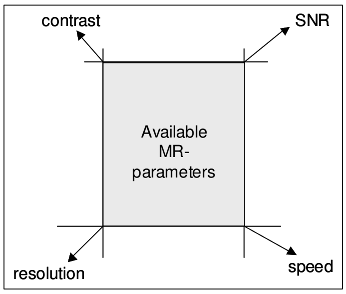
FYS-KJM 4740

MR-teori og medisinsk diagnostikk

Kap 8
Image quality, signal, contrast and noise



Main source of noise in MRI:

- •Noise generated within the reciever RF electronics
- •Brownian motion of electrons within the body (in conducting tissue)

Signal induced in received coil with N turns (ignoring effect of sequence parameters)

$$S(t) = \omega_0 N \int_v M(r)\exp(jk(t)r)dr + n(t)$$

N=number of turns in receiver coil

n(t)=complex noise term

NB: $M \propto MR-signal \propto B_0 = \omega_0 / \gamma$ so $S(t) \propto B_0^2 \propto \omega_0^2$

Noise-independent signal from a voxel of volume V_h (Macovski A. Magn Reson Med 1996)

$$M_{sig} = \omega_0^2 N \chi V_h / \gamma \qquad M(r)=\chi B_0$$

Signal-Noise ratio (single voxel, one measurement)

$$SNR = \frac{\omega_0^2 N \chi V_h}{\sqrt{2kT \cdot R / T_r}}$$

N=No of coil terms, χ=tissue susceptibility, k=Boltzmanns const, T=temp, Tr=read-out time (time to record echo), R=coil resistance,

Does SNR scale with B_o^2 ?
(probably not in reality)

Coil resistance R, complex function of B_o

SNR also function of sequence parameters and Q-factor of coil (Q=ωL/R)

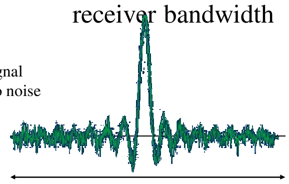
$$SNR = A \cdot \sqrt{\frac{QB_0^3 N_{SA} \cdot N_y N_s}{BW}} V_h \cdot S(TR, TE, \alpha, T1, T2, T2^*, \rho)$$

A=constant (susceptibility, temp, object geometry, size etc)
BW=pixel bandwidth=$1/T_r$
NSA=number of averages
Ny=number of phase encoding steps; Ns=number of slice enc steps (=1 for 2D)

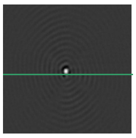
Pixel bandwdth (receiver bandwidth):

receiver bandwidth

measured signal
includes also noise



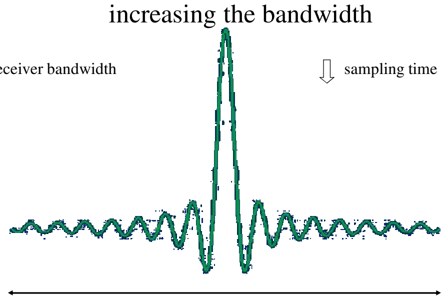
sampling time of echo



$$receiver\ bandwidth = \frac{number\ of\ samples}{sampling\ time\ of\ echo} = \frac{number\ of\ samples}{number\ of\ samples \cdot dwell\ time}$$

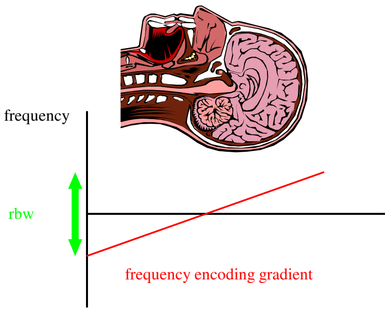
increasing the bandwidth

⇧ receiver bandwidth ⇩ sampling time



sampling time of echo

receiver bandwidth and gradient strength

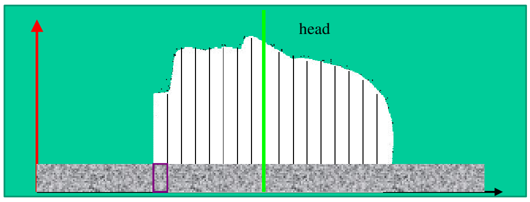


⇧ frequency encoding gradient

⇧ receiver bandwidth

faster rephasing due to gradient; i.e. echo forms faster

noise and frequency encoding



⇨ total amount of signal of signal per voxel is unchanged, bigger difference of resonance frequencies inside the voxel

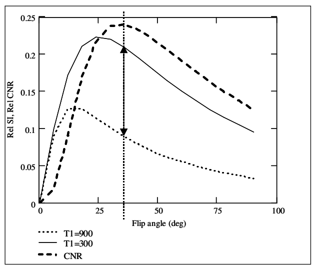
but : total amount of noise is increased !!!

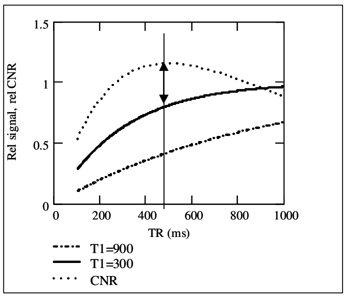
Signal vs contrast

$$CNR = SNR_A - SNR_B = \frac{S(A) - S(B)}{\sigma}$$

σ = image noise (assumed position independent)

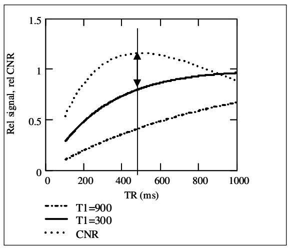
Signal vs contrast (T1.GRE)



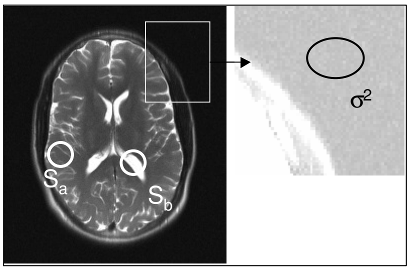


Signal vs contrast (SE)

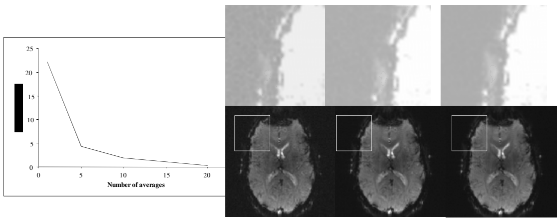
$$TR_{opt} = \frac{T1_1 T1_2}{T1_1 - T1_2} \cdot \ln(T1_1 / T1_2)$$



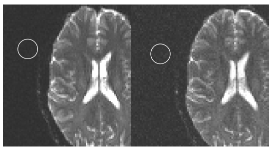
Practical measurement of SNR



Effect of NSA on SNR

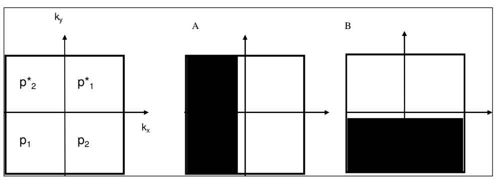


Effect of BW on SNR

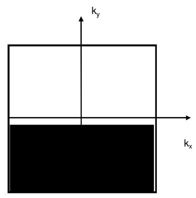


BW=750 Hz BW=2055 Hz

Partial k-space sampling

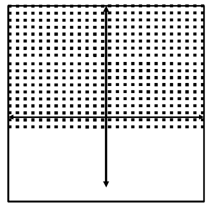


‘Half-scan’ (partial Fourier)



phase partial fourier

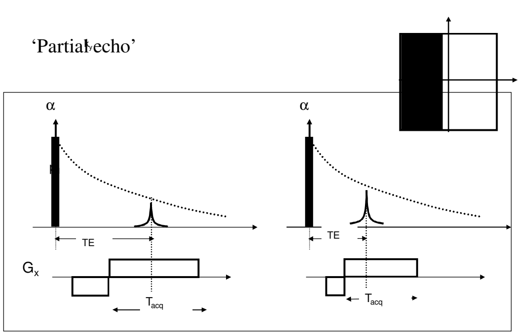
example: half fourier



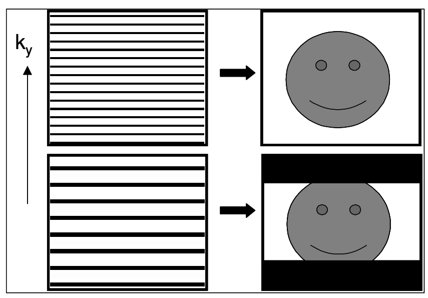
FOVx,y : 256 mm
matrix= 256 x (128+8)
pixel size: (1 x 1) mm2
acquisition time : ca. 50 % (256 x 256)
SNR (relative) = 1./1.41

phase error due to inhomogeneity of B_0
8 further steps required for phase correction

‘Partial-echo’



Rectangular field of view (rFoV)



$$SNR = A \cdot \sqrt{\frac{QB_0^{\,3} N_{SA} \cdot N_y N_s}{BW}} V_h \cdot \mathrm{S(TR, TE}, \alpha, \mathrm{T1, T2, T2^*}, \rho)$$

Working examples:

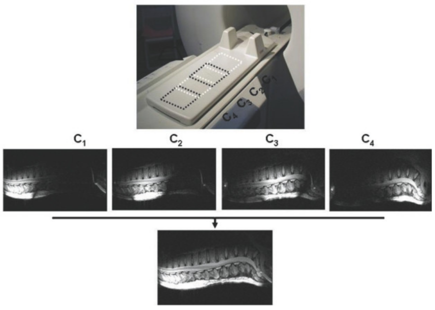
Ref scan: FoV 256 x 256; BW=1000 Hz/px; V=1x1x1 mm^3

1. 75% rFoV
2. Half-scan (partial fourier)
3. Reduced phase sampling (reduced Ny)
4. Reduced BW =BW/2
5. Increased TR (SE sequence)
6. Increased FA (GRE sequence)
7. Partial echo

Parallel imaging

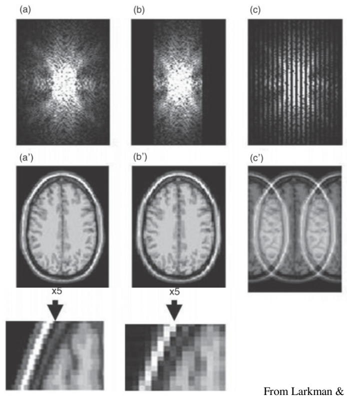
Basic concepts:
- Many small coils give better overall SNR than one large
- Phased array technology: parallel processing of signal from multiple coils
- Requires fast data handling and high processing capacity due to parallel processing of multiple data streams
- Use of signal sensitivity profile from each coil element to reconstruct corrected ’undersampled’ image

Use of multiple receive coils



From Larkman & Nunes; Phys Med Biol (2007)

Reduced K-space sampling

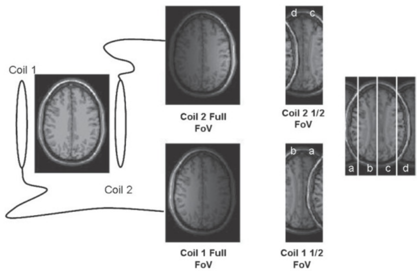


From Larkman & Nunes; Phys Med Biol (2007)

Sensitivity Encoding (SENSE)

- •Extent of k-space (resolution) unchanged
- •Distance between adjacent k-space lines increased by factor *r*
- •Results in signal components from *r* locations overlap in the (undersampled) image
- •Provided the coil sensitivty is different for each coil element, the correct signal distribution in the whole image can be reconstrcuted from the aliased image if the coil sensitivity profile for each coil element is known.

The concept of parallel imaging



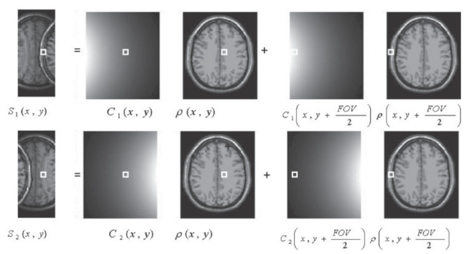
From Larkman & Nunes; Phys Med Biol (2007)

SENSE

$$S_1(x,y) = C_1(x,y)\rho(x,y) + C_1\left(x, y+\frac{\text{FOV}}{2}\right)\rho\left(x, y+\frac{\text{FOV}}{2}\right)$$
$$S_2(x,y) = C_2(x,y)\rho(x,y) + C_2\left(x, y+\frac{\text{FOV}}{2}\right)\rho\left(x, y+\frac{\text{FOV}}{2}\right).$$

S(x,y) =SI in the sub-sampled (alisased) image
C(x,y) = coil sensitivities at the location of the two aliased pixels
ρ = signal (spin density) from the object at the two locations (x,y) and (x, y+FoV/2)

The concept of parallel imaging



$$S_1(x,y) = C_1(x,y)\rho(x,y) + C_1\left(x, y+\frac{\text{FOV}}{2}\right)\rho\left(x, y+\frac{\text{FOV}}{2}\right)$$
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SENSE

$$S_1(x, y) = C_1(x, y)\rho(x, y) + C_1\left(x, y + \frac{\text{FOV}}{2}\right)\rho\left(x, y + \frac{\text{FOV}}{2}\right)$$
$$S_2(x, y) = C_2(x, y)\rho(x, y) + C_2\left(x, y + \frac{\text{FOV}}{2}\right)\rho\left(x, y + \frac{\text{FOV}}{2}\right).$$

In matrix notation: $\mathbf{S} = \mathbf{C}\rho$

=> $\rho' = (\mathbf{C}^H \Psi^{-1}\mathbf{C})^{-1}\mathbf{C}^H\Psi^{-1}\mathbf{S}.$

Where ψ=receive noise matrix

From Larkman & Nunes; Phys Med Biol (2007)

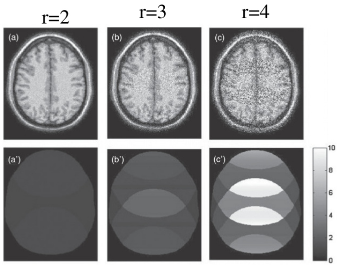
SENSE does not affect spatial resolution but reduced SNR:

$$\text{SNR}_p^{\text{red}} = \frac{\text{SNR}_p^{\text{full}}}{g_p\sqrt{r}}.$$

r= SENSE factor
g=’g-factor’ and is a function of coil geometry, noise profile and *r*

$$\text{SNR}_p^{\text{red}} = \frac{\text{SNR}_p^{\text{full}}}{g_p\sqrt{r}}.$$

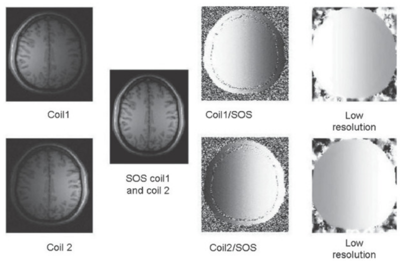
r=2 r=3 r=4



’g-factor’ images

From Larkman & Nunes; Phys Med Biol (2007)

Extraction of coil sensitivity data:



SOS = sum of squares

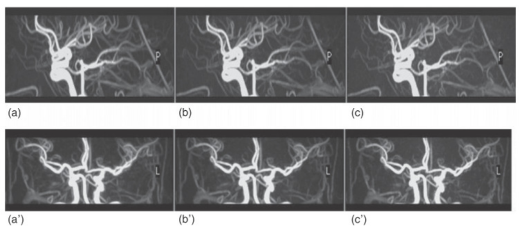
From Larkman & Nunes; Phys Med Biol (2007)

Applications of SENSE (and similar PI techniques):

- Reduced scan-time (all sequence types)
- Reduced geometric distortion and signal loss in EPI sequences

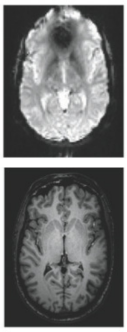
Phase contrast angiography (PCA)

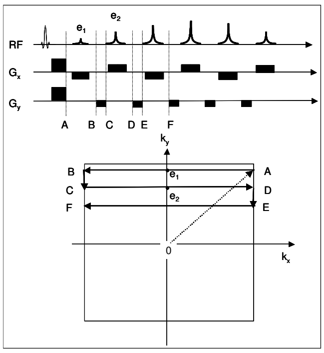
r=1 (12 min) r=2 (6 min) r=3 (4 min)



From Larkman & Nunes; Phys Med Biol (2007)

Echo Planar Imaging (EPI)





EPI – echo modulation:

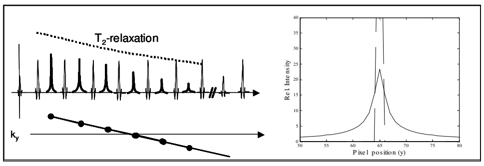
$$S(P) = \int_{-k_{max}/2}^{k_{max}/2} P(k_y)\exp(-jk_y)dk_y$$

Exp T2*-decay =>Lorentzian kernel

$$S(y,T2^*) = \frac{1/W}{1 + j2y/W}$$

W=δy·2/π (ETL · ES/T2*)

Δy= pixel dim in phase enc-dir



EPI – 'damping factor' in k-space:

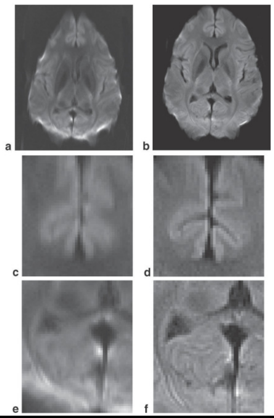
$1/T_2^* = 1/T_2 + 1/T_2'$ $\quad$ $1/T_2'$= 'inhomogeneity induced'

$$d(k_y) = rect(k_y)\cdot\exp\left[\frac{-TE-(k_y-k_{y,\min})/v_y}{T_2}\right]\exp\left[\frac{-|k_y-k_{y,\min}|/v_y}{T_2'}\right]$$

V_y = average 'k-space' speed in y-direction, which is proportional to SENSE reduction (r-) factor

SE-EPI (3 T)

r=1 $\quad$ r=2.4



Jaermann et al MRM (2006)