Lecture 17 – MRI Sequences

This lecture will cover: *(CH5.11-5.12)*

– Multiple-slice imaging;

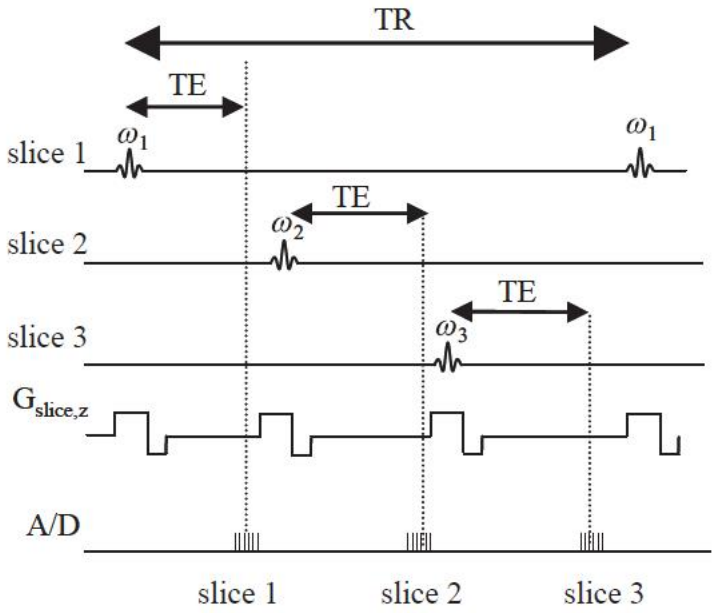
– Basic imaging sequences

- Saturation recovery sequence (SR,饱和恢复序列)
- Spin echo sequence (SE,自旋回波序列)
- Inversion recovery sequence (IR,反转恢复序列)
- Gradient echo sequence (GE,梯度回波序列)

(*Supplementary reading: The Essential Physics of Medical Imaging CH12.4-12.5)*

Multiple-slice imaging

- TR (time of repetition, 脉冲重复时间):
  - the delay between successive RF pulses;
  - related to T_1 relaxation time;
- TE (time of echo, 信号采集时间):
  - the time between the excitation pulse and the appearance of the peak amplitude of an induce echo;
  - related to T_2 or T_2^* relaxation time;
- The “waiting time” TR-TE can be used to acquire data from other slices.



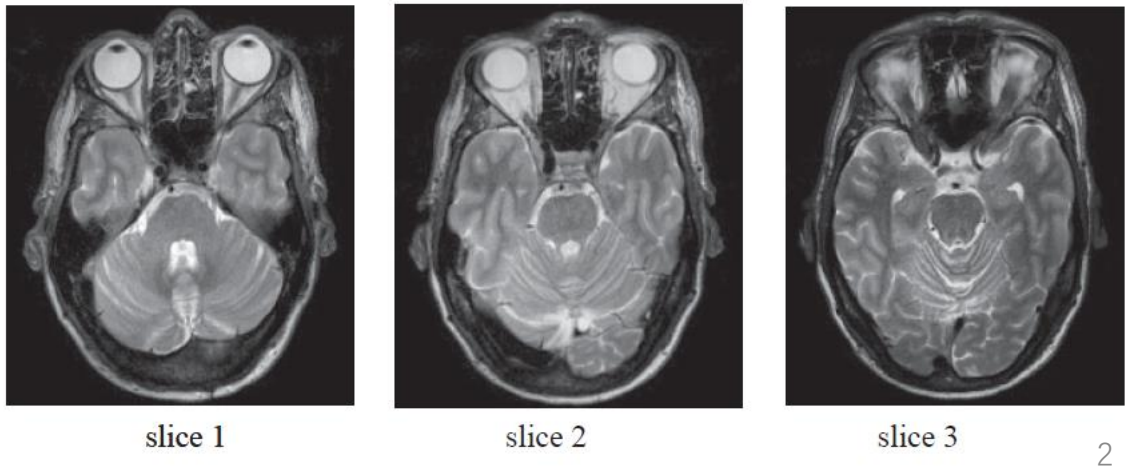


Fig. (top) Multiple-slice gradient echo sequence, which can be used to acquire many adjacent slices during one TR interval. For clarity, only the slice select gradient is shown: in practice the phase encoding and frequency encoding gradients are applied according to Figure (b) in Slide 4 for each slice in turn. (bottom) Three adjacent axial slices through the brain acquired with the slice select direction being in z.

Basic imaging sequence

- Weighted imaging (WI, 加权图像)

Emphasizing the difference of T1 and T2, relaxation time constants and proton density of the tissue to exquisite contrast sensitivity of MR images.

- Basic sequences used in most clinical scans:
  - Saturation recovery sequence (SR,饱和恢复序列)
  - Spin echo sequence (SE,自旋回波序列)
  - Inversion recovery sequence (IR,反转恢复序列)
  - Gradient echo sequence (GE,梯度回波序列)

Saturation recovery sequence

- Saturation recovery sequence (SR,饱和恢复序列)

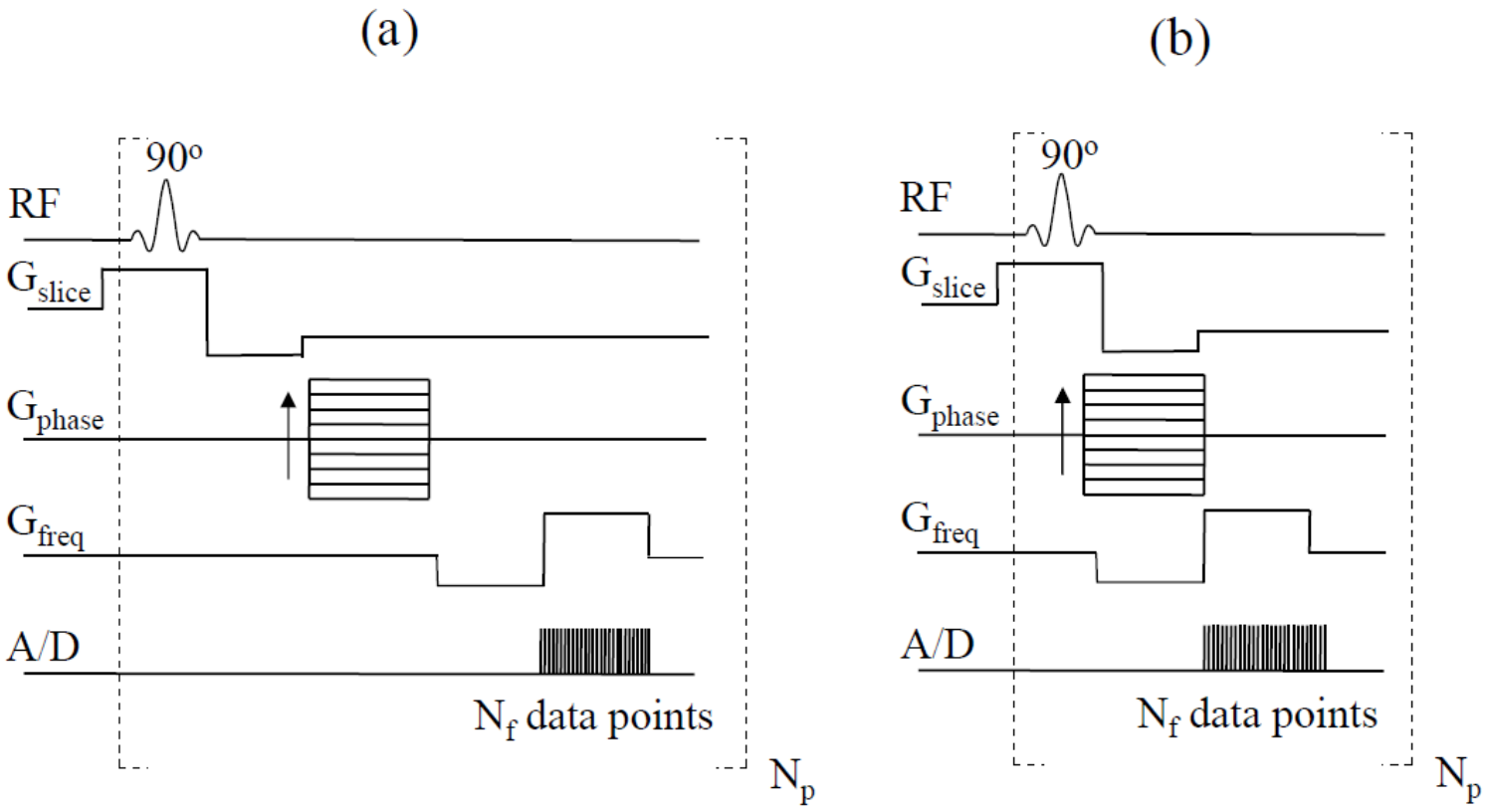
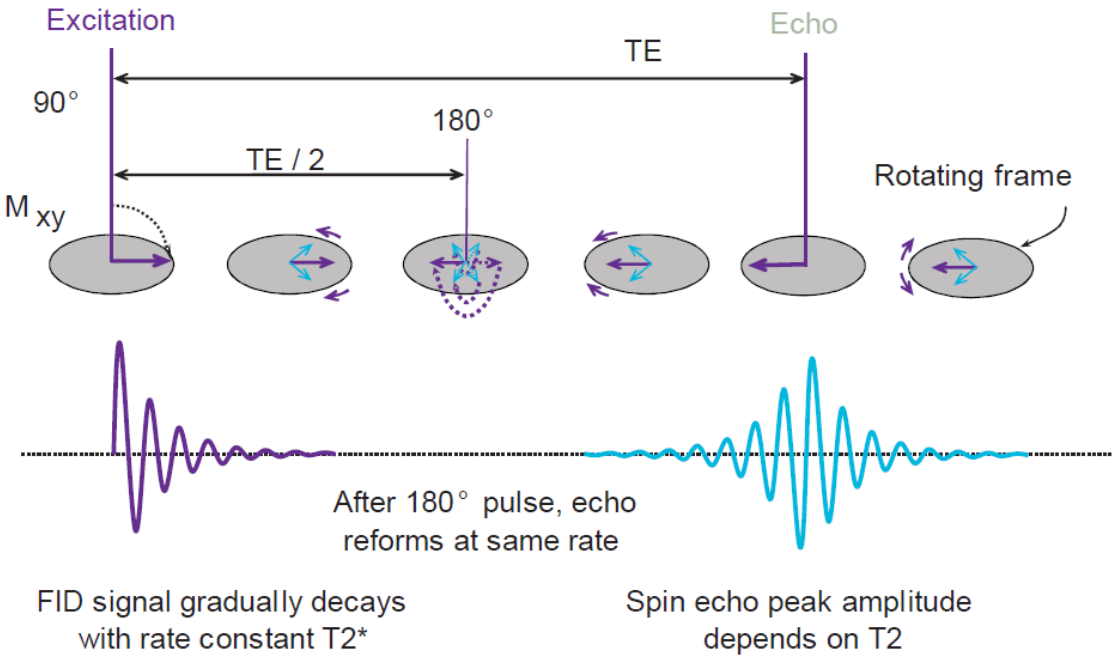


Fig. Pulse sequence diagrams for imaging sequences. An RF pulse is applied, various gradients are turned on and off, and the analogue-to-digital (A/D) converter is gated on to acquire data. (a) Individual steps in image formation can be considered independently in terms of slice selection (RF and G_{slice}), phase encoding (G_{phase}) and frequency encoding (G_{freq} and the A/D on). (b) In practice, the gradients are applied simultaneously where appropriate in order to minimize the time between RF excitation and signal acquisition.

Spin echo sequence

- The 180° RF pulse starts at the time of TE/2 since precession and refocusing the same angle;
- The effect of T_2^+ are cancelled for all protons;
- The refocused M_y' is smaller than M_{y0} due to the relaxation of T_2;



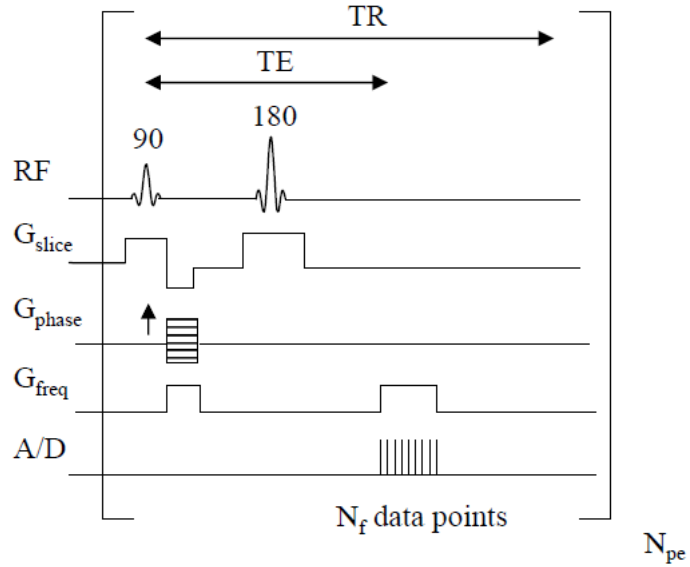


Fig. Basic spin echo imaging sequence.

Fig. The SE pulse sequence starts with a 90° pulse and produces an FID that decays according to T_2* relaxation. After a delay time TE/2, a 180° RF pulse inverts the spins that re-establishes phase coherence and produces an echo at a time TE. Inhomogeneities of external magnetic fields are canceled, and the peak amplitude of the echo is determined by T_2 decay. The rotating frame shows the evolution of the echo vector in the opposite direction of the FID. The sequence is repeated for each repetition period, TR.

Weighted Imaging for SE

- The net magnetization at *x*-*y* plane: $M_{xy} = M_0(1 - e^{-T_R/T_1})e^{-T_E/T_2}$
- Therefore FID signal amplitude: $I = K\rho\,(1 - e^{-T_R/T_1})e^{-T_E/T_2}$
- Define: Long $T_R \gg T_1$, short $T_E \ll T_2$

Table SE PULSE SEQUENCE CONTRAST WEIGHTING PARAMETERS

PARAMETER	T1 CONTRAST	PROTON DENSITY CONTRAST[a]	T2 CONTRAST
TR (ms)	400–600	2,000–4,000	2,000–4,000
TE (ms)	5–30	5–30	60–150

[a]Strictly speaking, SE images with TR less than 3,000 ms are not proton density with respect to the CSF; because of its long T1, only 70% of the CSF magnetization recovery will have occurred and will not appear as bright as for a true PD image. True PD image intensities can be obtained with fast spin echo methods (Chapter 13) with longer TR (e.g., 8,000 ms).
TE, time of echo; TR, time of repetition.

Weighted image

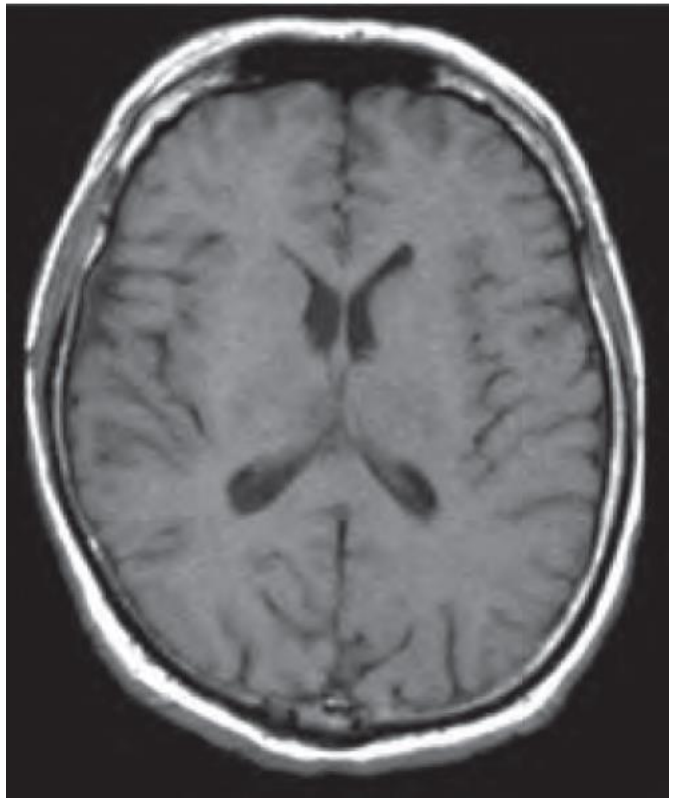


Fig. T1 contrast weighting, TR=500 ms, TE=8 ms. Short TR (400 to 600 ms) generates T1 relaxation-dependent signals. Signals with short T1 have high signal intensity (fat and white matter), while signals with long T1 have low signal intensity (CSF).

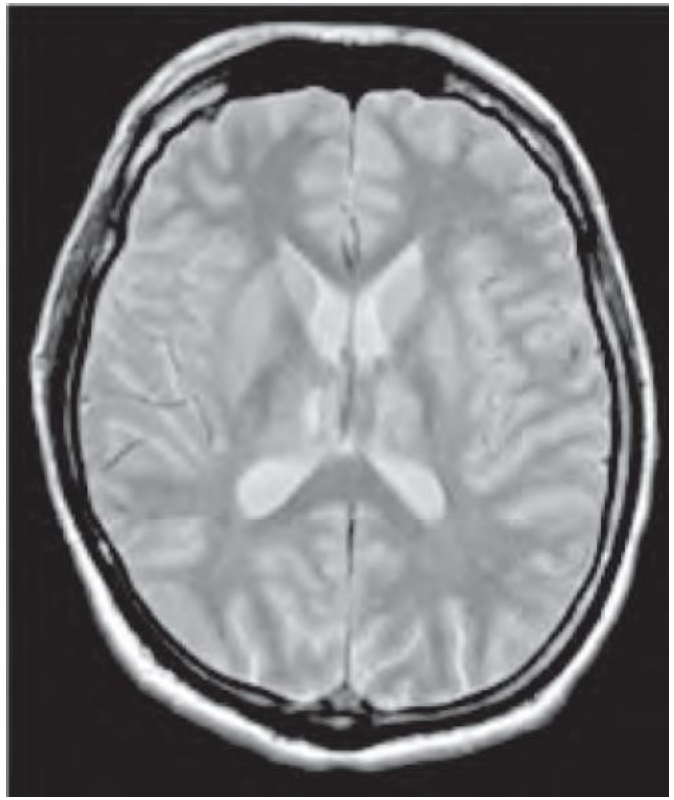


Fig. Proton density contrast weighting, TR=2400 ms, TE=30 ms. Signals with large proton density have higher signal intensity (CSF). This sequence produces a high peak SNR, even though the contrast differences are less than a T2-weighted image.

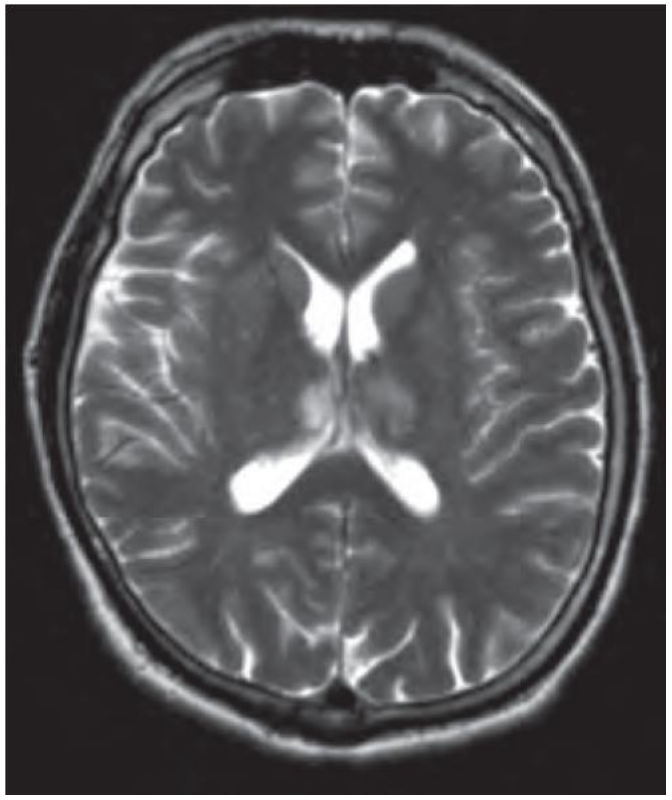


Fig. T2 contrast weighting. Long TE allows T2 decay differences to be manifested. A T2 W image is typically acquired in concert with a PD W image. While this sequence has high contrast, the signal decay reduces the overall signal and therefore the SNR.

Inversion recovery sequence

- IRSE (inversion recovery spin echo) sequence is more common;
- Emphasizing T_1 by extending the amplitude of the longitudinal recovery by a factor of 2;
- TI (Time of inversion) is the delay between initial 180° excitation RF pulse and 90° RF pulse;
- There is a null point where M_z=0

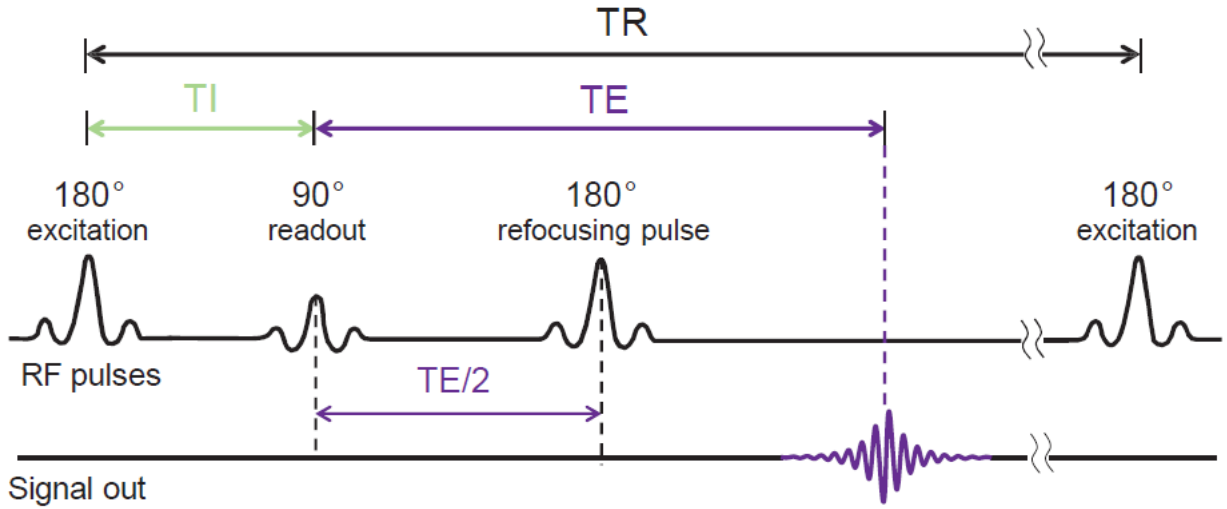


Fig. Inversion-recovery SE sequence is shown. The initial 180° excitation pulse inverts the longitudinal magnetization, and thus requires a factor of two times recovery of the longitudinal magnetization over time. The "inversion time" (TI) is the delay between the excitation pulse and conversion to transverse magnetization of the recovered longitudinal magnetization. Subsequently, a second 180° pulse is applied at TE/2, which refocuses the transverse magnetization as an echo at time TE. The signal strength is chiefly a function of the T1 characteristics of the tissues, as the TE values are kept short.

Inversion recovery sequence

- The signal density at location (x, y) in the image for an IRSE acquisition

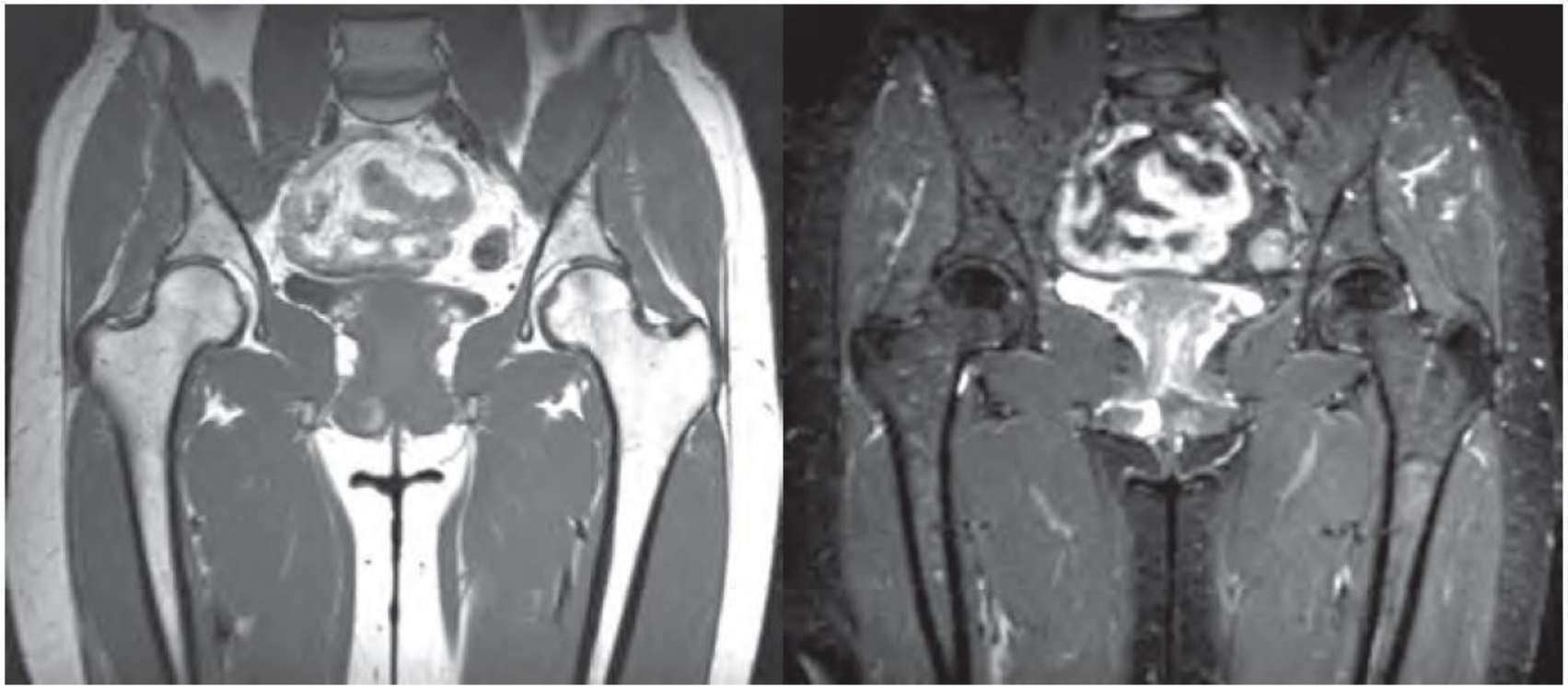
$$I = K\rho(1 - 2e^{-\frac{T_I}{T_1}})(1 - e^{-\frac{T_R}{T_1}})e^{-\frac{T_E}{T_2}}$$

- TR is relatively long for the relaxation of M_z, therefore

$$I = K\rho(1 - 2e^{-\frac{T_I}{T_1}})e^{-\frac{T_E}{T_2}}$$

- When $T_I = \ln 2 * T_1 = 0.693T_1$, $I = 0$
  - Short tau inversion recovery (STIR, 短时反转恢复, “压脂肪”): $T_I = 0.693T_{1\text{fat}}$
  - Fluid attenuated inversion recovery (FLAIR, 流动衰减反转恢复, “压水”): $T_I = 0.693T_{1\text{CSF}}$

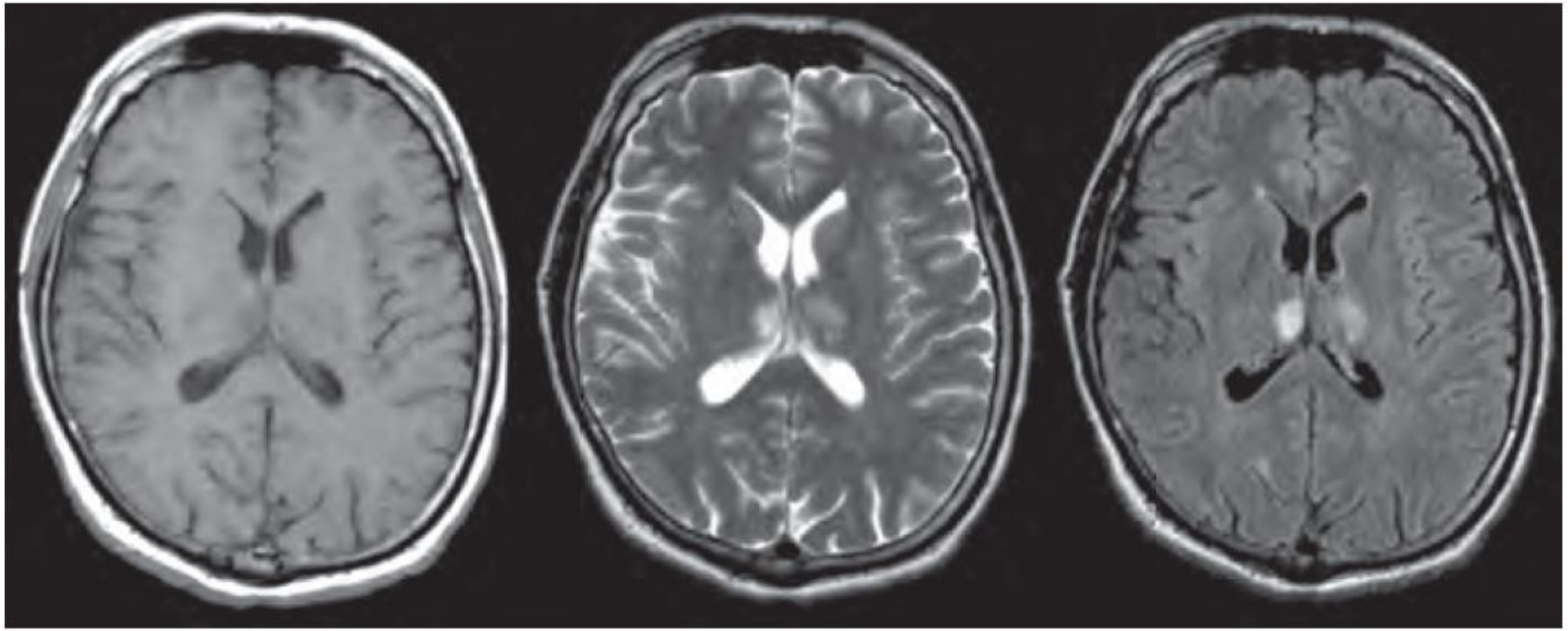
STIR



T1 STIR

Fig. SE T1-weighting versus STIR technique. (Left) T1 W with TR = 750 ms, TE = 13 ms. (Right) STIR with TR = 5,520 ms, TI = 150 ms, TE = 8 ms. The fat is uniformly suppressed in the STIR image, providing details of nonfat structures otherwise difficult to discern.

FLAIR



T1 T2 FLAIR

Fig. (Left) T1-weighted spin-echo axial brain image (TR = 549 ms, TE = 11 ms); (Middle) T2 weighted spin-echo image (TR = 2,400 ms, TE = 90 ms); (Right) FLAIR image (TR = 10,000 ms, TI = 2,400 ms, TE = 150 ms)..

Gradient echo sequence

- The image intensity of each voxel (x,y)

$$I(x,y) \propto \rho(x,y)\frac{(1-e^{-\frac{T_R}{T_1}})\sin\alpha}{1-e^{-\frac{T_R}{T_1}}\cos\alpha}\, e^{-\frac{T_E}{T_2^*}}$$

- Tip angle α is reduced to a value considerable smaller than 90° to image rapidly.
- The Ernst angle maximizes the signal intensity for a given T_R. (In the gradient-echo sequence, the M_z reaches a steady state)

$$\alpha_{\text{Ernst}} = \arccos(e^{-\frac{T_R}{T_1}})$$

- Reverse the dephasing by applying a negative rephrasing gradient.

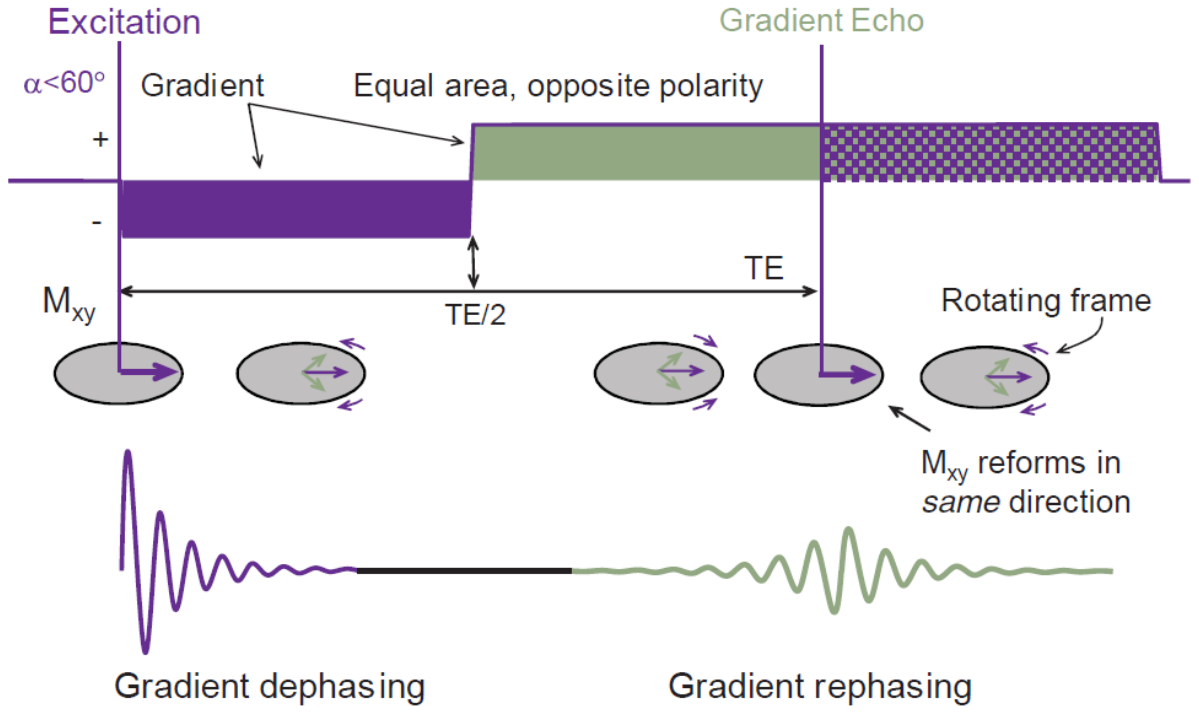


Fig. A magnetic field gradient induces the formation of an "echo" (instead of a 180° RF pulse). Transverse magnetization spins are dephased with an applied gradient of one polarity and rephrased with the gradient reversed in polarity; this produces a "gradient echo." Note that the rotating frame depicts the magnetic moment vector of the echo in the same direction as the FID relative to the main magnetic field, and therefore extrinsic inhomogeneities are not cancelled.

GE Imaging

Table GRADIENT RECALLED ECHO WEIGHTING (STEADY-STATE)

TABLE 12-6 GRADIENT RECALLED ECHO WEIGHTING (STEADY-STATE)

PARAMETER	T1	T2/T1	T2	T2*	PROTON DENSITY
Flip angle (degrees)	45–90	30–50	5–15	5–15	5–30
TR (ms)	200–400	10–50	200–400	100–300	100–300
TE (ms)	3–15	3–15	30–50	10–20	5–15

A 46-year-old male patient with familial CCM. A, Axial T2-weighted FSE image shows no significant abnormalities.

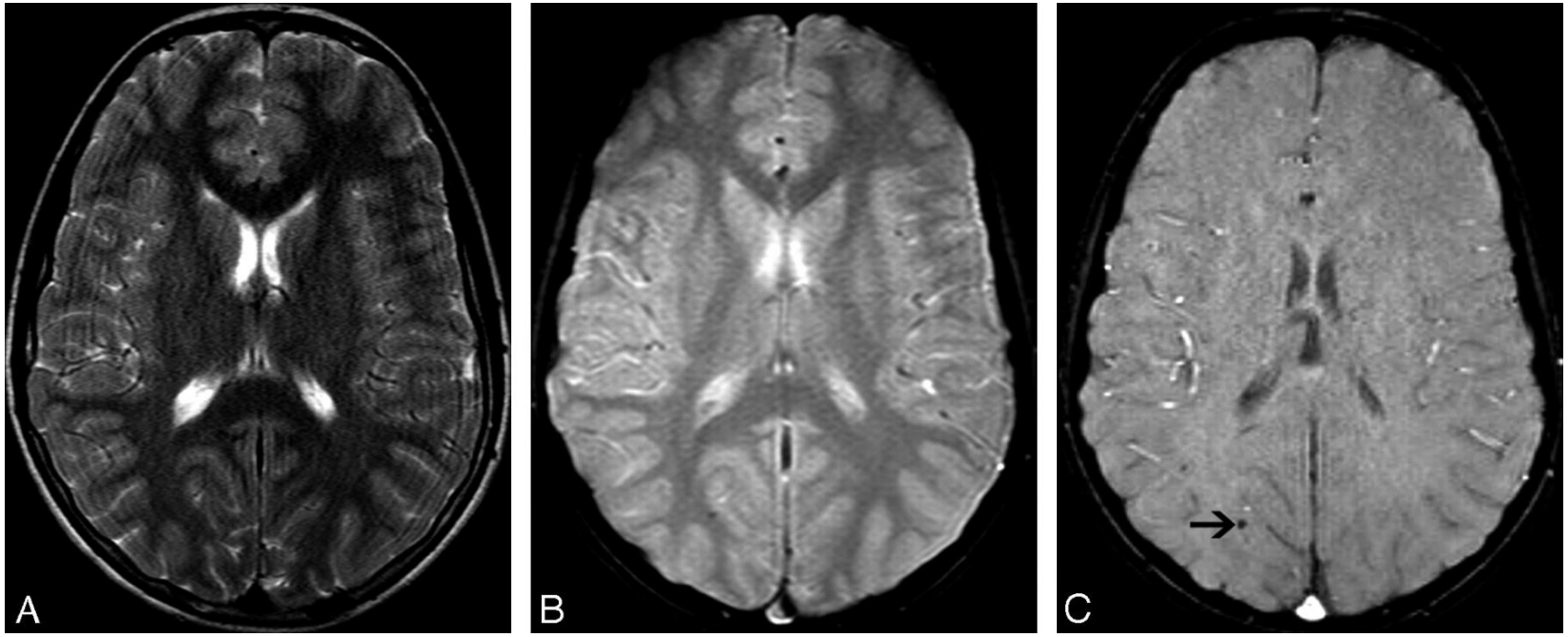


Fig. A 46-year-old male patient with familial CCM. (*A*), Axial T2-weighted FSE image shows no significant abnormalities. (*B*) Axial T2-weighted GRE image demonstrates a small extinction on the right parietal region, though it is larger on SWI (Susceptibility weighted imaging, type IV lesion) (*C*, *arrow*).

J.M. de Souza et al. AJNR Am J Neuroradiol 2008;29:154-158

AJNR
AMERICAN JOURNAL OF NEURORADIOLOGY

3D imaging sequence

- The in-plane image resolution is typically much higher than the slice thickness (0.5-1mm vs 3mm);
- 3D GE sequence can be run for high spatial resolution;
- The slice selection gradient is replaced by a gradient similar as phase encoding gradient with different increments;
- The 3D acquired signal can be represented as

$$S(k_x, k_y, k_y) = \iiint \rho(x, y, z)\, e^{-j2\pi(k_x x + k_y y + k_z z)} dx dy dz$$

- 3D inverse Fourier transform is used for image reconstruction;
- The total imaging time is TR*N_{pe1}*N_{pe2}. TR must be short for a practical clinical time. GE sequence is commonly used.

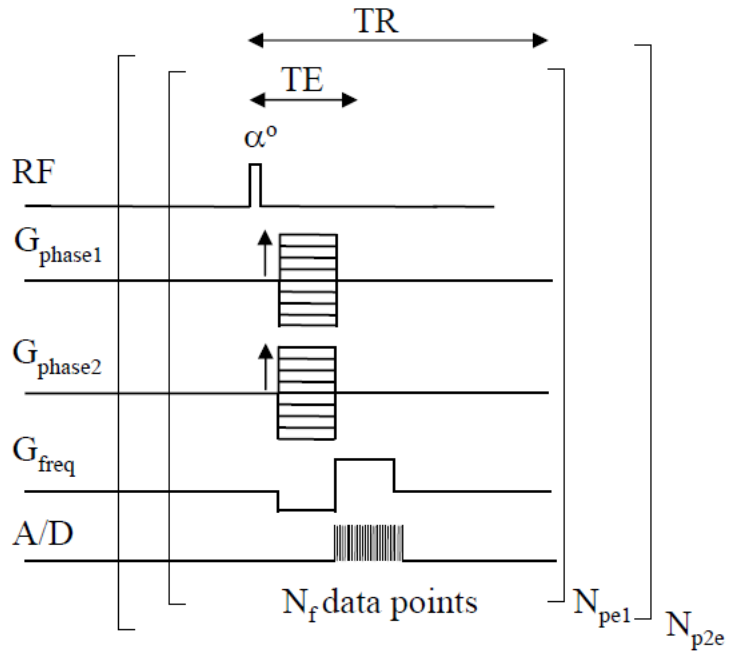


Fig. Three-dimensional gradient echo sequence. There are two incremental phase encoding gradients and one frequency encoding gradient.