Basic Signal Equation

Spatial resolution ↑
Imaging Time ↑
SNR ↓

Imaging Time ↓
Spatial Resolution ↓
SNR ↓

SNR ↑
Spatial Resolution ↓
Imaging Time ↓

$$SNR \sim \underbrace{(\Delta x)(\Delta y)(\Delta z)}_{\text{Voxel size}} \underbrace{\sqrt{N_y \, x \, N_z \, \mathbf{x} \, T_{measurement}}}_{\text{Total readout interval}} \underbrace{f(\rho, T_1, T_2)}_{\text{Tissue parameter}}$$

SNR in MRI

SNR in MRI

Electrical noise

Coils have finite resistance

thermal motion of electrons in resistive components

Intrinsic noise

random motion of electrons in patient

External noise

stray RF, fans that cause vibrations, …

Shot-to-shot noise

instabilities in system: flip angle,

patient motion,

cardiac pulsatility, …

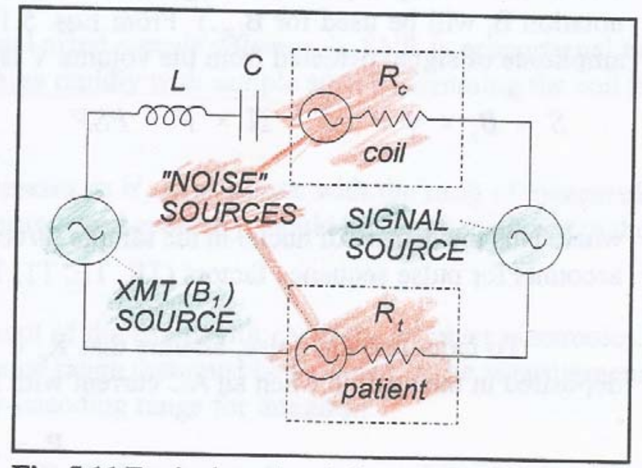

Fig. 5.11 Equivalent circuit for MR signal detection circuitry.

From James Sorenson
Course Notes for Medical Physics 568
UW-Madison, 1998

SNR in MRI

Electrical noise

Coils have finite resistance

thermal motion of electrons in resistive components

Fairly low contribution

Intrinsic noise

random motion of electrons in patient

Dominating noise

External noise

stray RF, fans that cause vibrations, …

Fairly low contribution

Shot-to-shot noise

instabilities in system: flip angle,

patient motion,

cardiac pulsatility, …

Should be kept low

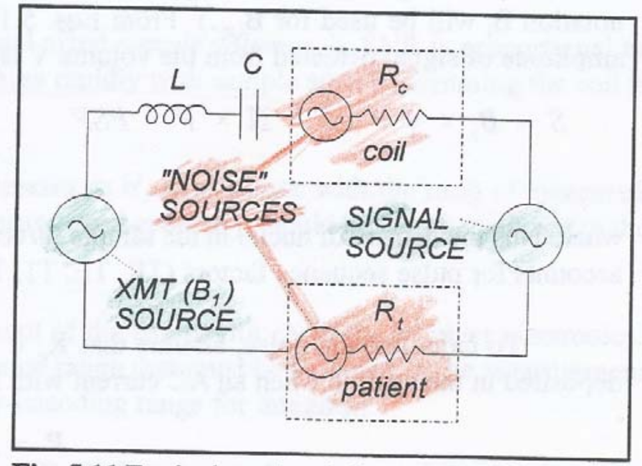

Fig. 5.11 Equivalent circuit for MR signal detection circuitry.

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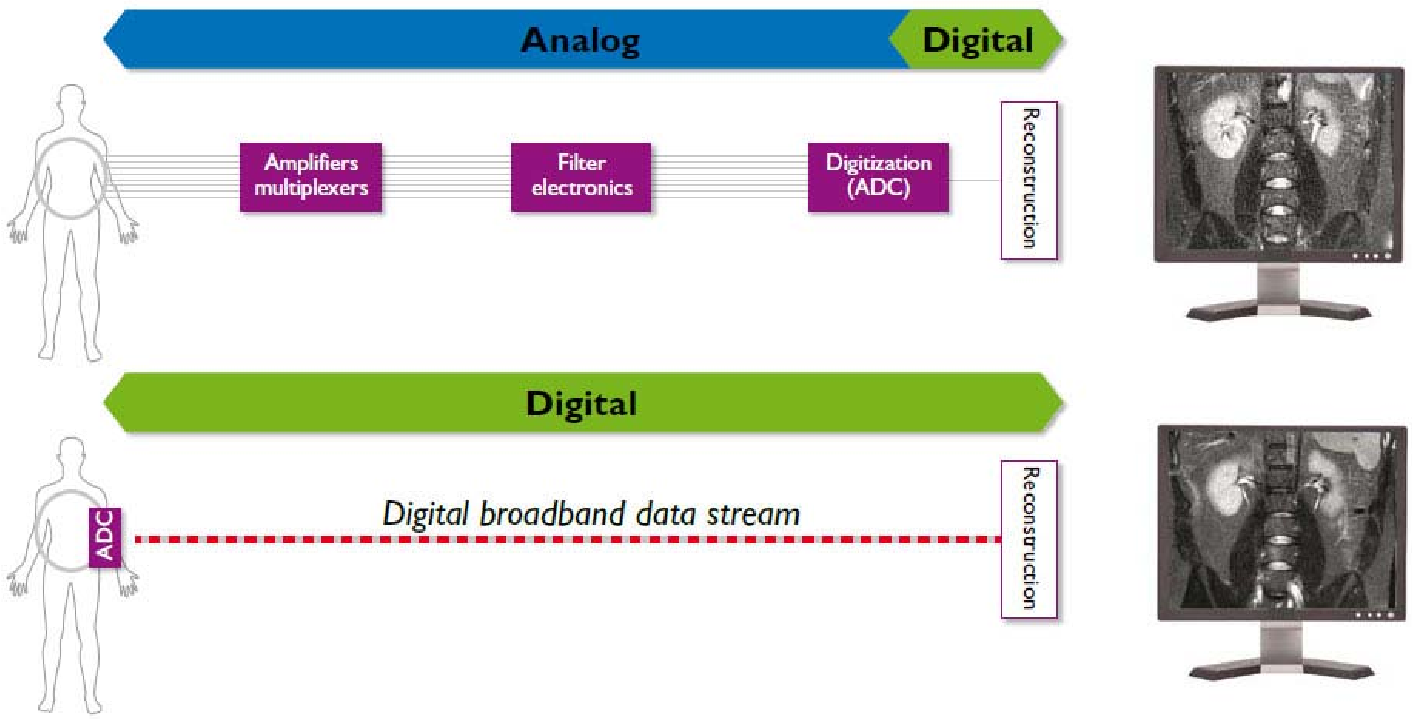
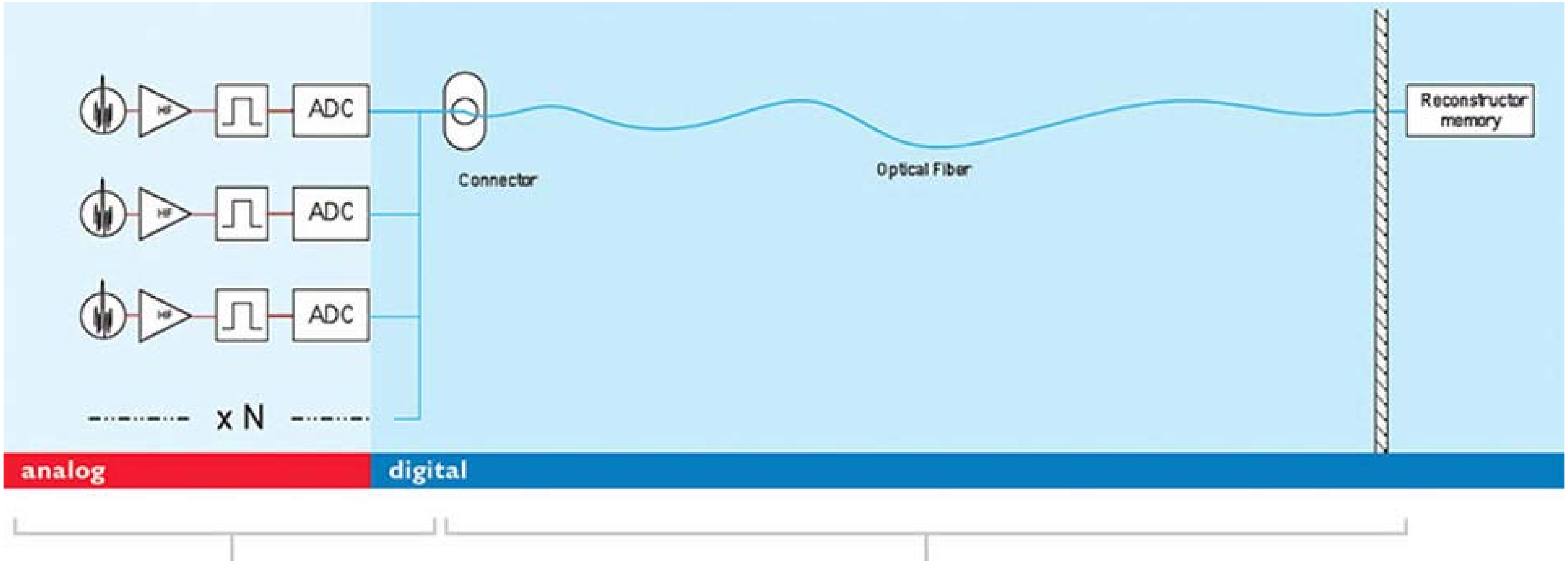
Philips dStream

Moving from analog to digital broadband



Source: http://www.usa.philips.com/healthcare/education-resources/technologies/mri/dstream

Philips dStream



- simplified receiving architecture, with few components
- low power consumption
- high SNR and dynamic range
- enhanced signal and phase stability.

Source: http://www.usa.philips.com/healthcare/education-resources/technologies/mri/dstream

Philips dStream

Other rf receive
Result: Noisy images using identical scan parameters

dStream receive
Result: Improved SNR and image resolution

Source: http://www.usa.philips.com/healthcare/education-resources/technologies/mri/dstream

Intrinsic SNR

2. ***Intrinsic SNR***

Intrinsic noise generated by thermal motion of electrons is characterized as *white noise*, i.e., constant amplitude vs. frequency. The RMS amplitude of the noise across a resistive component is called *Johnson noise* and is given by

$$\boxed{N(volts) = \sqrt{4kTR\Delta\nu}} \quad (5.35)$$

where $\Delta\nu$ is the bandwidth of the signal recording system. Thus,

$$\boxed{SNR \propto (B_{i,xy} \times \text{source terms})/\sqrt{4kT(R_c + R_t)\Delta\nu}} \quad (5.36)$$

where R_c and R_t are coil and tissue resistances, respectively.

Intrinsic SNR for an MR apparatus and procedure can be estimated as follows (see Fig 5.12). Suppose the signal is detected from a localized volume V (e.g., an image voxel) inside a larger sample of radius b. Suppose further that the signal is measured with a coil that produces a (uniform) field $B_{i,xy}$ within the sample when a current I = 1 amp is passed through the coil. (For simplicity, the notation B_i will be used for $B_{i,xy}$.) From Eqs. 5.12 and 5.34, the amplitude of signal detected from the volume V is

$$\boxed{S \propto B_i \times \gamma \times \omega_0^2 \times N \times V \times PSF} \quad (5.37)$$

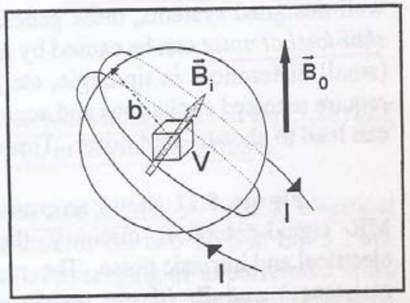


Fig. 5.12 Simplified coil and sample model for calculating intrinsic SNR.

where N is the density of nuclei in the sample (#/volume), and PSF accounts for pulse sequence factors (TR, TE, T1, T2, etc.).

N = # / of nuclei/V
V = voxel volume
PSF = pulse sequence factors (TR/TE, …

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To calculate the noise, assume that $R_c \ll R_t$ (usually a reasonable assumption). Then the power deposited in the sample when an AC current with RMS amplitude, I_{RMS}, is passed through the coil is

$$P = I_{RMS}^2 \times R_t \tag{5.38}$$

tissue resistance

where R_t is the resistance of the sample. The power deposited in the sphere by the oscillating B_1 field generated by this current can be calculated from first principles (Chen & Hoult, p.128, see also C&H problem 4.7).

$$P = \pi \omega_0^2 \, B_1^2 b^5 / 15 \rho \tag{5.39}$$

5-11

where ρ is the resistivity of the sample (~1 Ω•m for biological materials). Since B_i is the amplitude of the B_1 field generated by a current of unit amplitude

$$B_1 = \sqrt{2} \, B_i \, I_{RMS} \tag{5.40}$$

Thus, combining Eqs. 5.38-5.40, the sample resistance is

tissue resistance
$$\boxed{R_t = 2\pi\omega_0^2 \, B_i^2 / 15\rho} \tag{5.41}$$

Inserting Eq. 5.41 into the equation for Johnson noise (Eq. 5.35), combining with the equation for signal, and saving only the MR-relevant variables, one obtains for the *intrinsic SNR*

$$\boxed{\begin{aligned} \psi_{int} &\propto \gamma \; \omega_0 \; N \; V \; PSF / \sqrt{b^5 \Delta\nu} \\ &\propto \gamma^2 \; B_0 \; N \; V \; PSF / \sqrt{b^5 \Delta\nu} \end{aligned}} \tag{5.42}$$

Equations for intrinsic SNR also are derived in Edelstein et al., Magn. Reson. Med. *3*:604, 1986.

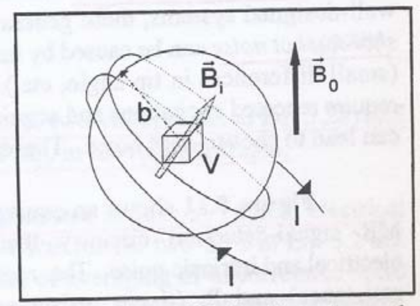

Fig. 5.12 Simplified coil and sample model for calculating intrinsic SNR.

N = # / of nuclei/V
V = voxel volume
PSF = pulse sequence factors (TR/TE, …
B = radius of coil 'sphere'

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Specific Absorption Rate - SAR

D. SAR AND TISSUE HEATING

Equation 5.39 can be used to estimate the SAR, or *specific absorption rate* (watts/kg), for an MR pulse sequence. For example, modeling the body as a spherical volume with specific gravity 1, the SAR is given by

$$SAR \propto \omega_0^2 B_1^2 b^2/\rho \tag{5.43}$$

With further rearrangement and substitution, this can be written as

$$SAR \propto (B_0^2 \theta^2 b^2)/(t_p^2 \rho) \tag{5.44}$$

This equation shows that:

✔ SAR increases as the square of the tip angle. This can be a consideration for pulse sequences that use several refocusing (π) pulses. One solution is to increase the duration of the pulse, but this may be impractical in some situations.

✔ Shorter B_1 pulses result in higher SAR, even for the same tip angle.

✔ Since SAR increases with $\sim b^2$, SAR is higher in a heavier patient, even for the same pulse sequence.

✔ SAR increases with B_0^2. This can be a limiting factor for some applications using high-field systems.

✔ SAR decreases with resistivity, ρ. Tissue interfaces, airways, bone, etc., create higher resistivity and thereby decrease SAR, as compared to what would be predicted for simple models of uniform resistivity (e.g., spheres of saline).

✔ SAR does not depend directly on γ; however, there is an indirect dependence. Most nuclei have

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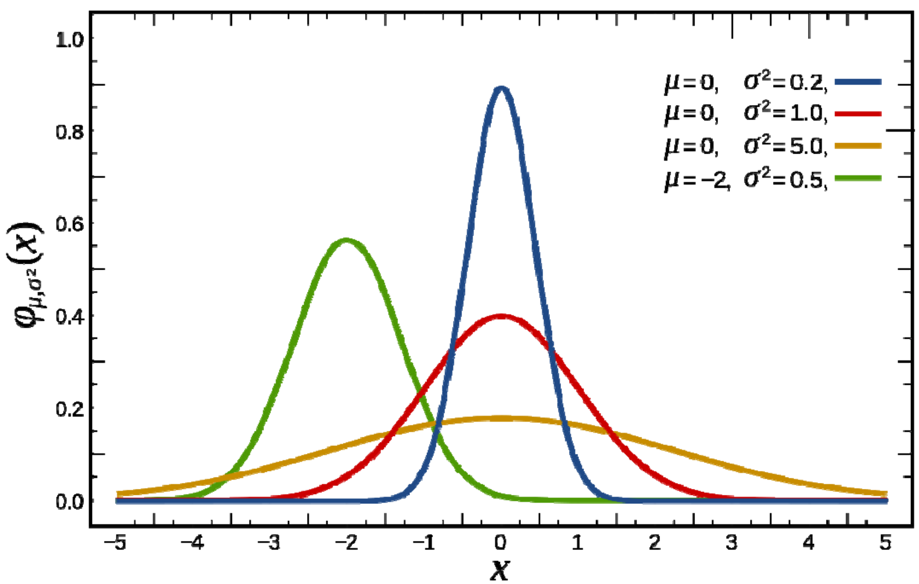
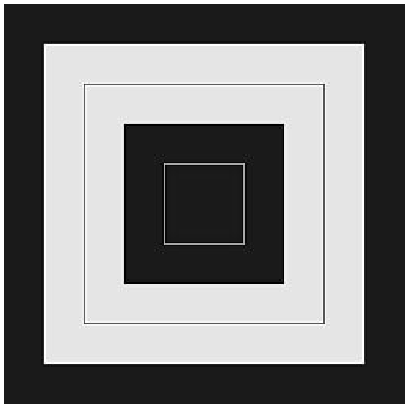
Noise Characteristics in MRI

- Noise is often assumed to be Gaussian with zero mean
- Real and imaginary channel
- Called ‘white noise’: uncorrelated
  - When is that true??

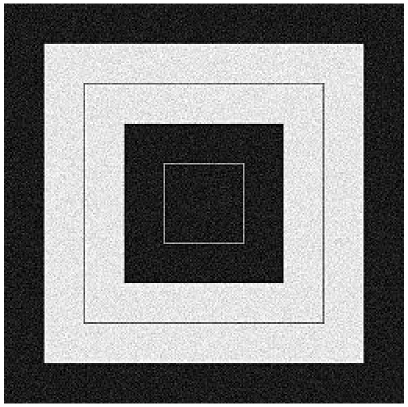
Gaussian distribution



No noise

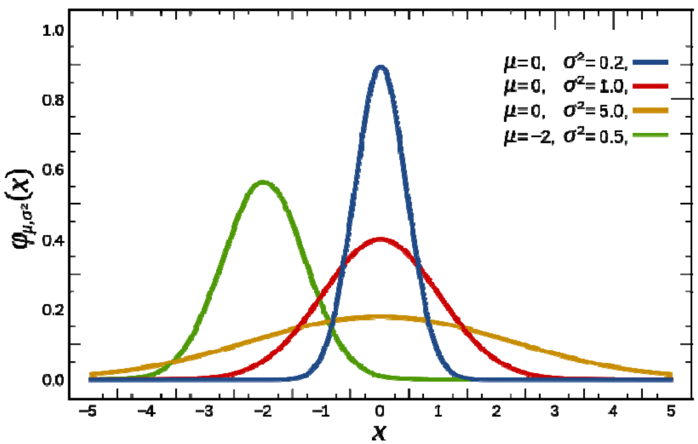


Gaussian noise

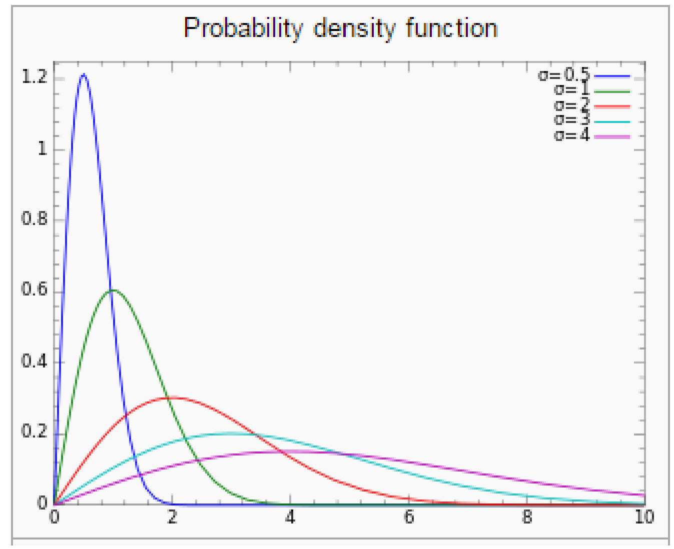


Rayleigh Distribution

Gaussian distribution



Rayleigh



Source: https://en.wikipedia.org/wiki/Rayleigh_distribution

MRI background signal: Random complex numbers whose real and imaginary components are independently and identically distributed <u>Gaussian</u> with equal variance and zero mean.

In that case, the absolute value of the complex number is Rayleigh-distributed.

CNR

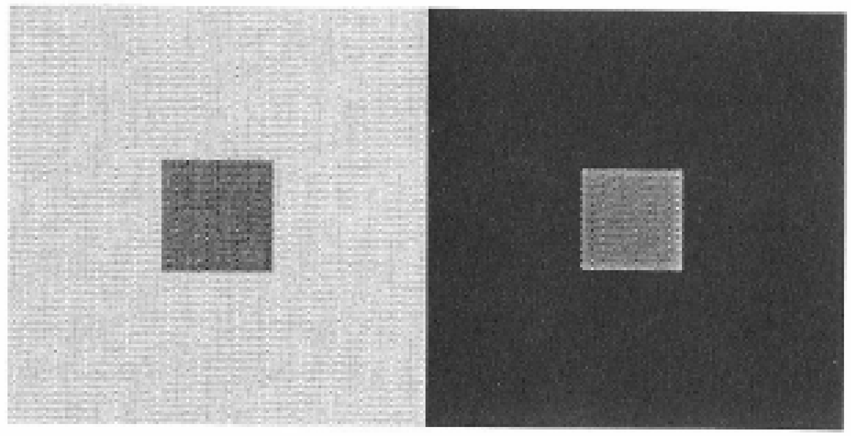


Figure 7.1 Visual illusion: small squares in the middle have equal intensity but do not appear equally bright.

$$\mathcal{C}_{\mathrm{AB}} = \frac{|I_{\mathrm{A}} - I_{\mathrm{B}}|}{I_{\mathrm{ref}}}$$

How to assess SNR ?