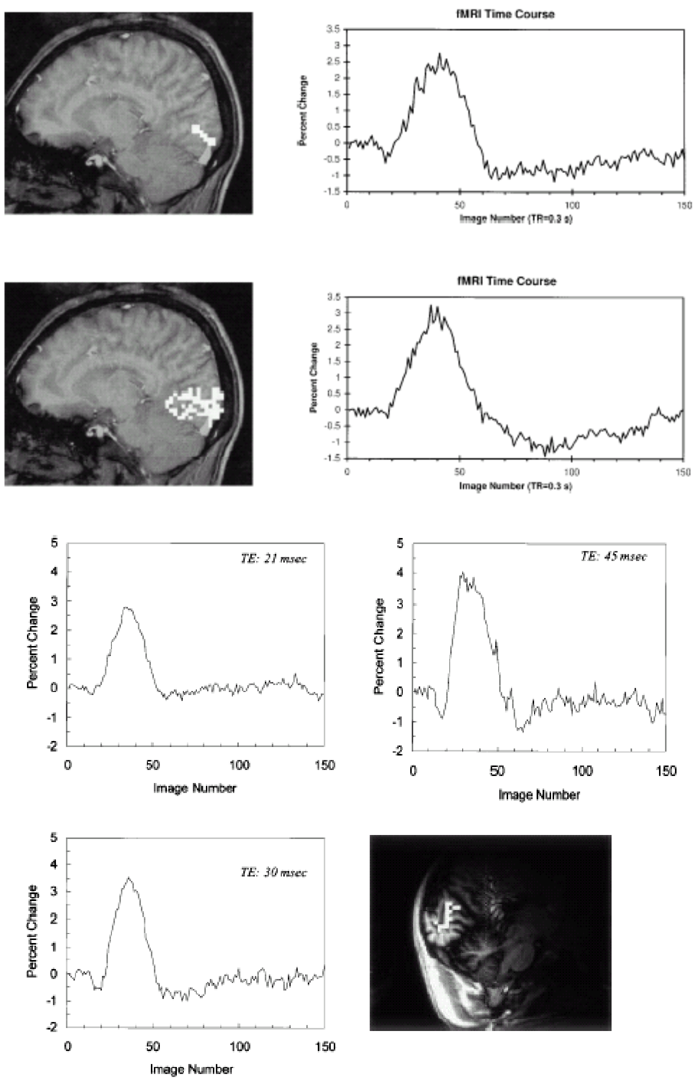


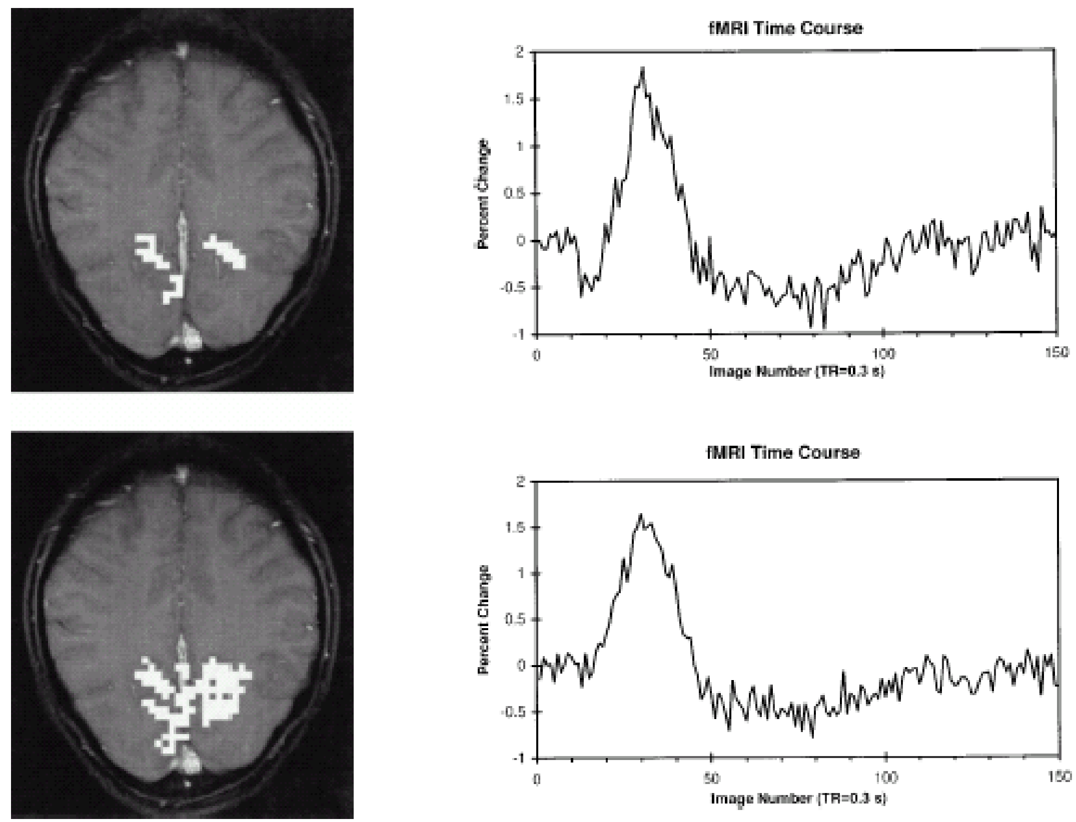
High-resolution mapping of iso-orientation columns by fMRI

Dae-Shik Kim, Timothy Q. Duong and Seong-Gi Kim

nature *neuroscience* • volume 3 no 2 • february 2000

Yacoub, E. and Hu, X. (1999). Detection of the early negative response in fMRI at 1.5 Tesla. *Mag Reson Med*. **41**: 1088-1092.





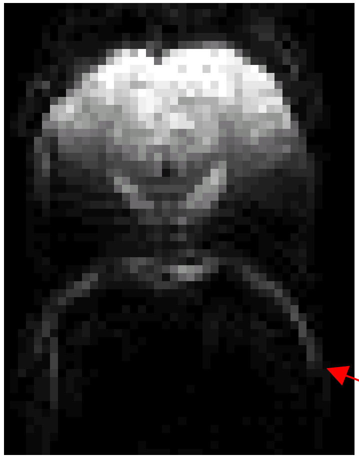
Yacoub et al. (1999). “Further evaluation …” *Mag Reson Med*. **41**: 436.

Optimizing acquisition for BOLD

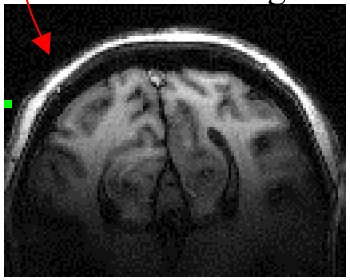
- Echo time
  - BOLD effect is strongest when TE ~ $T2^*$
- Ernst angle
  - For repetition times ~ T1, steady state signal is greatest when flip angle is less than 90 degrees
- Resolution/SNR trade-off
- Total scan time

Distortion in EPI images

- Basic problem: a voxel's location is inferred from it's resonant frequency
- Each accumulated 360 phase shift moves the signal one voxel
- Example: chemical shift of fat at 7T
  - Fat resonates at 3.5 ppm
  - At 7T, this is 3.5 x 10^{-6} x 300MHz, or ~1000Hz
  - A 64 x 64 EPI image has a read-out time of 500us
  - So time for phase evolution along phase encode direction is 64 x 500us = 32ms
  - 32ms x 1000Hz = 32 pixel shift



Subcutaneous fat, shifted 32 / 64 pixels in EPI image



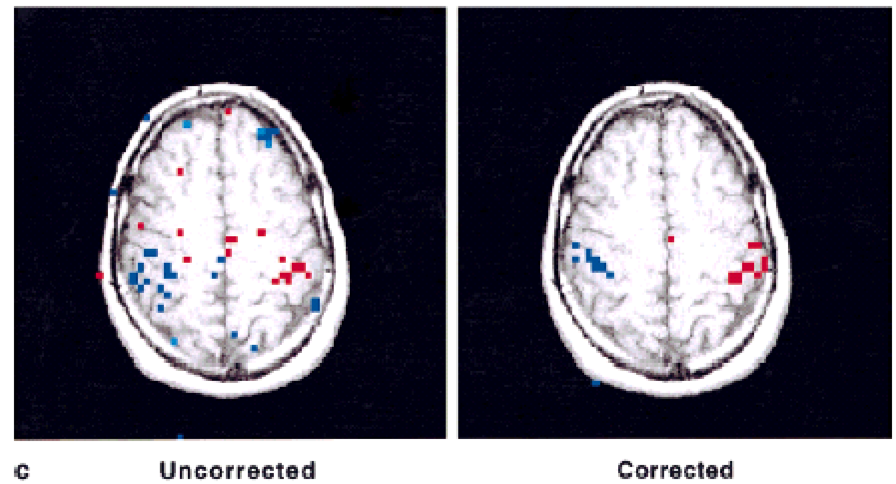
Prospective motion correction

Navigator echo samples k-space before each image:

$$S(k,\theta) = S_{ref}(k, \theta - \alpha)e^{ik(x\cos + y\sin)}$$

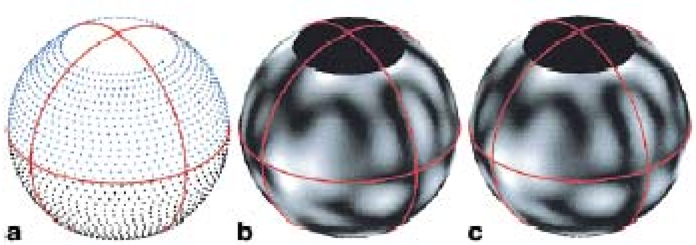
rotation shows up as rotation

translation shows up as a phase shift



Ward et al. (2000). Prospective multi-axial motion correction for fMRI. *Mag Reson Med*. **43**: 459.

ONAV successfully corrects stimulus-related head motion



SNAV. Welch et al, MRM 47:32-21 (2002)

SNAV is more computationally demanding