Fast Scan: Fast Gradient Echo

莊子肇 副教授
中山大學電機系

Advantages of short scan time

- Comfort of patients
- Lower risk of motion artifacts
- Possibility of acquiring versatile protocols
- Efficiency of MRI usage

- EPI?

To accelerate the scan…

- Need to reduce the scan time
  - Scan time = TR x N_{PE} x NEX
- Decrease the number of phase encoding?
- Decrease the number of averages?
- Tradeoff and benefit?

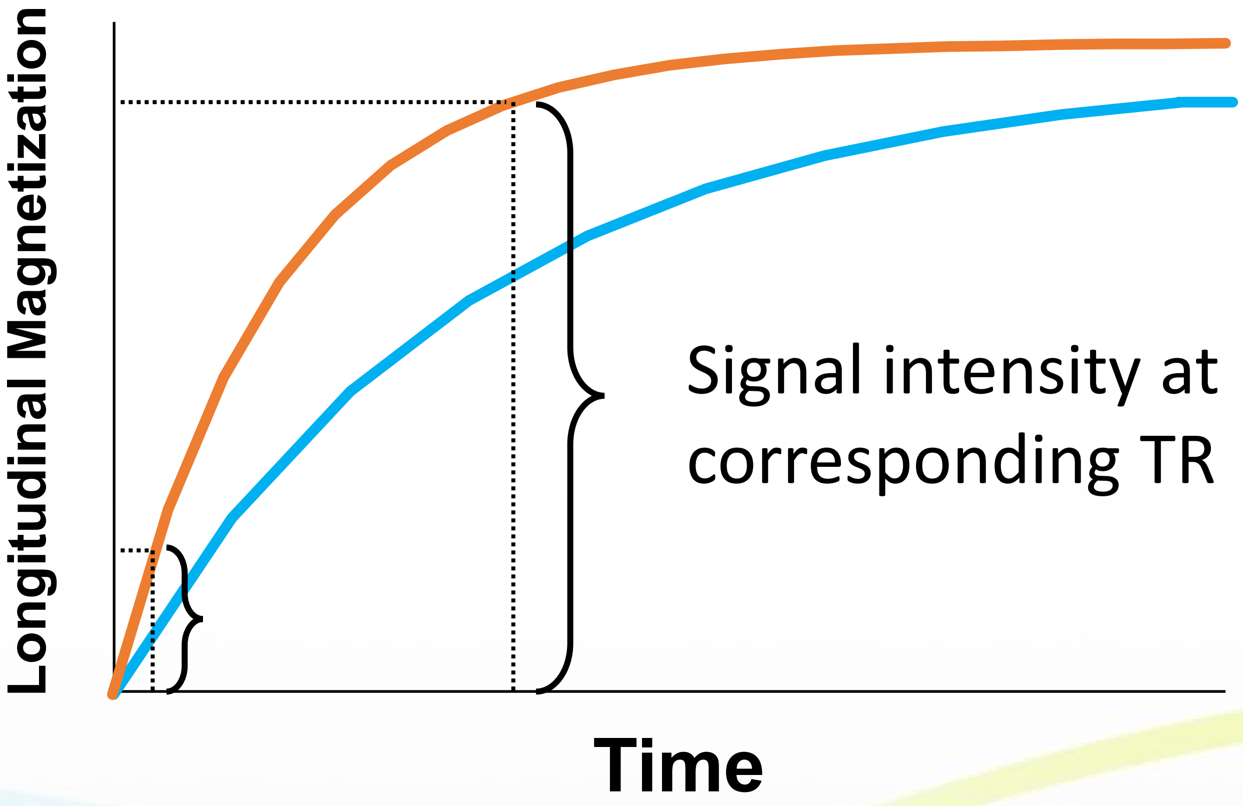
How about shorten TR?

- Scan time in 1990s: 256x256, 2 NEX
  - PD or T2: 16 mins (TR = 2000)
  - T1: 5 mins (TR = 600)
- If TR is shortened from 2000 ms to 50 ms
  - 40-fold acceleration
  - 256x256, 1 NEX: 13 sec (WOW!)

Sounds exciting, but what is the tradeoff?

- Short TR means…
  - Less time for T1 recovery
  - Strong T1-weighting
  - Low SNR

Mz is suppressed at short TR



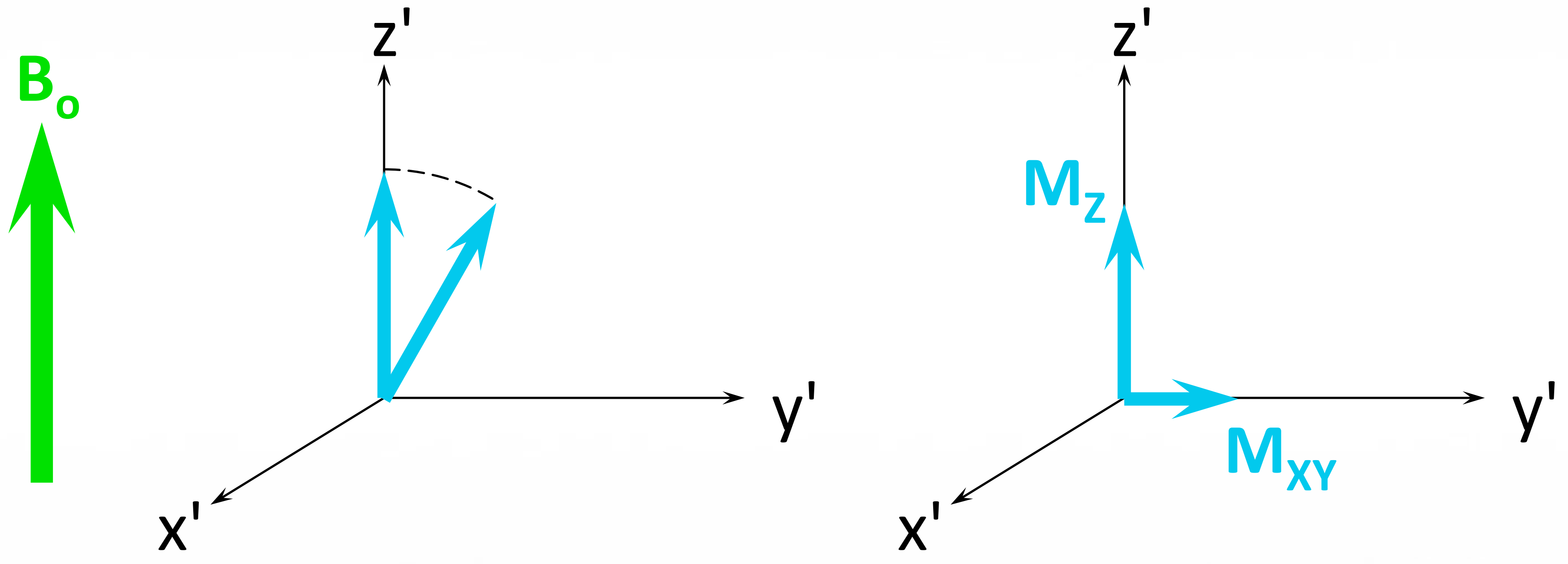
Effect of TR on signal intensity

- M_0: magnetization at thermal equilibrium
- When TR = T1
  - ~ **63**% of M_0
- When TR = 0.1 T1
  - ~ **9.5**% of M_0
  - Substantial loss of SNR

How to compensate the loss of M_Z?

- Key factor: slow T1 recovery
  - Example: T1 of CSF = 2-4 sec
- How about M_Z not recovered from 0?
  - M_Z partially preserved after excitation?
- RF excitation less than 90°?

Excitation of a small flip angle



Transverse and longitudinal magnetization: M_{XY} and M_Z

Shorten TR with less loss in M_Z

- Short TR + small flip angle (α)
  - Adjust B1 amplitude to control α
- Fast Low-Angle SHot (FLASH)
  - Haase et al., 1985

Comparison of M_Z

- TR = T1, $\alpha = 90^{\circ}$ → M_Z ~ **63**% of M_0
- TR = 0.1 T1
  - $\alpha = 90^{\circ}$: ~ **9.5**% of M_0
  - $\alpha = 25^{\circ}$: ~ **22**% of M_0

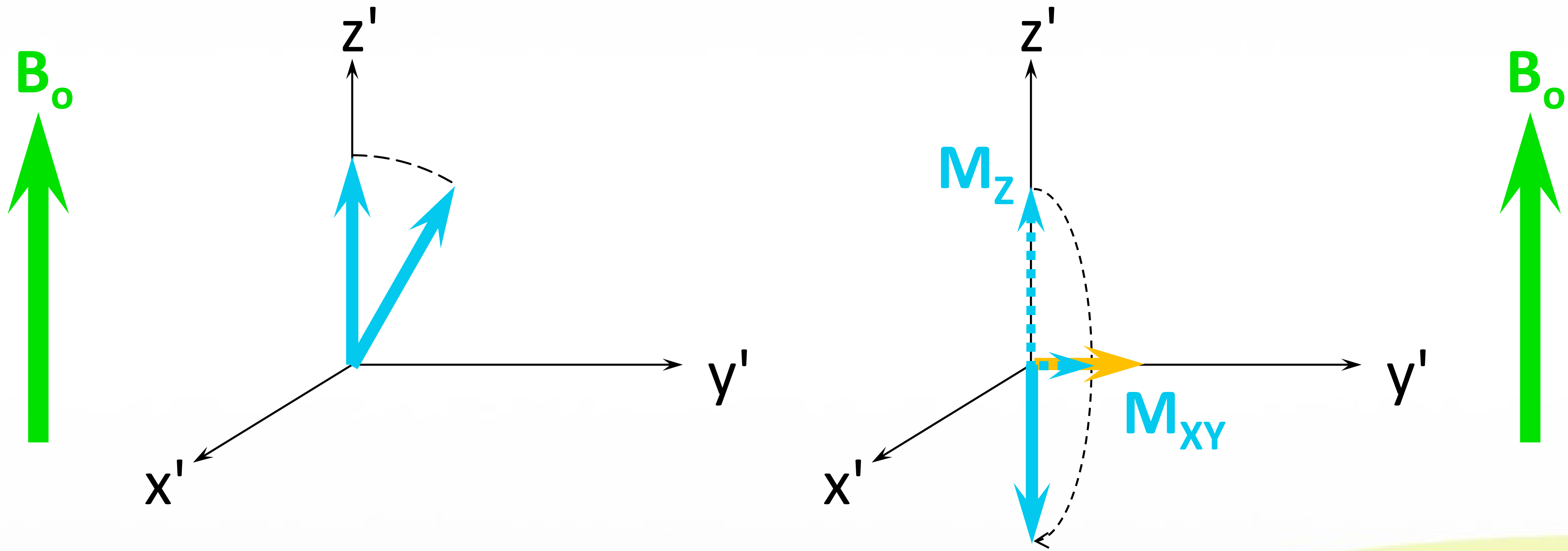
Taking liver as an example

- T1 of liver parenchyma at 1.5 T ~ 500 ms
  - TR = 0.1 T1 = 50 ms
  - Scan time (256x256) < 13 sec
  - Possible for breath holding
  - Acceptable SNR

Limitation

- Not compatible with spin echo
- Small flip angle only works with gradient echo
  - T2* relaxation
  - Sensitive to field inhomogeneity
  - Reflect different biological information

Effect of the inversion pulse

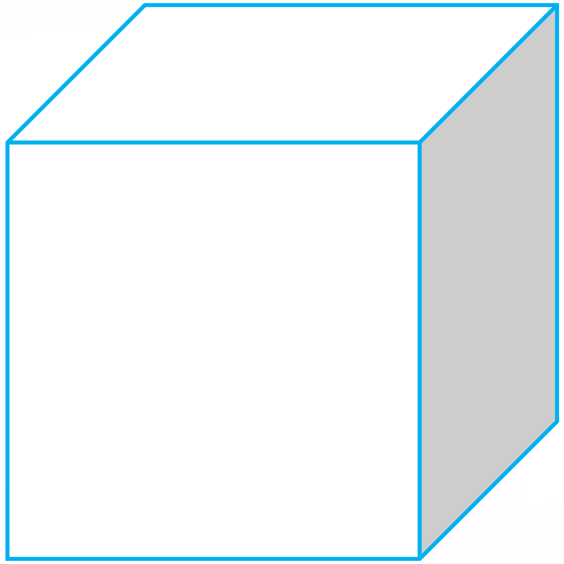


Inversion pulse helps M_{XY} refocused, but makes M_Z inverted

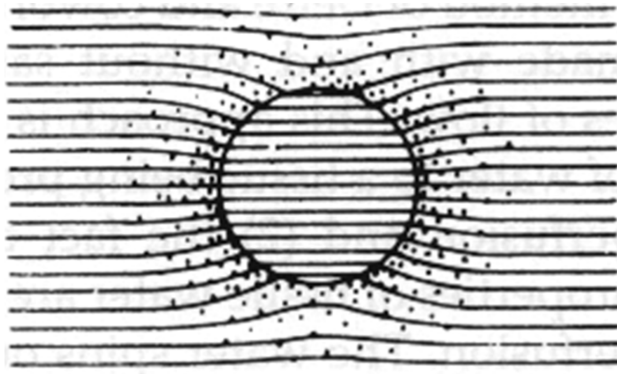
Properties of gradient echo

- No refocusing of M_{XY}
- Sensitive to field inhomogeneity
  - B_0 inhomogeneity
  - Air-tissue interfaces
  - Hemorrhage, venous vasculature, calcification…

Intra-voxel field inhomogeneity

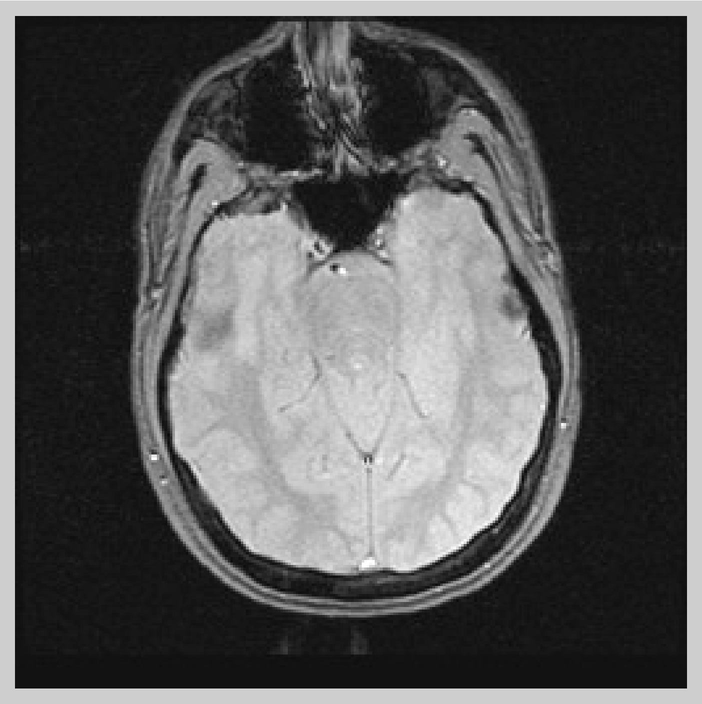


An image voxel

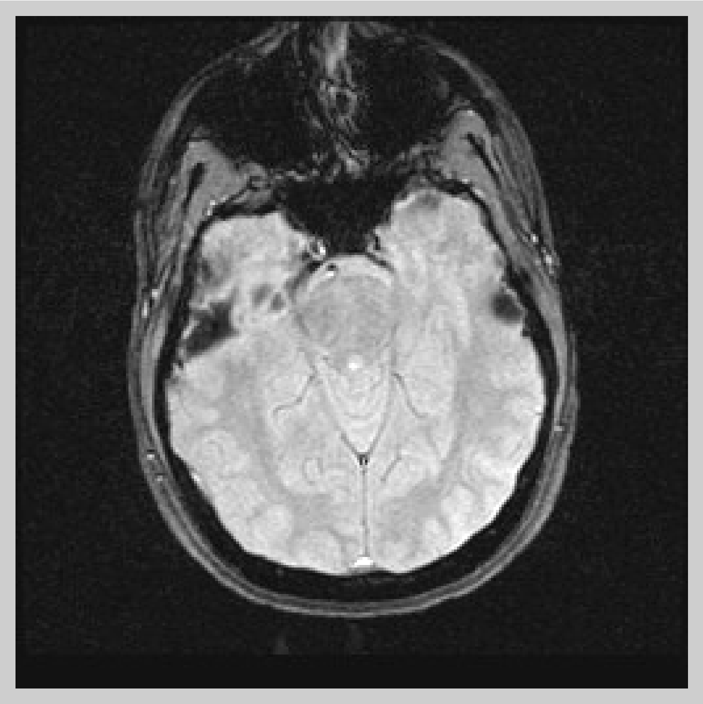


Intra-voxel dephasing: short T2*

Signal attenuation of intra-voxel dephasing



TE = 9 msec



TE = 18 msec

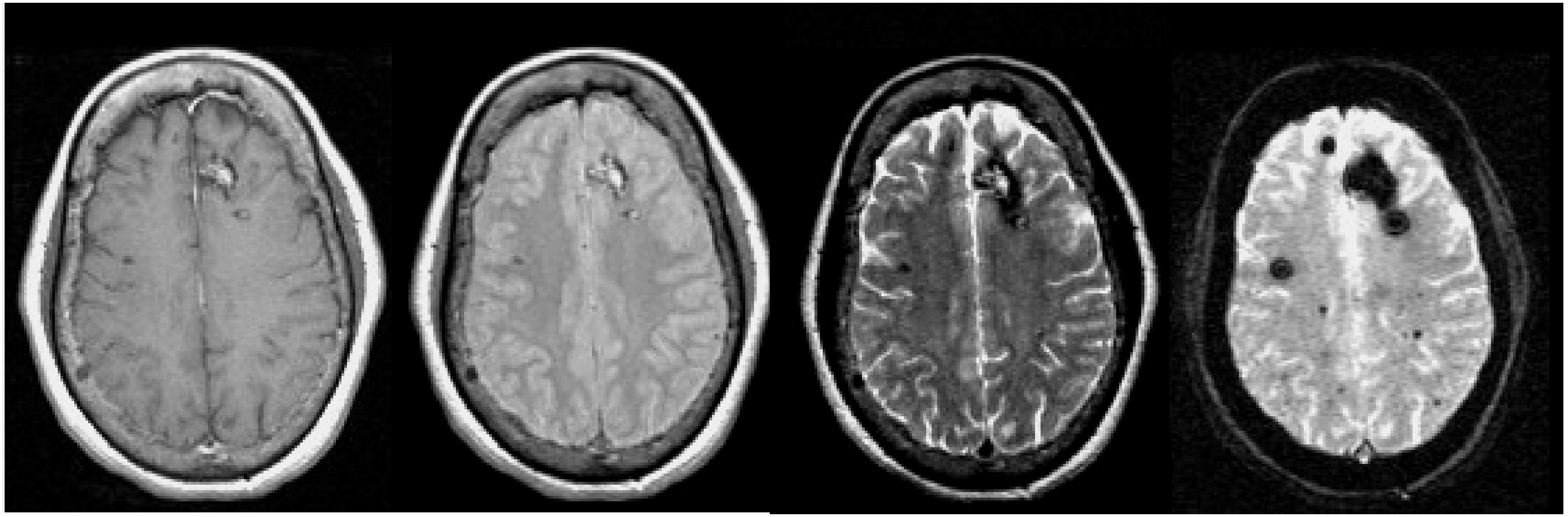
Gradient echo inferior to spin echo?

- Image quality of gradient echo might be less stable.
- But gradient echo also collects some information that spin echo does not have.

Gradient echo is sensitive to…

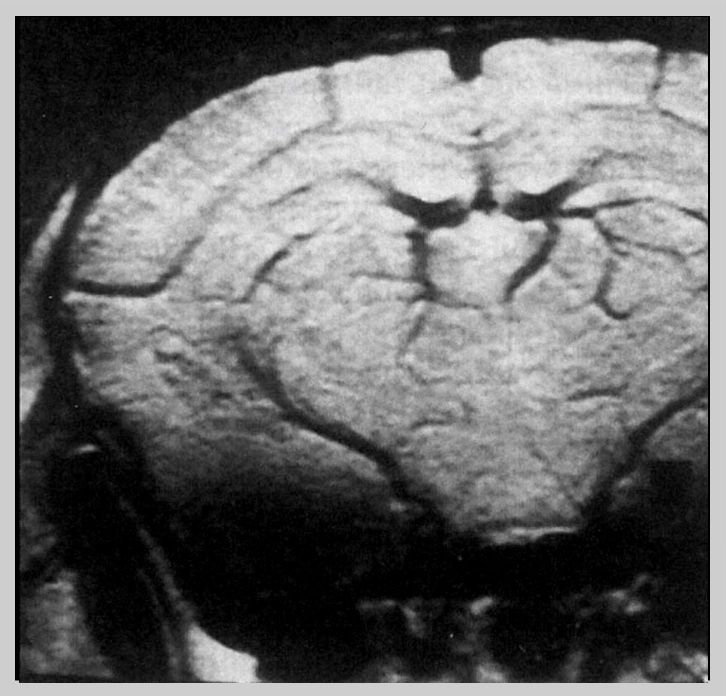
- Hemorrhage and related blood products
- Paramagnetic contrast agent: brain perfusion
- Deoxyhemoglobin: blood oxygenation
- Brain functional MRI

Short T2* in hemorrhage

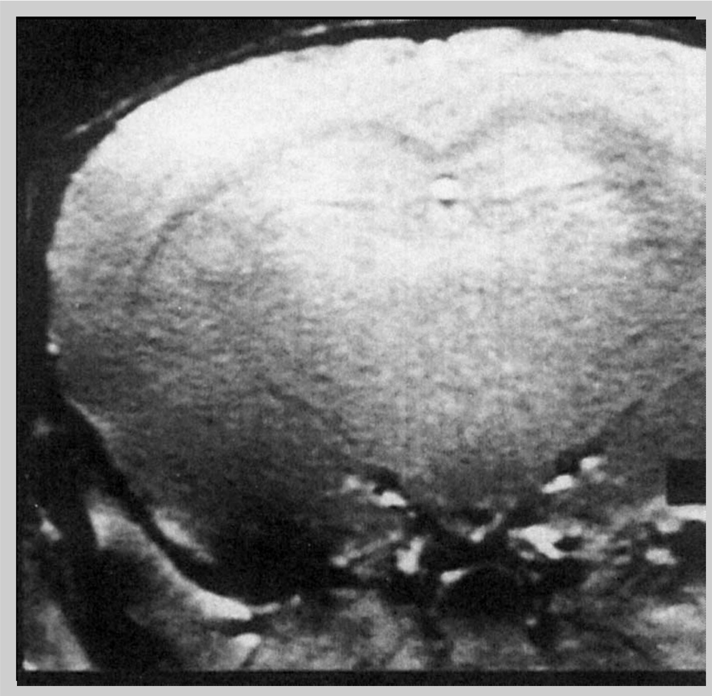


T1 PD T2 T2*
(Gradient echo)

T2* and blood oxygenation



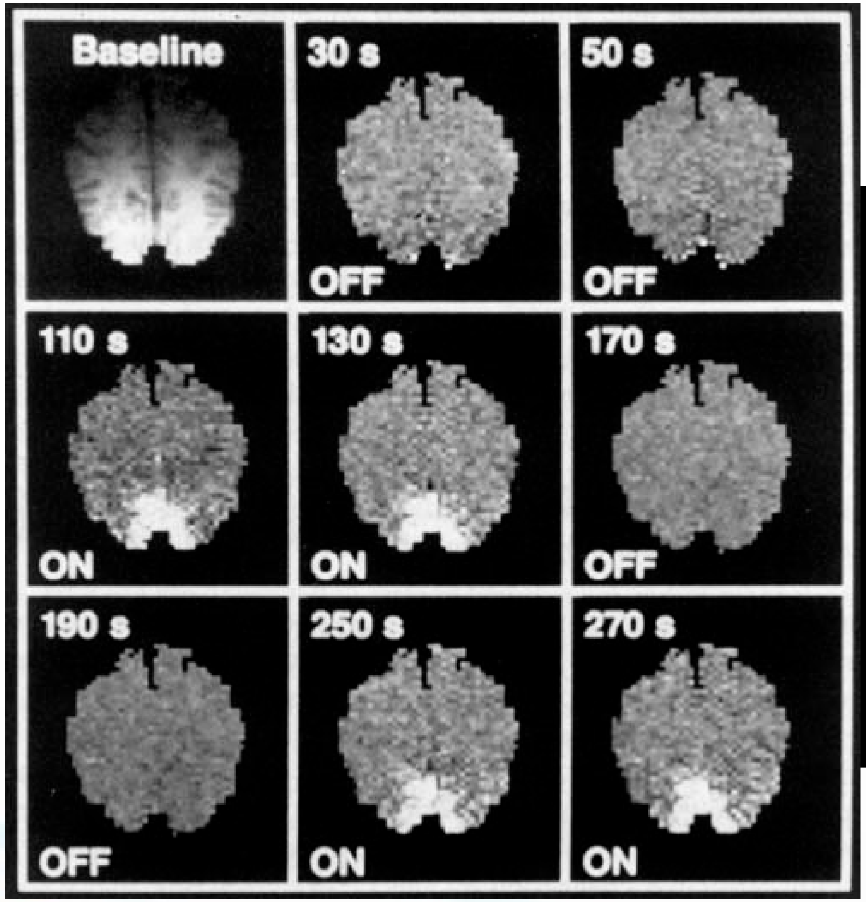
Room air

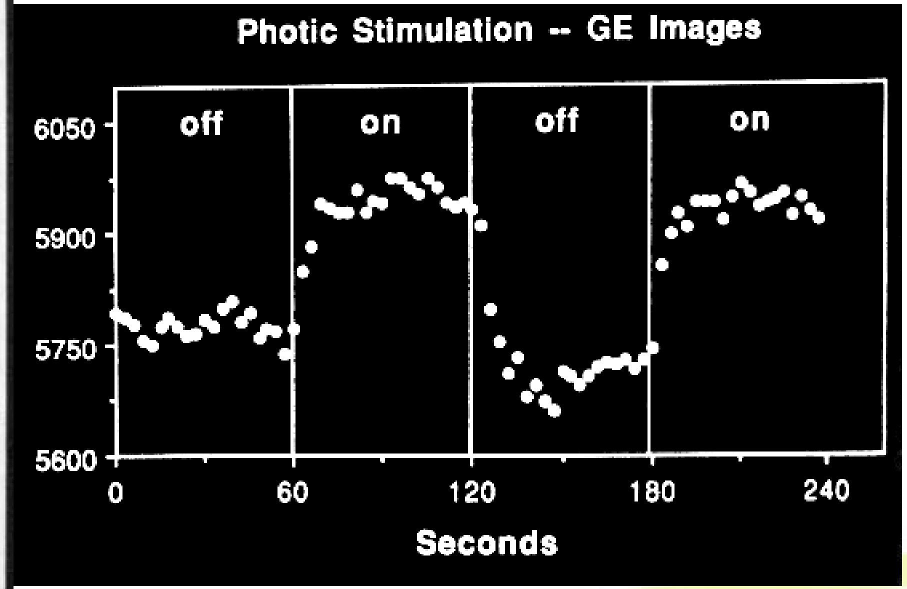


Pure O_2

Ogawa S, et al. (1990), "Oxygenation-sensitive contrast in magnetic resonance image of rodent brain at high magnetic fields", Magnetic Resonance in Medicine, 14 (1): 68–78.

Blood-Oxygen-Level Dependent (BOLD)





Kwong KK, et al (1992). "Dynamic magnetic resonance imaging of human brain activity during primary sensory stimulation". Proc Natl Acad Sci USA. 89 (12): 5675–5679.

Sounds good overall…

- Very short TR → accelerate scan
- Small flip angle → compensate the SNR loss
- Gradient echo → sensitive to certain biological substances
- Let's dig into it!

Question 1: how small is the flip angle?

- Small flip angle, partial flip angle…
- 10°? 30°? 70°?
- Which one is better?

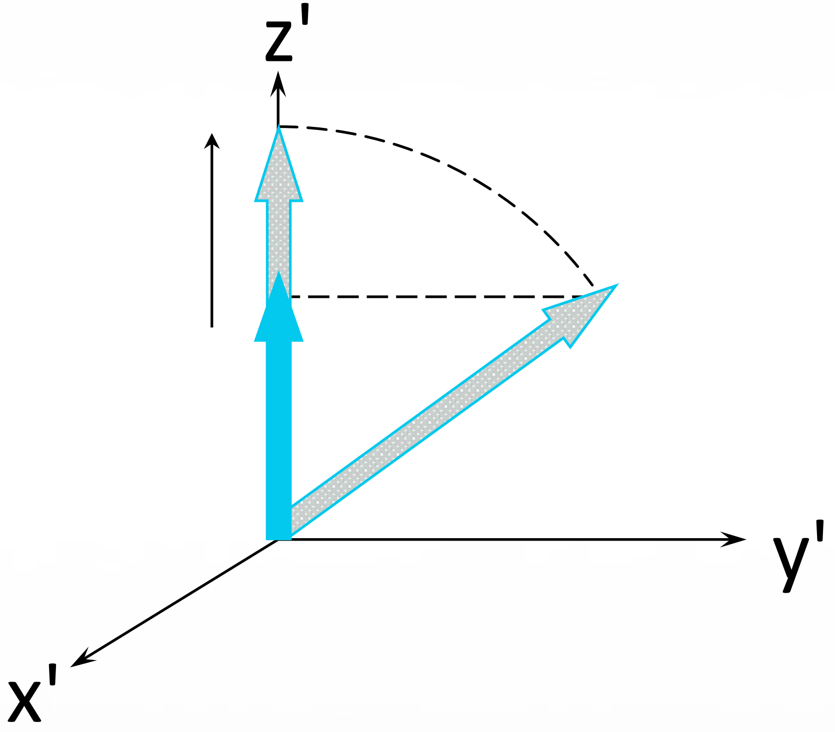
Review: TR and image contrast

- Perhaps you remember short TR for T1WI and long TR for T2WI…
  - Under the assumption of 90° RF
- Very short TR → unable to control T1 contrast by changing TR

How to control image contrast?

- After several RF excitations, magnetization enters steady state from transient state.
  - Steady state: M_Z costed after RF pulse = M_Z gained from T1 recovery after one TR
- Signal intensity of fast gradient echo is determined by the steady state

Steady state of serial RF excitations



Assume that M_{XY} is totally decayed before next RF pulse

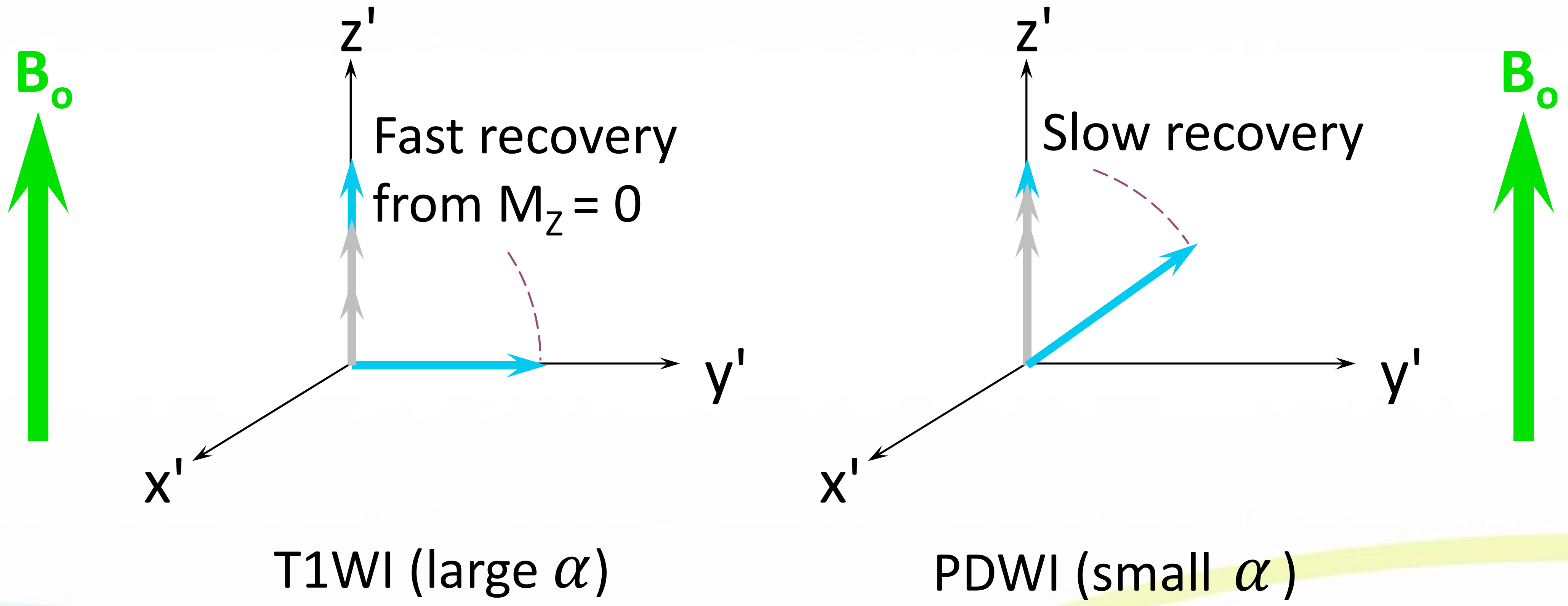
Signal intensity of steady state is…

- Proportional to

$$\frac{\left(1 - e^{\frac{-TR}{T_1}}\right) \cdot \sin\alpha}{1 - e^{\frac{-TR}{T_1}} \cdot \cos\alpha} e^{\frac{-TE}{T_2^*}}$$

- α: flip angle

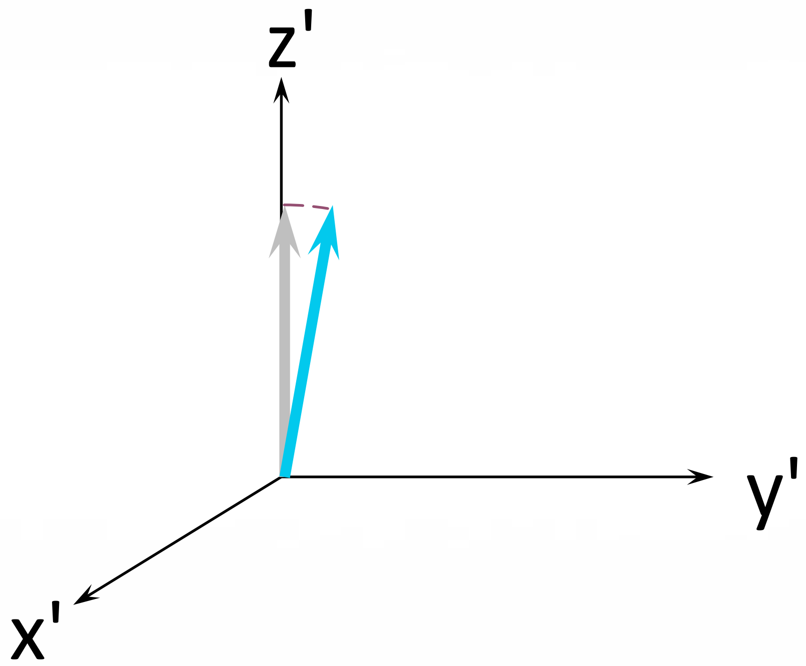
Simple rule to control T1/PD contrast



Control T1 contrast by flip angle

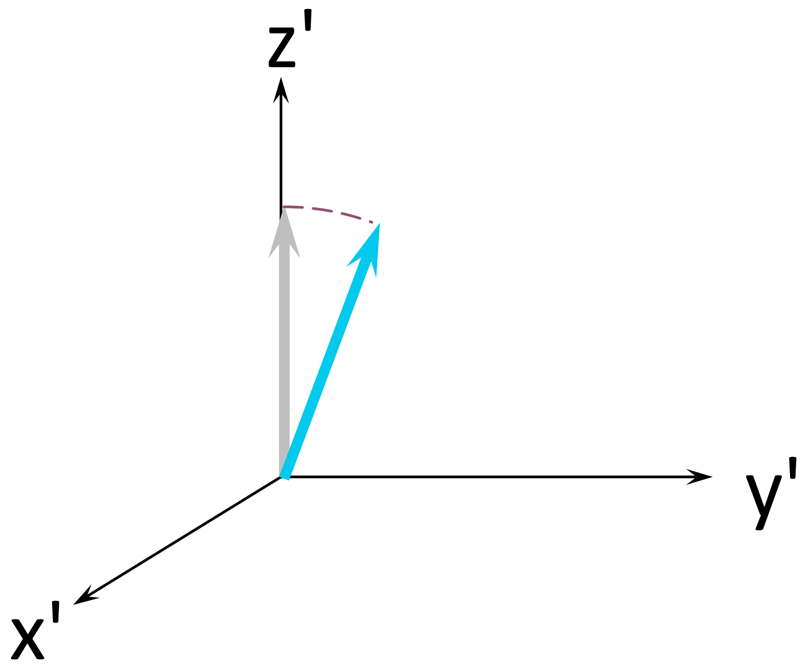
- Large flip angle (~90°)
  - Similar with short-TR T1WI
- Small flip angle (20° -40°)
  - Less T1 contrast: PD weighting

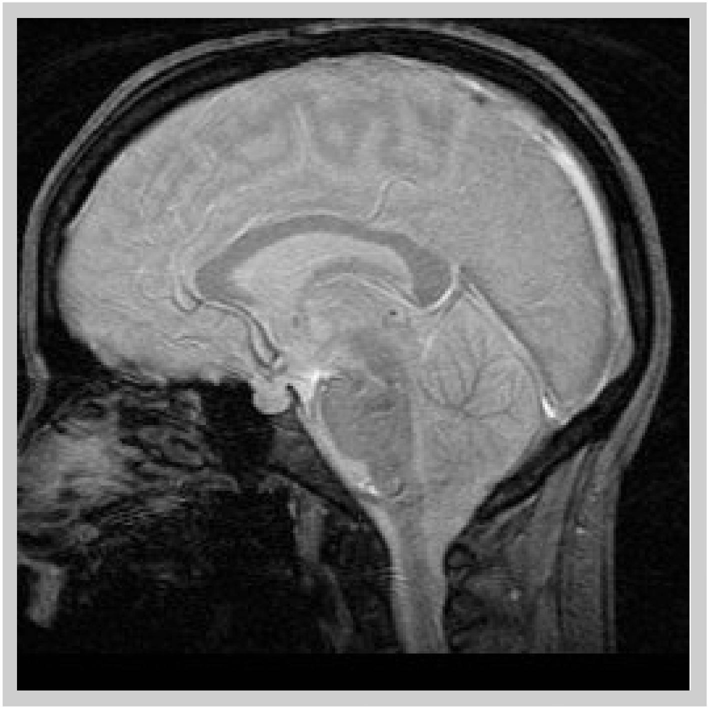
Flip angle = 10°



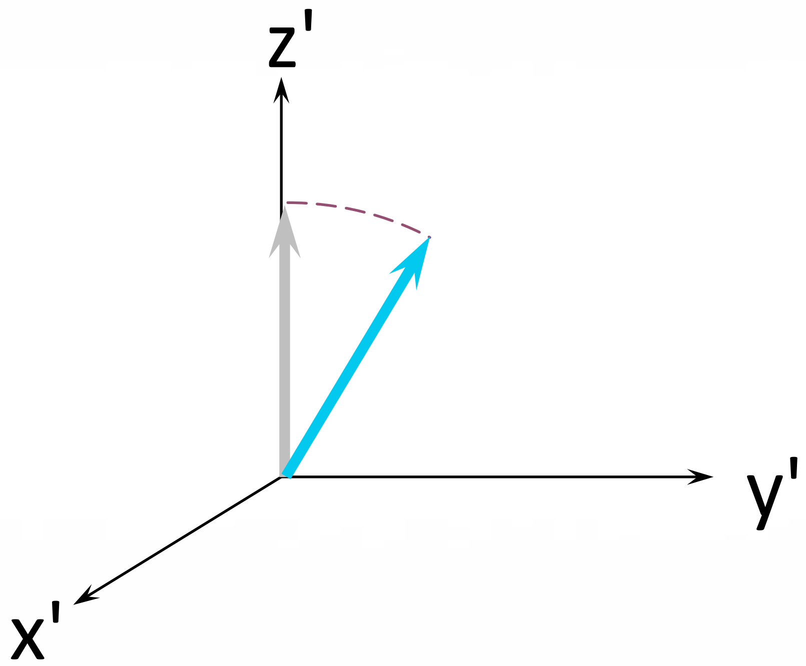
Proton-density-weighted image

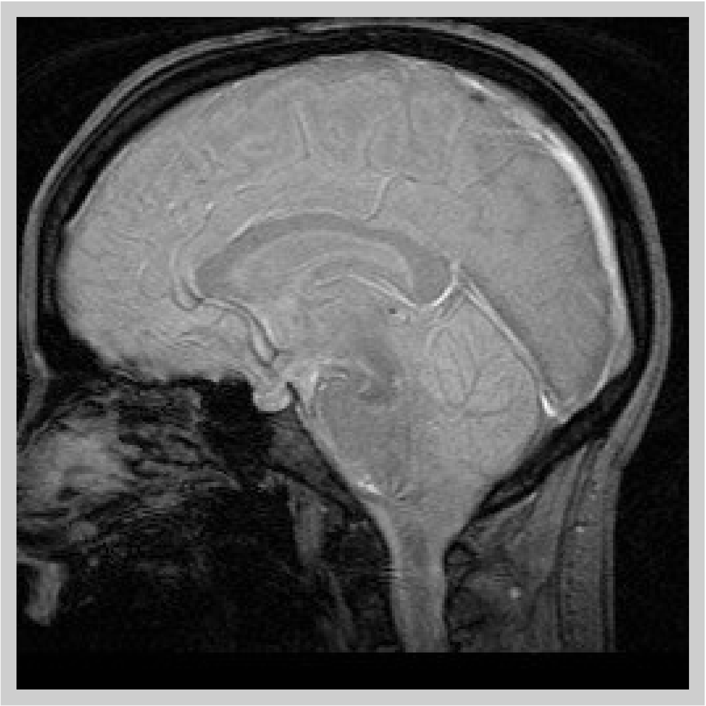
Flip angle = 20°



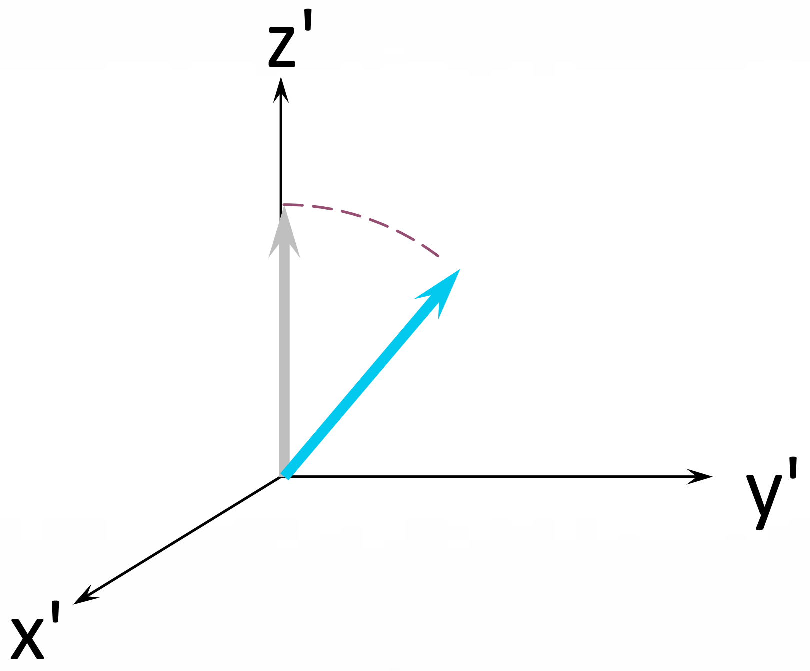


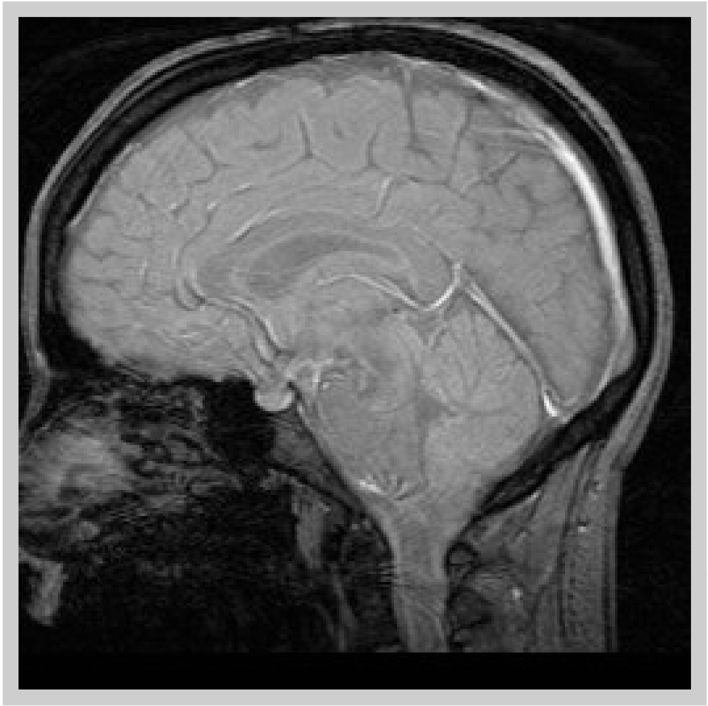
Flip angle = 30˚



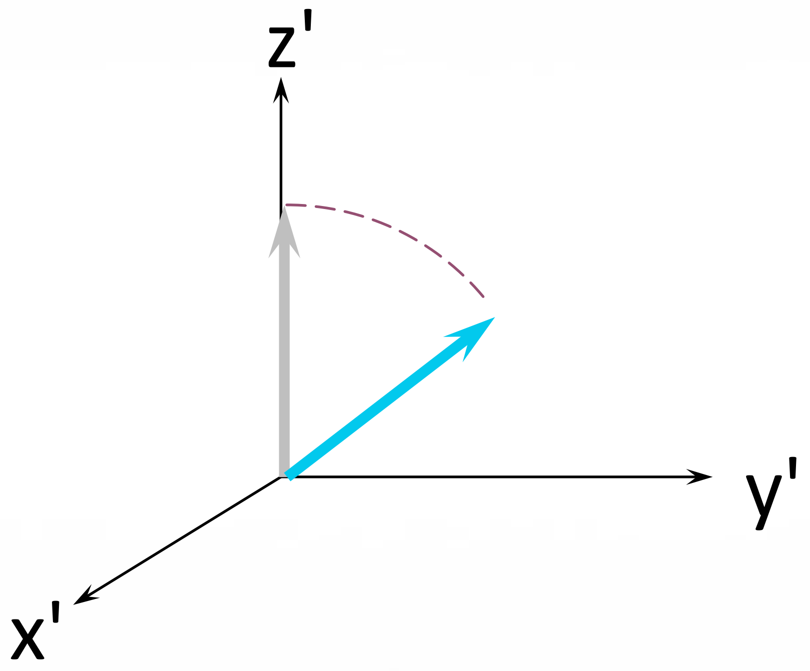


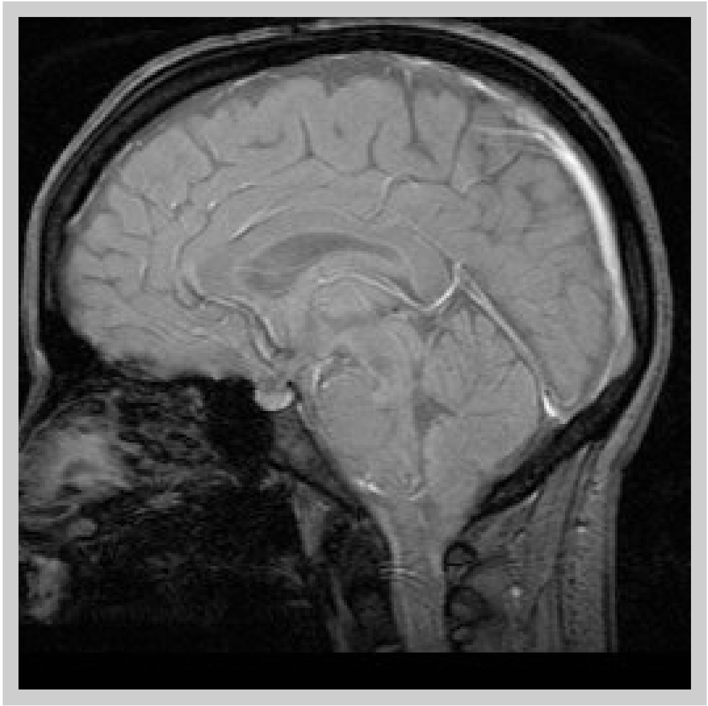
Flip angle = 40°





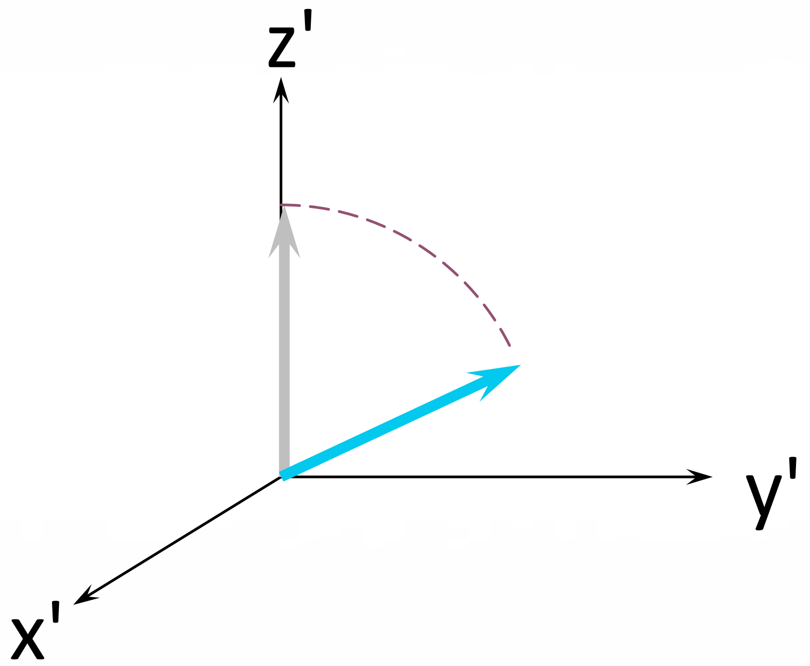
Flip angle = 50°

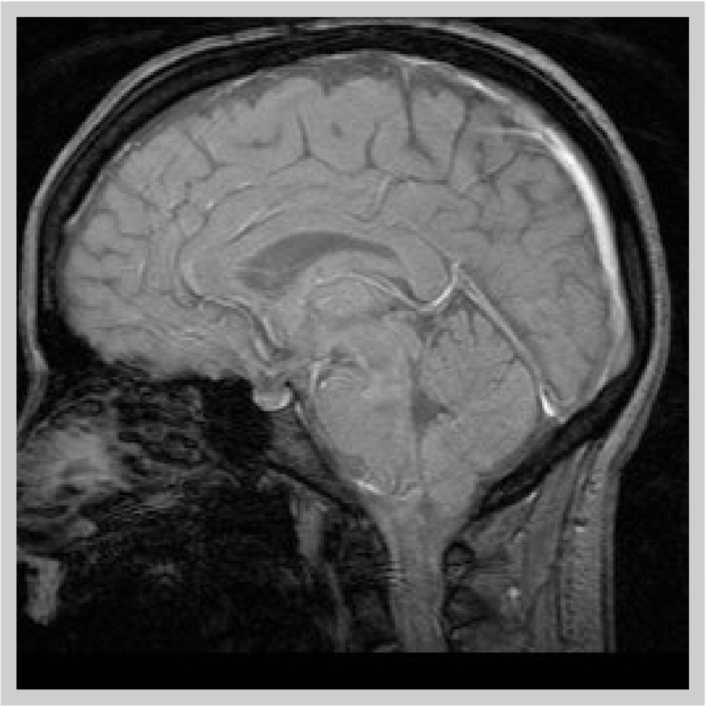




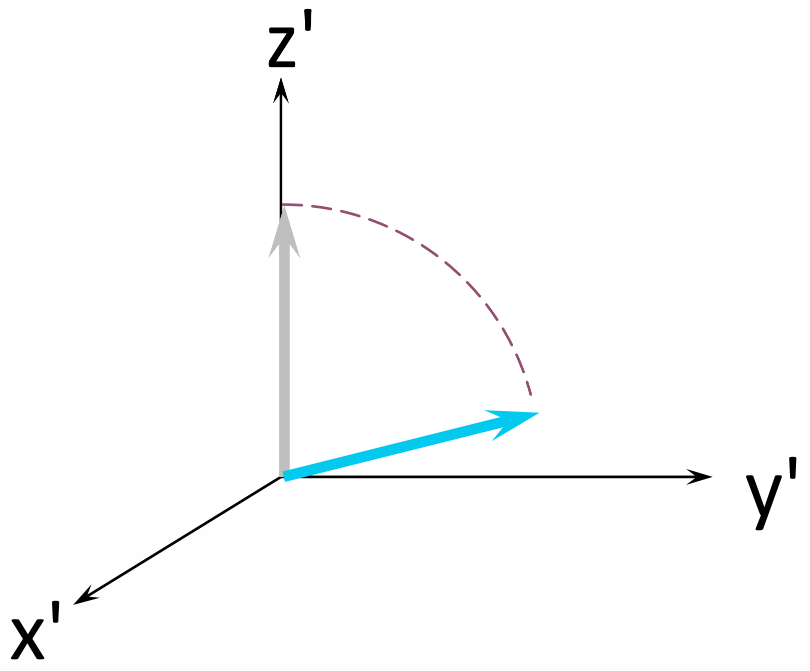
T1-weighted image

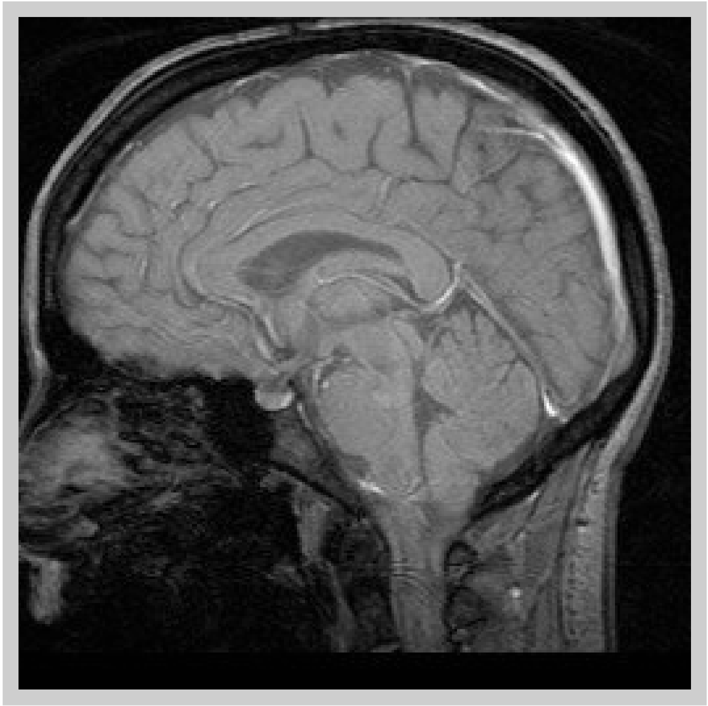
Flip angle = 60°





Flip angle = 70°

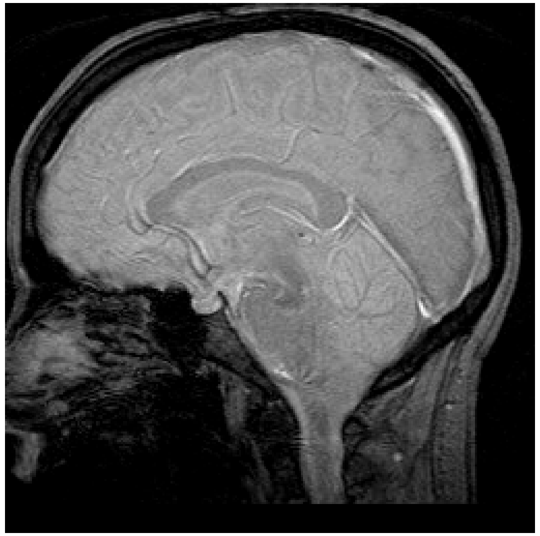




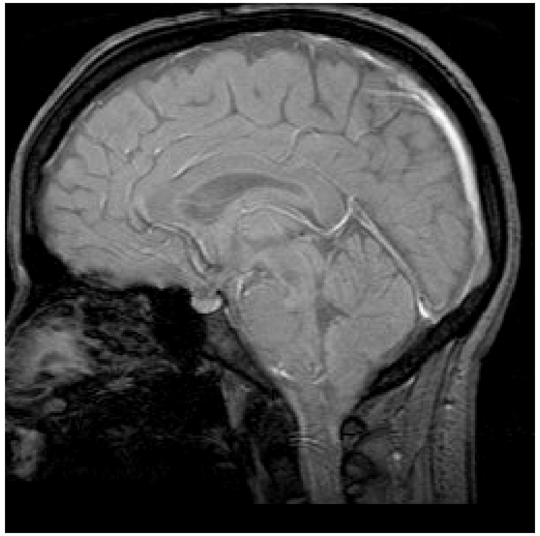
Strong T1-weighted image

Comparison of PDWI and T1WI

10°



30°

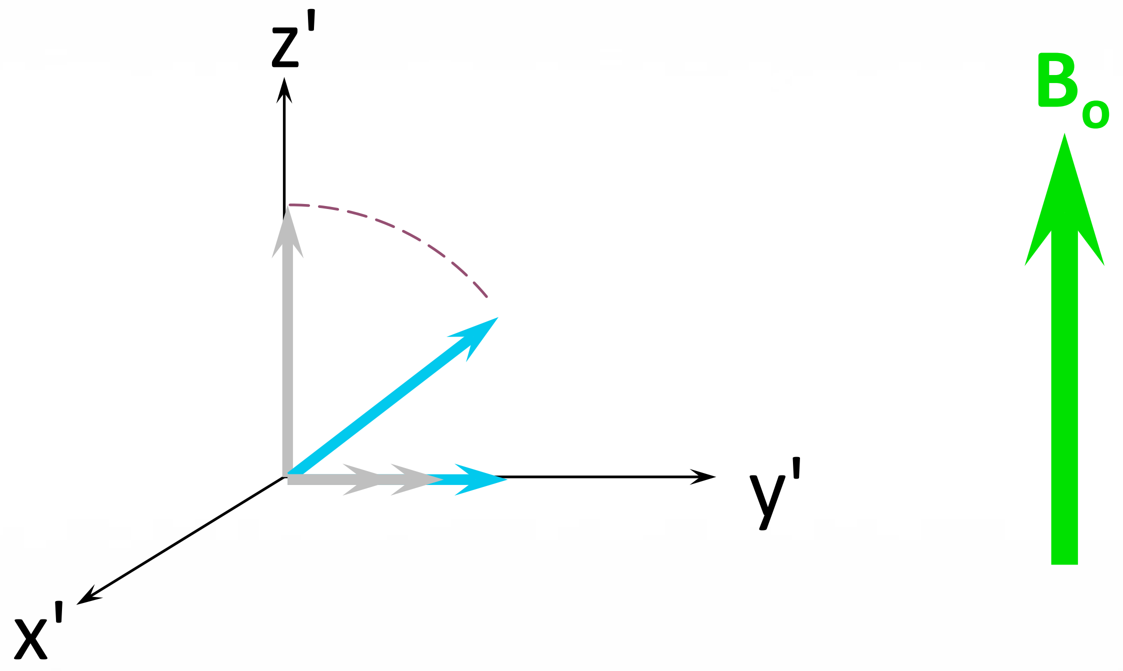


50°

Question 2: Control of T2 weighting?

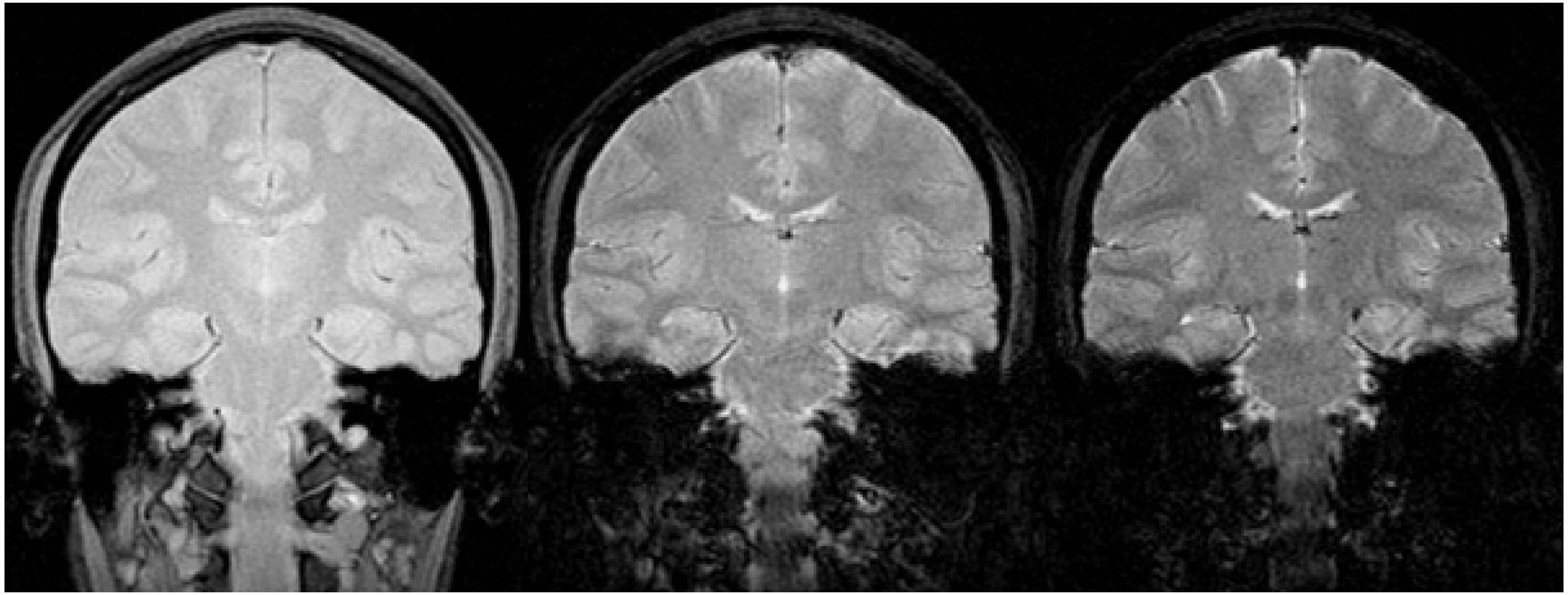
- Depend on TE (<TR)
- T2* decay for gradient echo
  - TE not as long as that for spin echo
  - Similar with T2 weighting

T2(*) weighting



Determined by transverse relaxation

Use TE to control T2(*) weighting

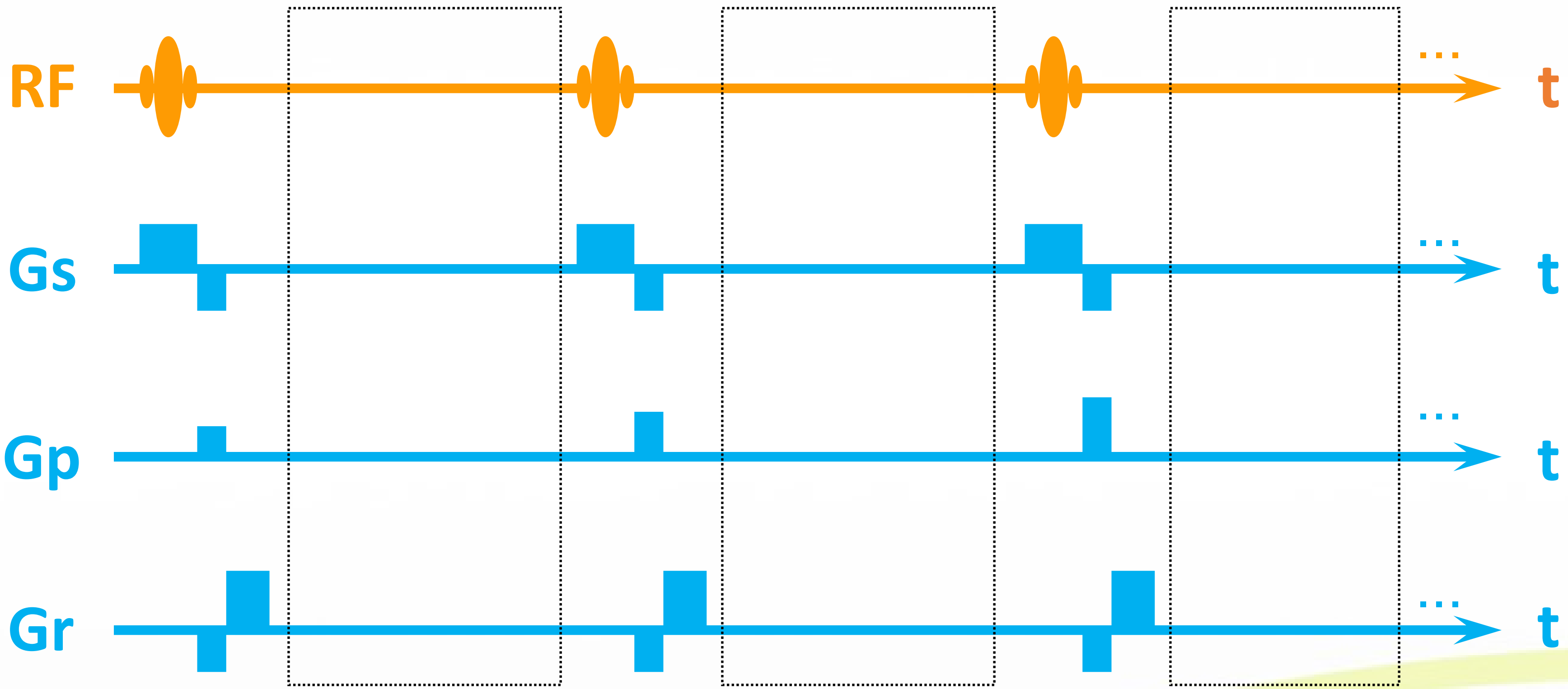


TE = 10 TE = 30 TE = 50

Question 3: True or false?

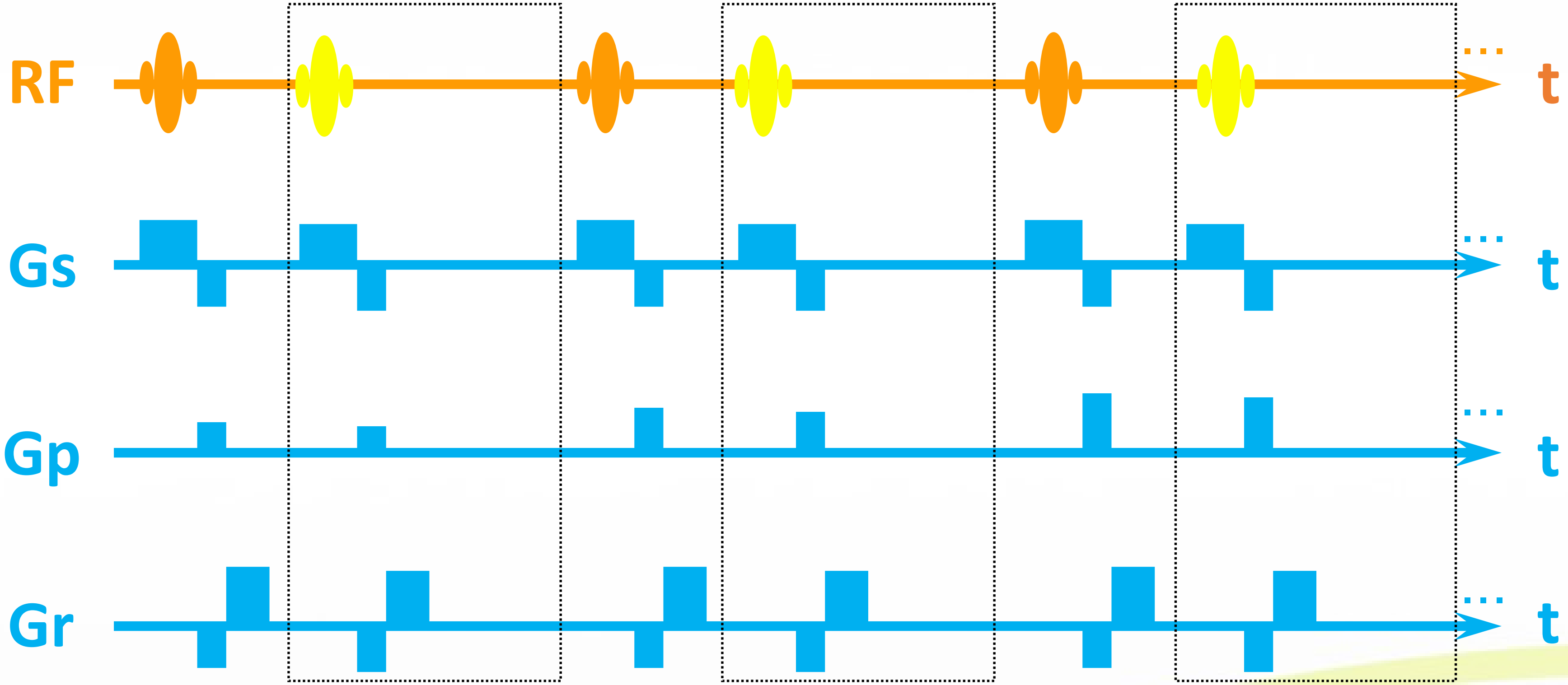
- Is scan time really shortened?

Pulse sequence of more TR cycles…



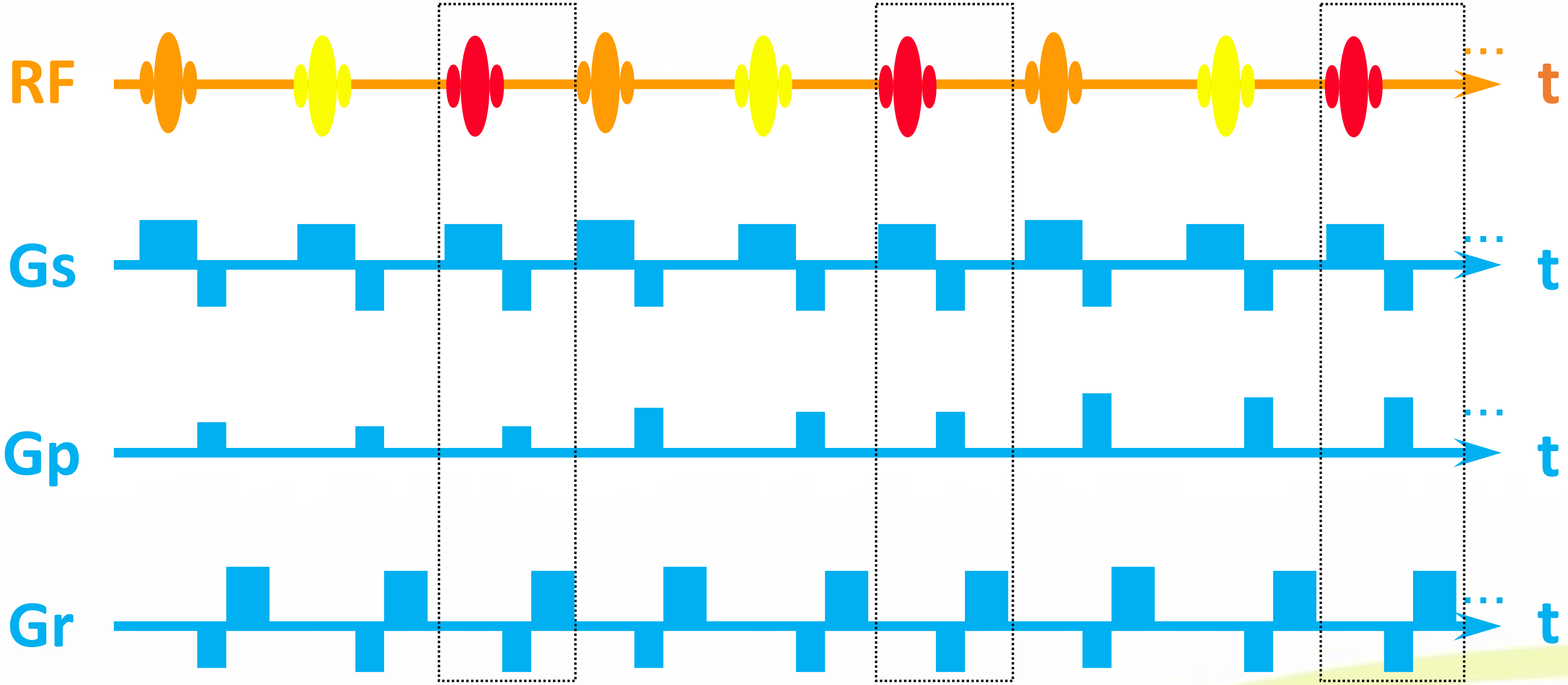
TE >> TR: do nothing for most of time

Insertion of another slice



Taking advantage of the spare time

Insertion of one another slice again



Multi-slice imaging

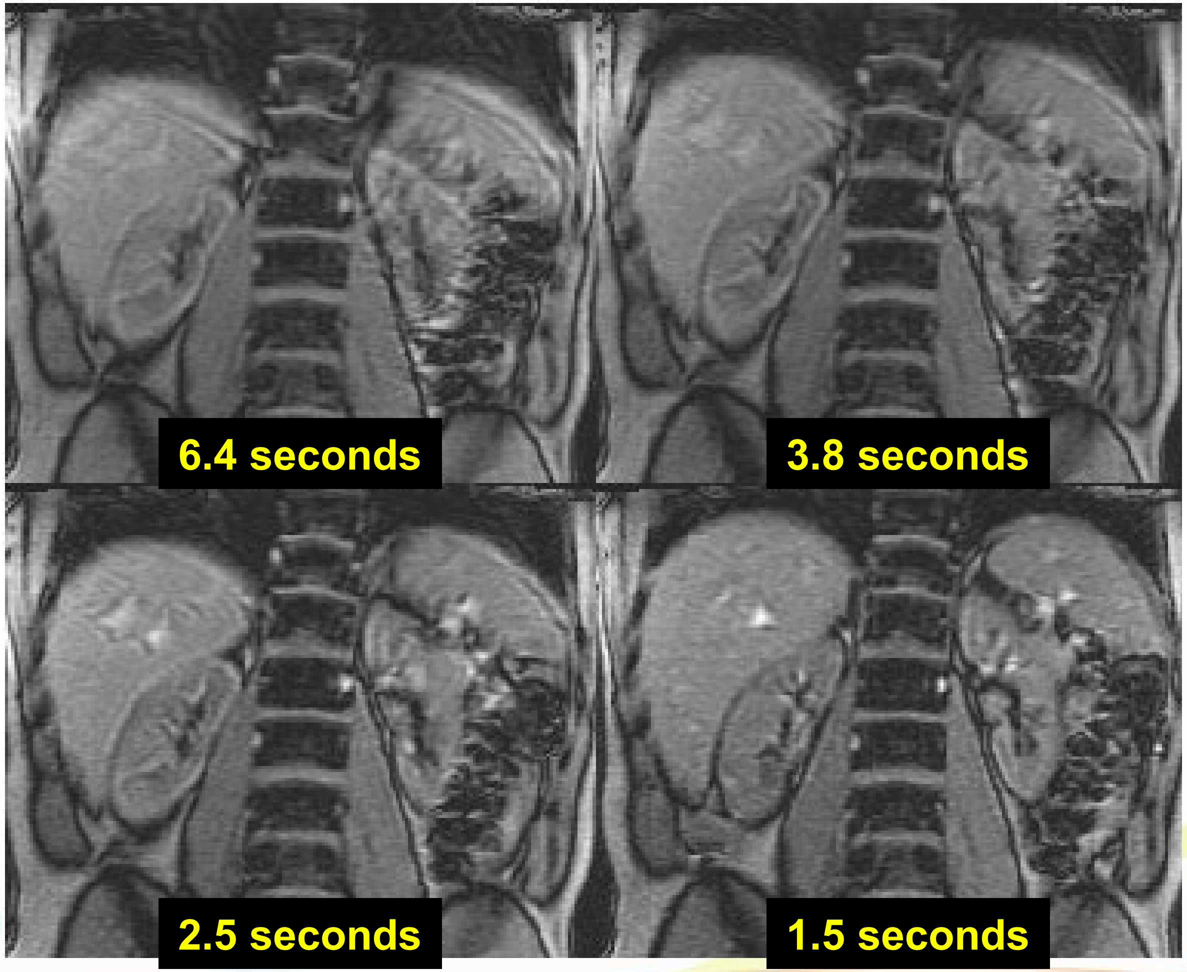
Myth of fast scan?

- Short TR also reduce the number of slices that can be inserted during a TR cycle
- Multi-slice imaging?
  – Scan one (set) after another (set)
- Total scan time almost the same?
  – Priceless or worthless?

Benefit of fast scan

- Accelerate the acquisition of single slice.
  - Less intra-scan motion
- 3D imaging becomes feasible!
- But the total scan time of multi-slice 2D imaging is not necessarily reduced.

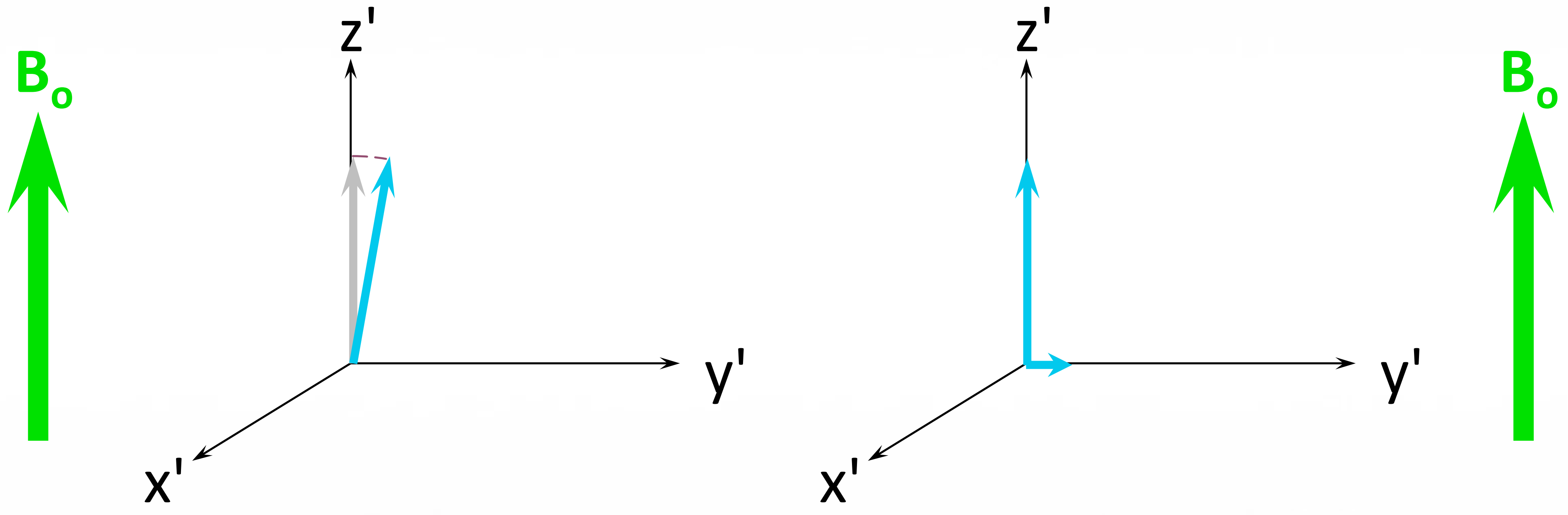
The necessity of fast scan



Further acceleration?

- Reduce TR to around 10 ms!?
  - Flip angle is reduced to ~10°
  - Scan time ~ 2 sec
  - Motion-free protocol for difficult patients?

Very short TR and very low flip angle

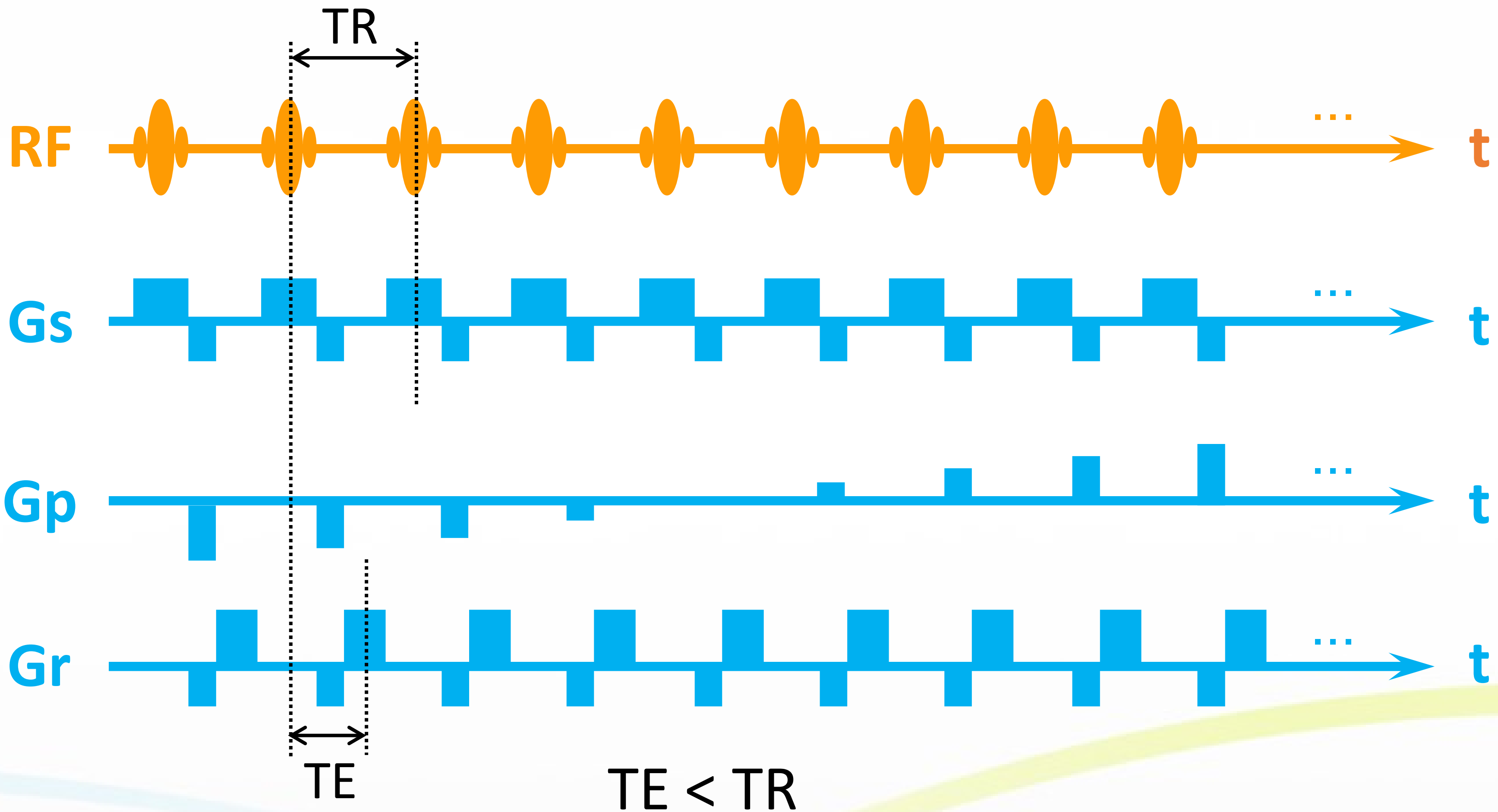


Strong PD-weighting

Limitation of very short TR

- Flip angle is reduced to $\sim 10^{\circ}$
  - PDWI (not very useful in clinical routine)
  - TE < TR
  - Limited T2* weighting

Gradient echo with very short TR



TE < TR

You might have heard of…

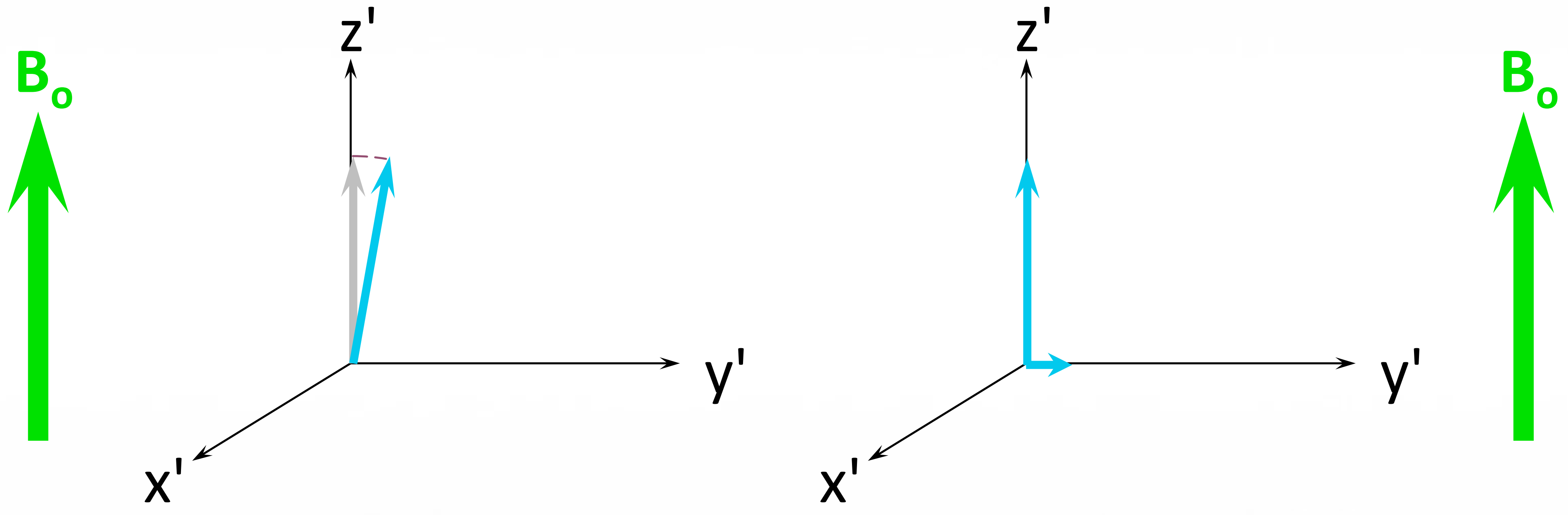
- CE-FAST, PSIF, SSFP-echo…
  - TE could be longer than TR

- Neglected here due to its complexity and limited applications

Limitation of very short TR

- Very small flip angle
- Very short TR for T1 and T2 relaxation
  - Limited T1 or T2 contrast
- Followed by next RF pulse

Very short TR and very small flip angle



Magnetizations before and after excitation are very close to each other

Little influence by T1 and T2 relaxation

- Very short TR and very small flip angle limit the influence of T1 and T2 relaxation
- Image contrast = proton density?
- Signal intensity = M_Z before excitation!
  - Acquisition parameters (TE, TR, α) won't give additional contrast

Magnetization preparation

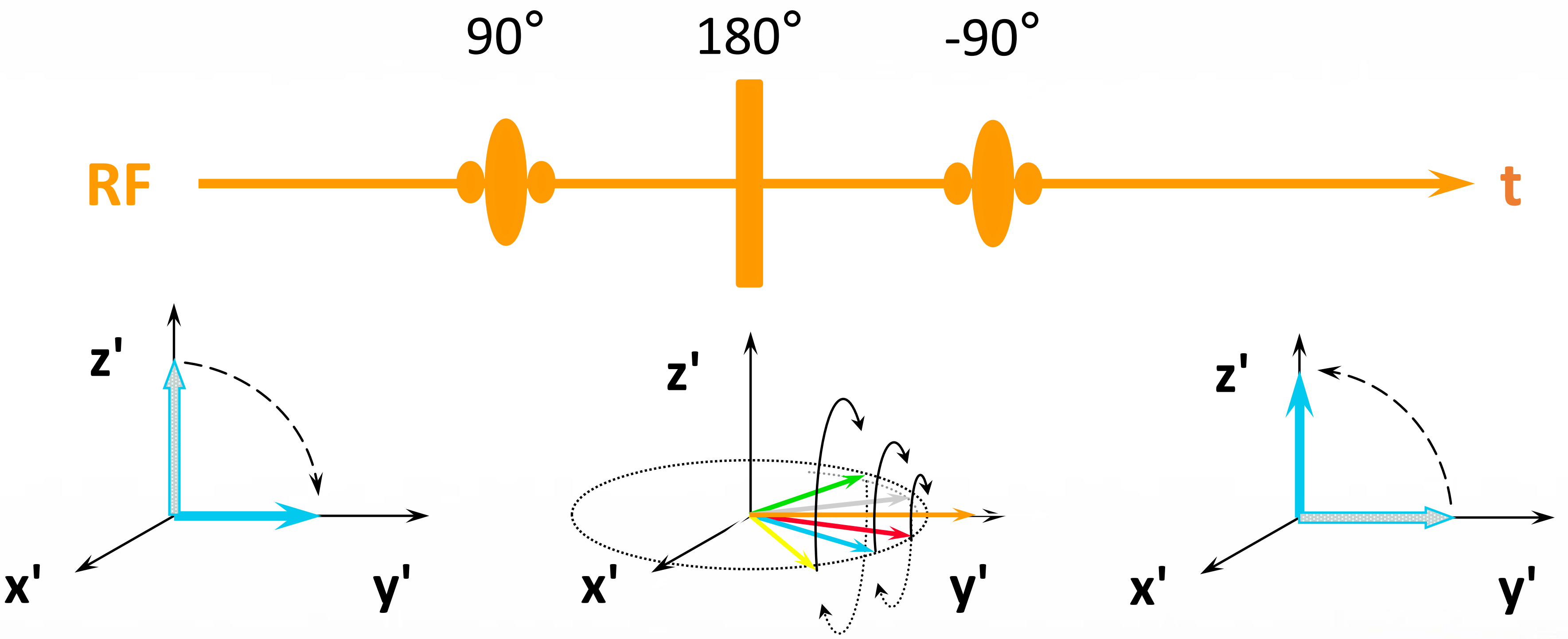
- Pulse train with very short TR and very small flip angle will not make M different
- Image contrast: dominated by M before excitation
  - Prepare your ingredients before cooking

How to prepare magnetization?

- Use RF excitations

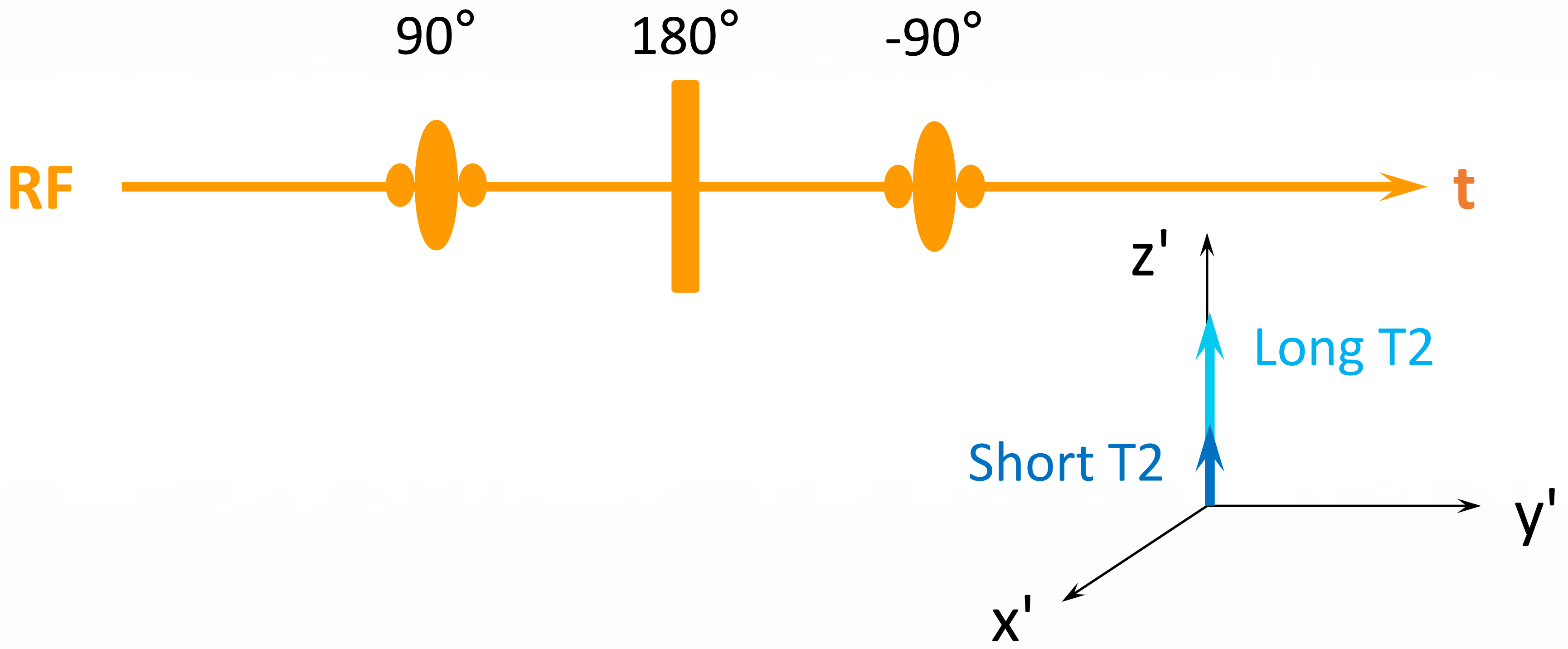
- Ex: $90^\circ + 180^\circ + (-90^\circ)$
  - T2-weighted magnetization

RF: 90° + 180° + (-90°)



Refocusing of spin echo

RF: 90° + 180° + (-90°)

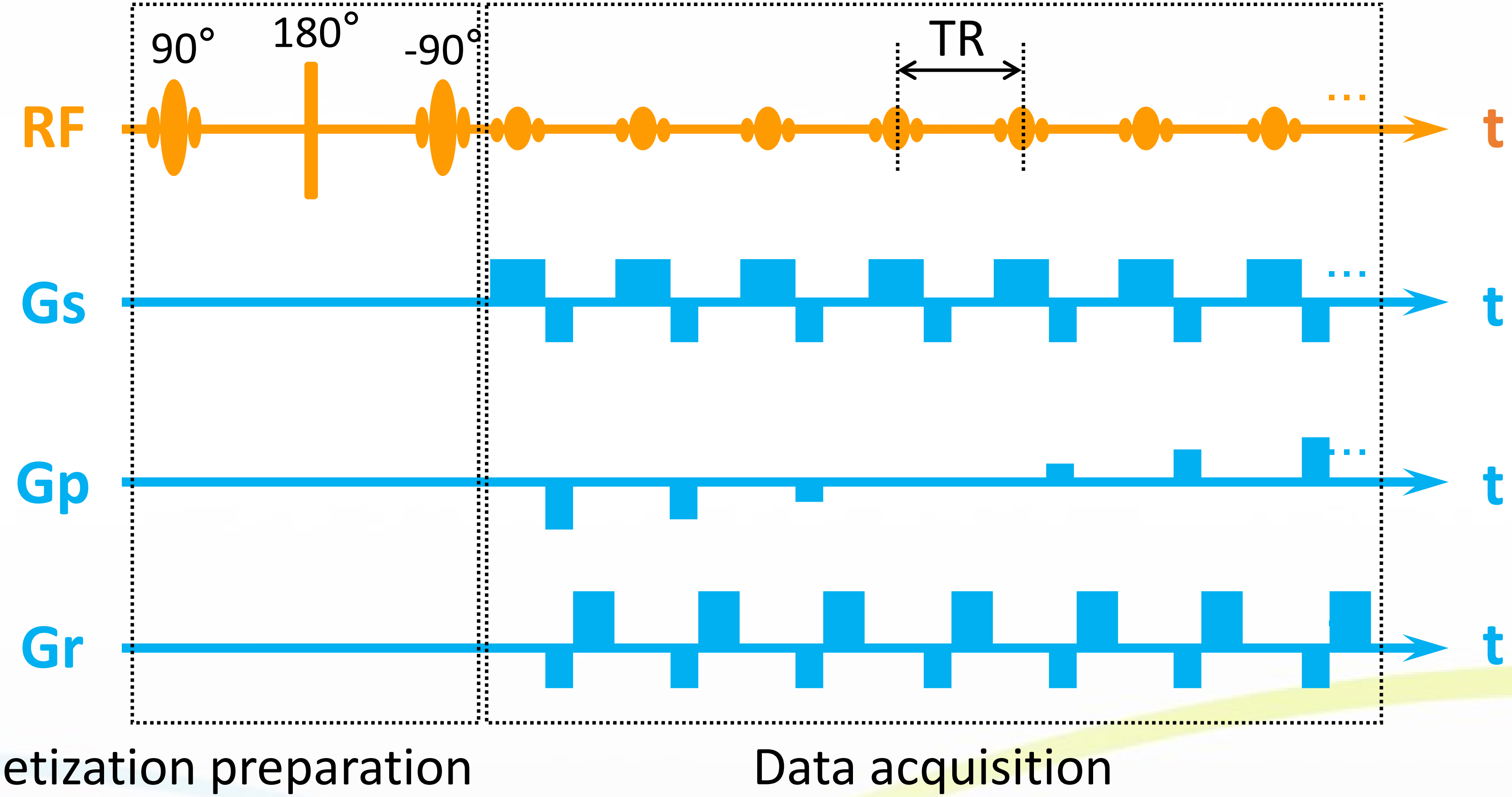


M_{XY} is dependent on T2 at the end

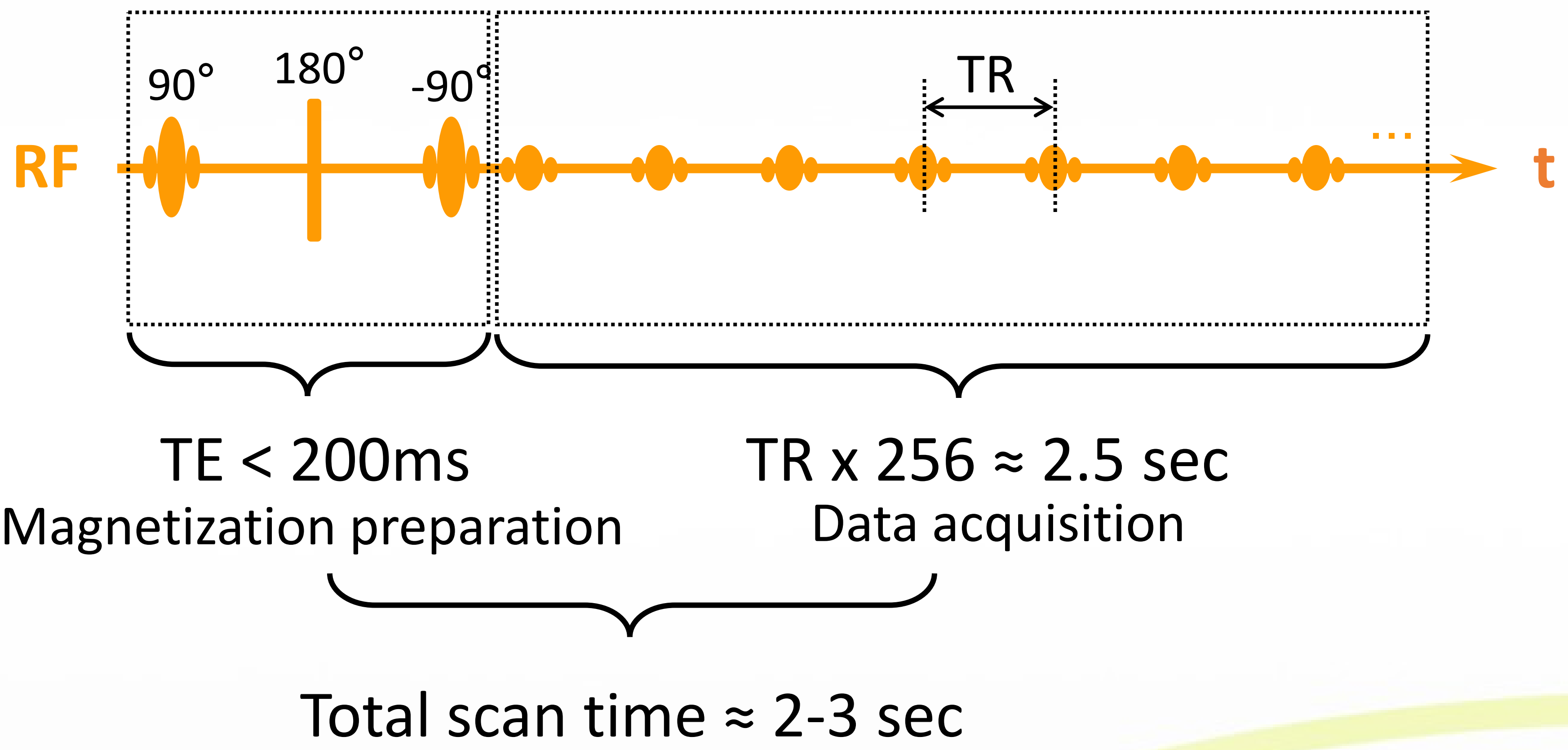
Reminding

- Very short TR and very small flip angle
  - Signal intensity = M_Z before excitation
- Image contrast: dominated by M before excitation

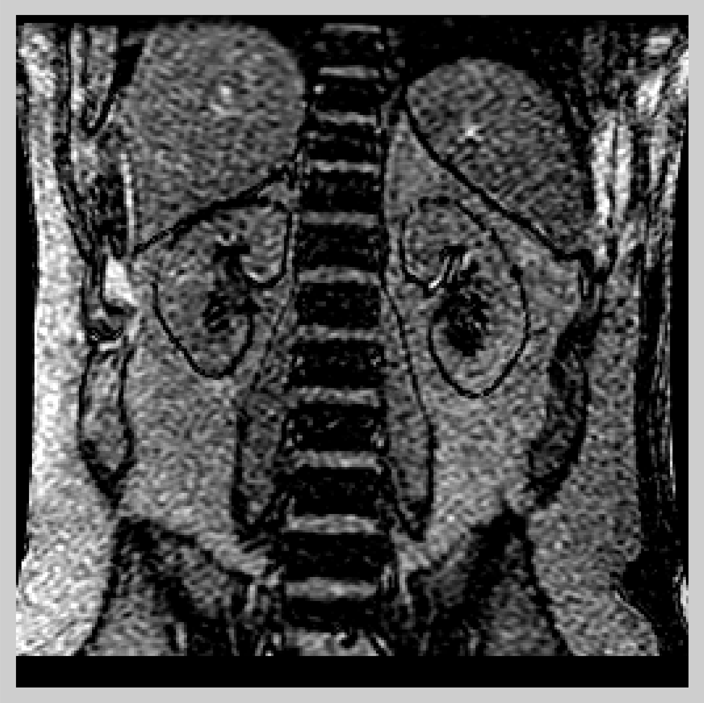
Combination of preparation and acquisition



Magnetization preparation



Magnetization-prepared T2-contrast



PD (no prep)

T2 (with prep)

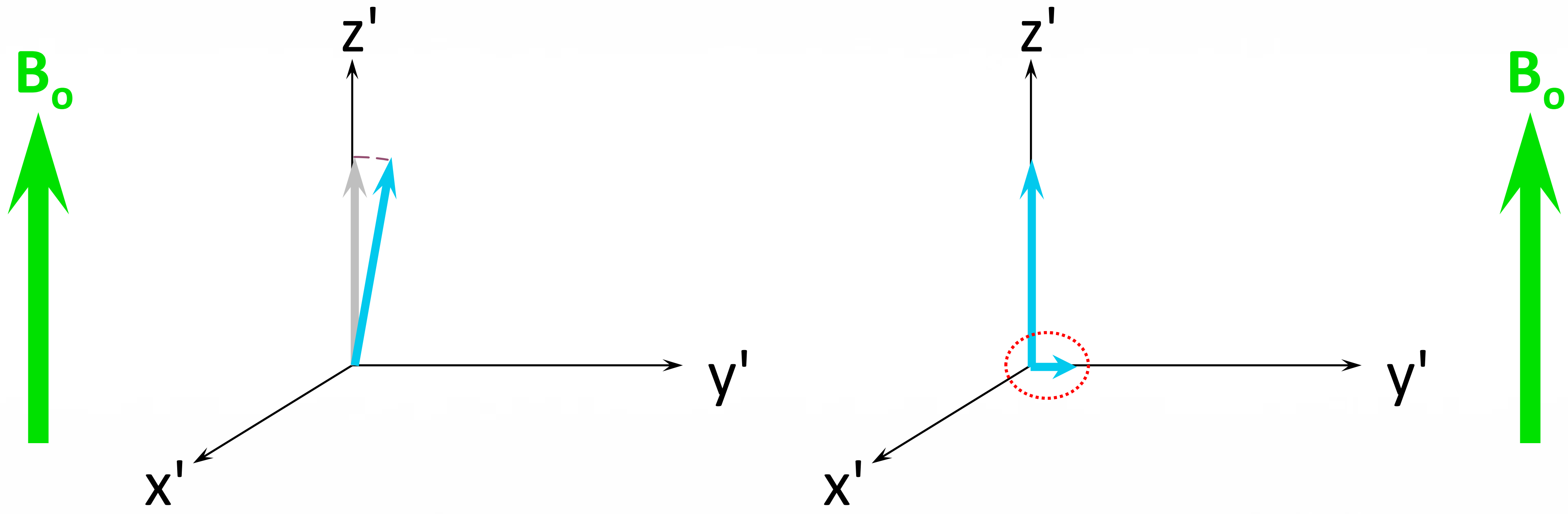
Acronyms

- Magnetization preparation
- Turbo-FLASH, MPRAGE (Siemens)
- Driven-equilibrium fast SPGR (GE)

Brief summary

- Very short TR (< 20 ms)
- Very small flip angle (5°-20°)
- Generally low SNR
- Image contrast: determined by magnetization preparation

Low SNR due to very small flip angle



Very small M_{XY}

Combination of modules

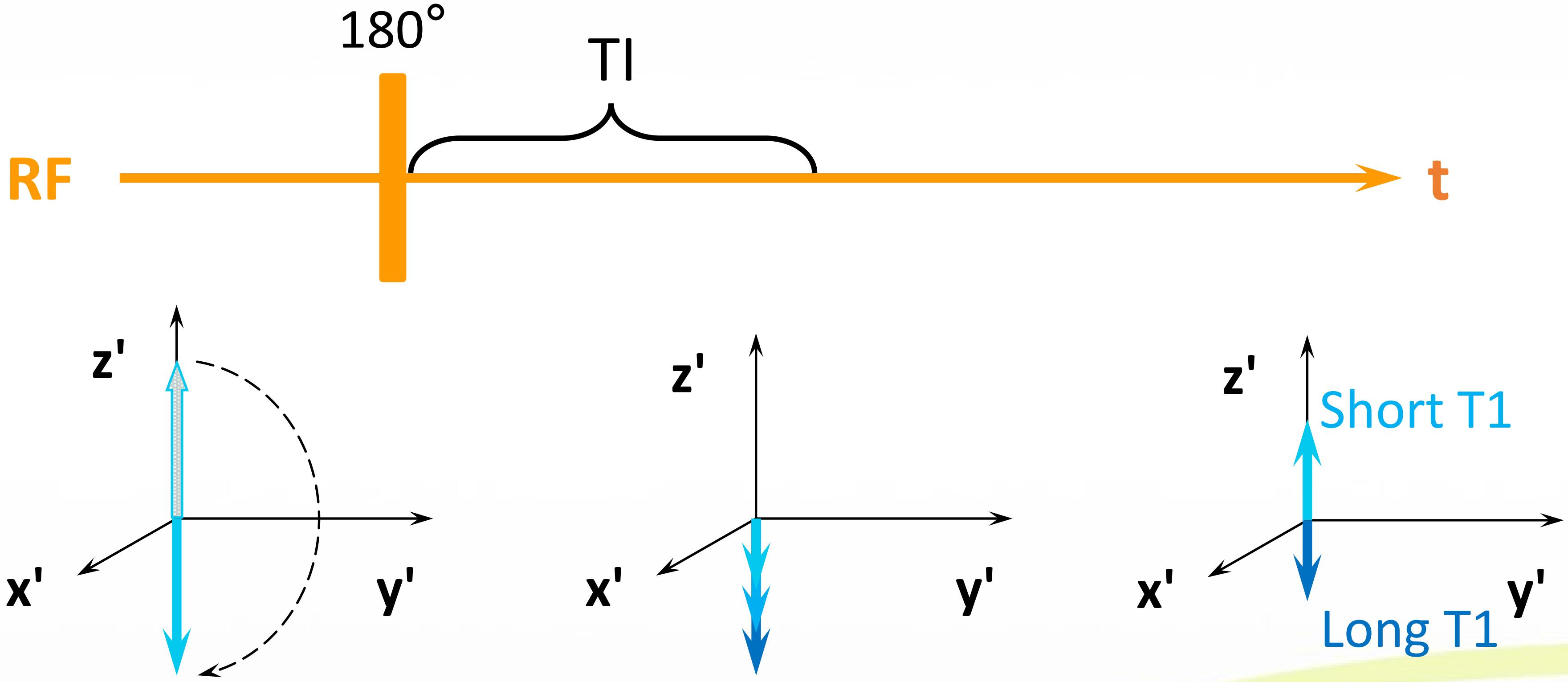
- Modules of magnetization preparation
- Modules of data acquisition

- Combination of specific modules for clinical applications

Variations of magnetization preparation

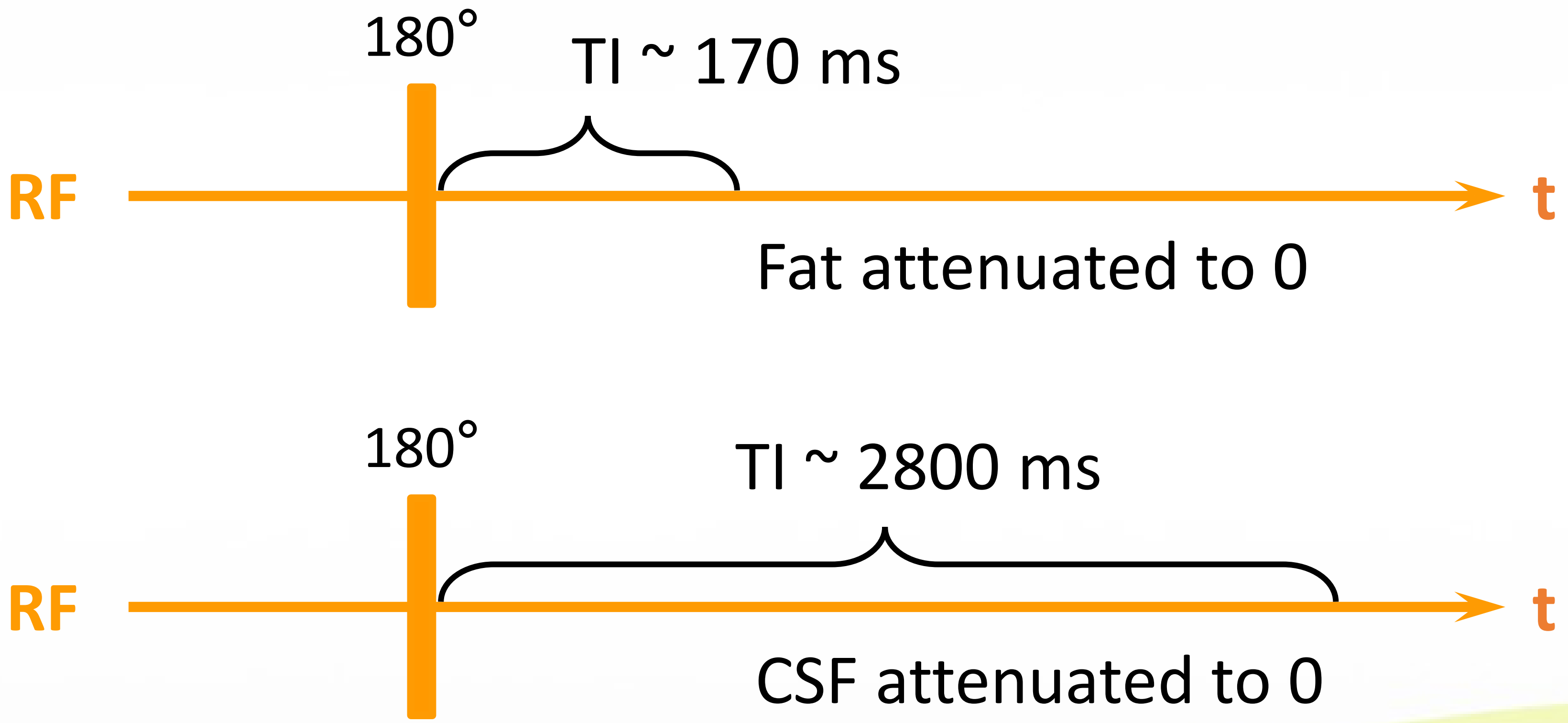
- STIR/FLAIR (inversion recovery)
- Fat-SAT (off resonance excitation)
- Diffusion (spin-echo + bipolar gradients)
- ….

Inversion recovery

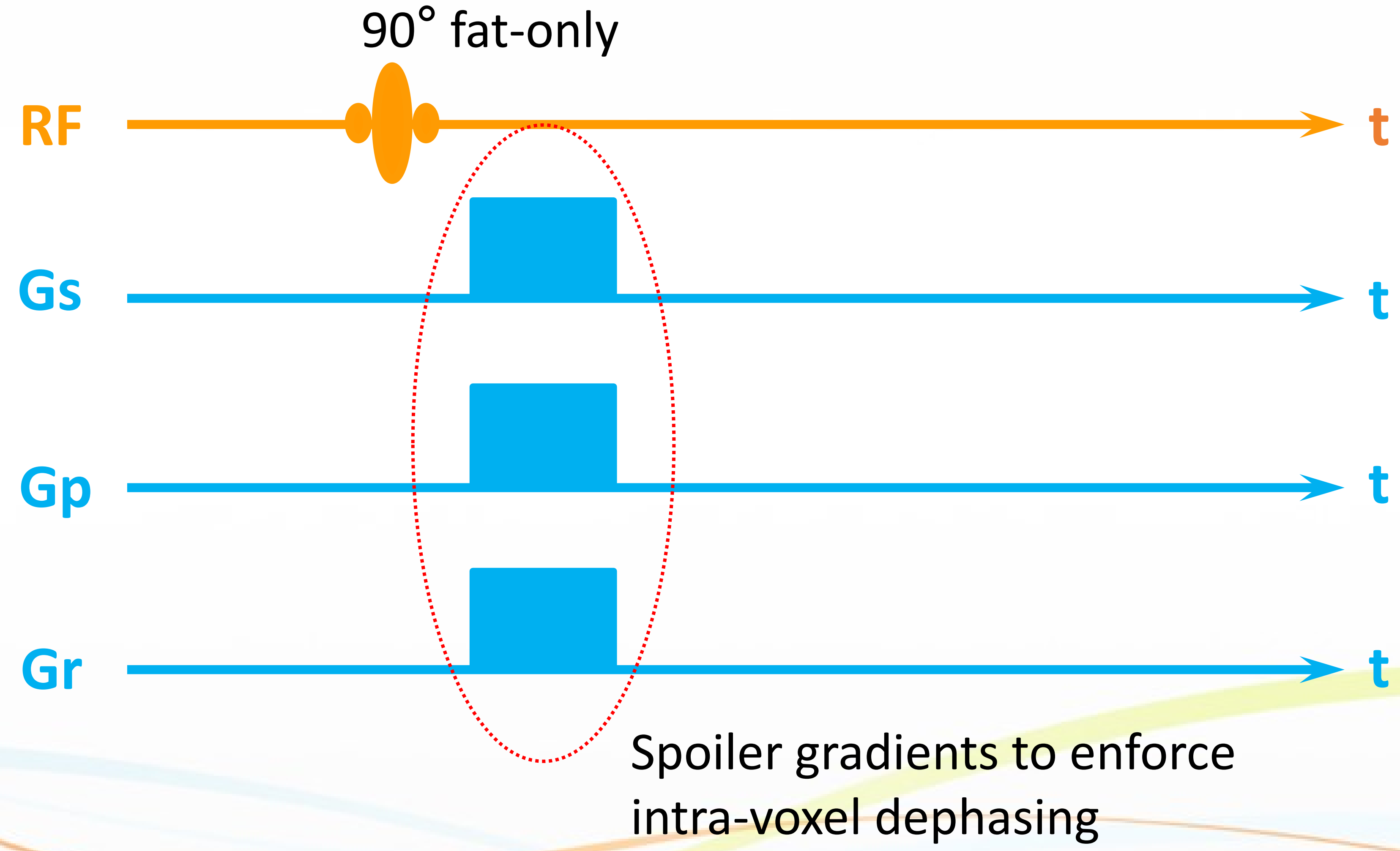


M_Z is related to T1 relaxation

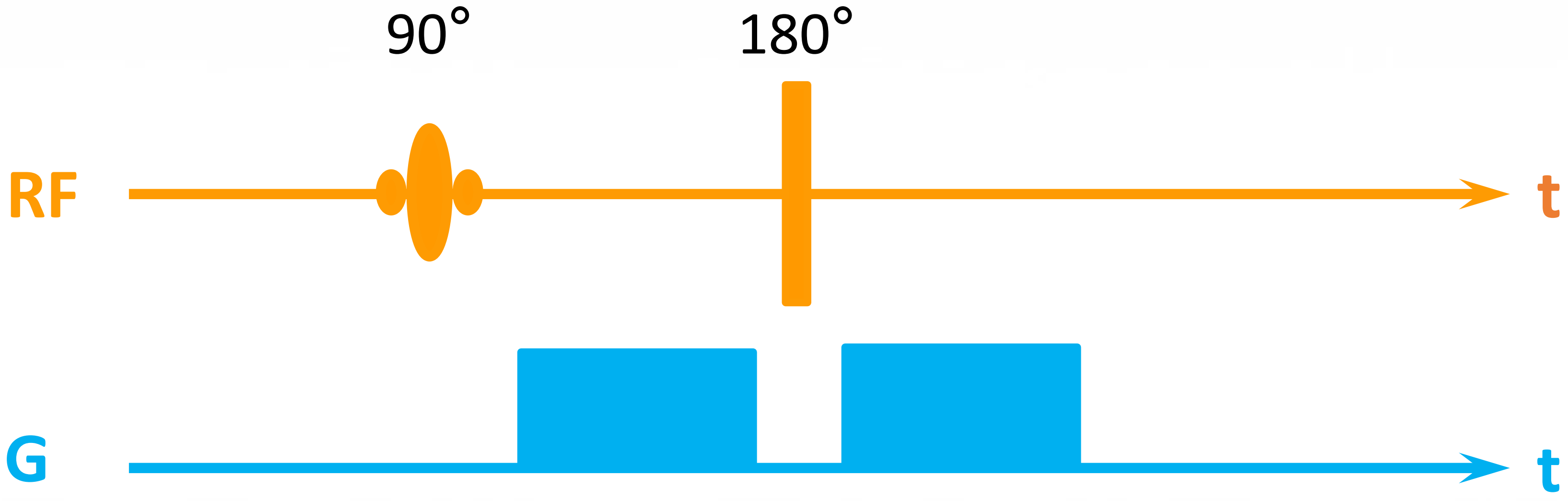
STIR and FLAIR



Preparation of Fat-SAT



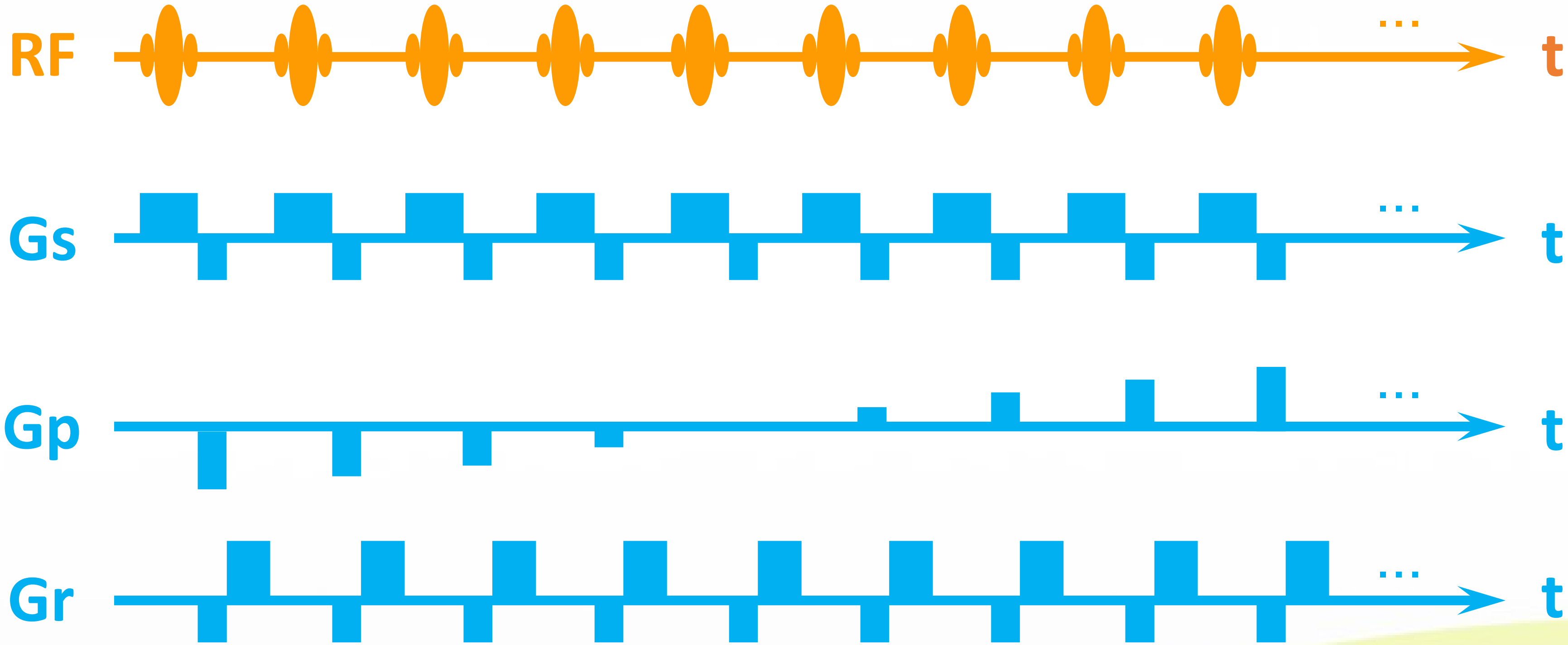
Preparation of diffusion gradients



Variations of readout module

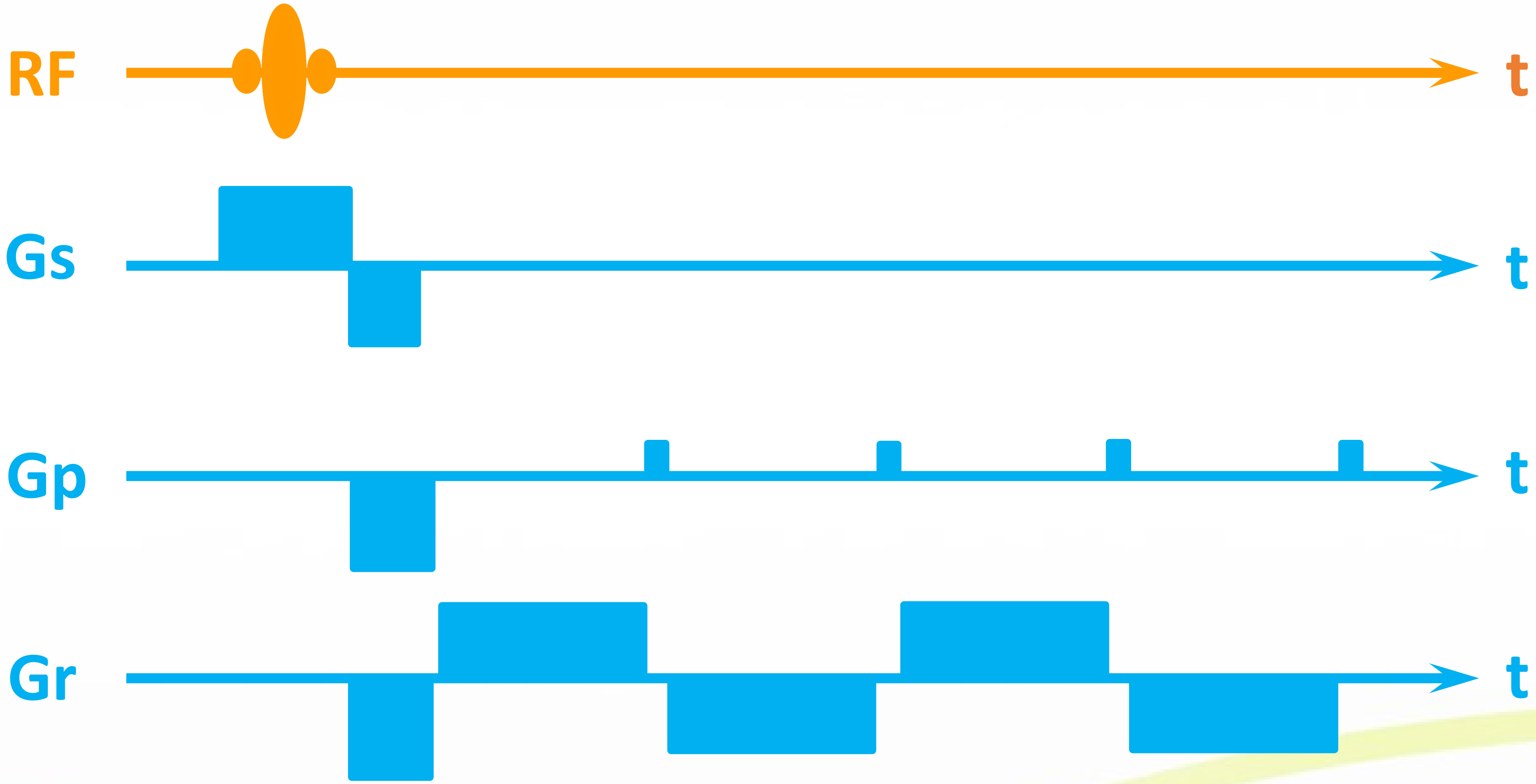
- Fast gradient echo: FLASH, GRASS, SPGR, balanced SSFP…
- Echo planar imaging
- Fast spin echo (Turbo spin echo)
- Even conventional spin echo!

FLASH

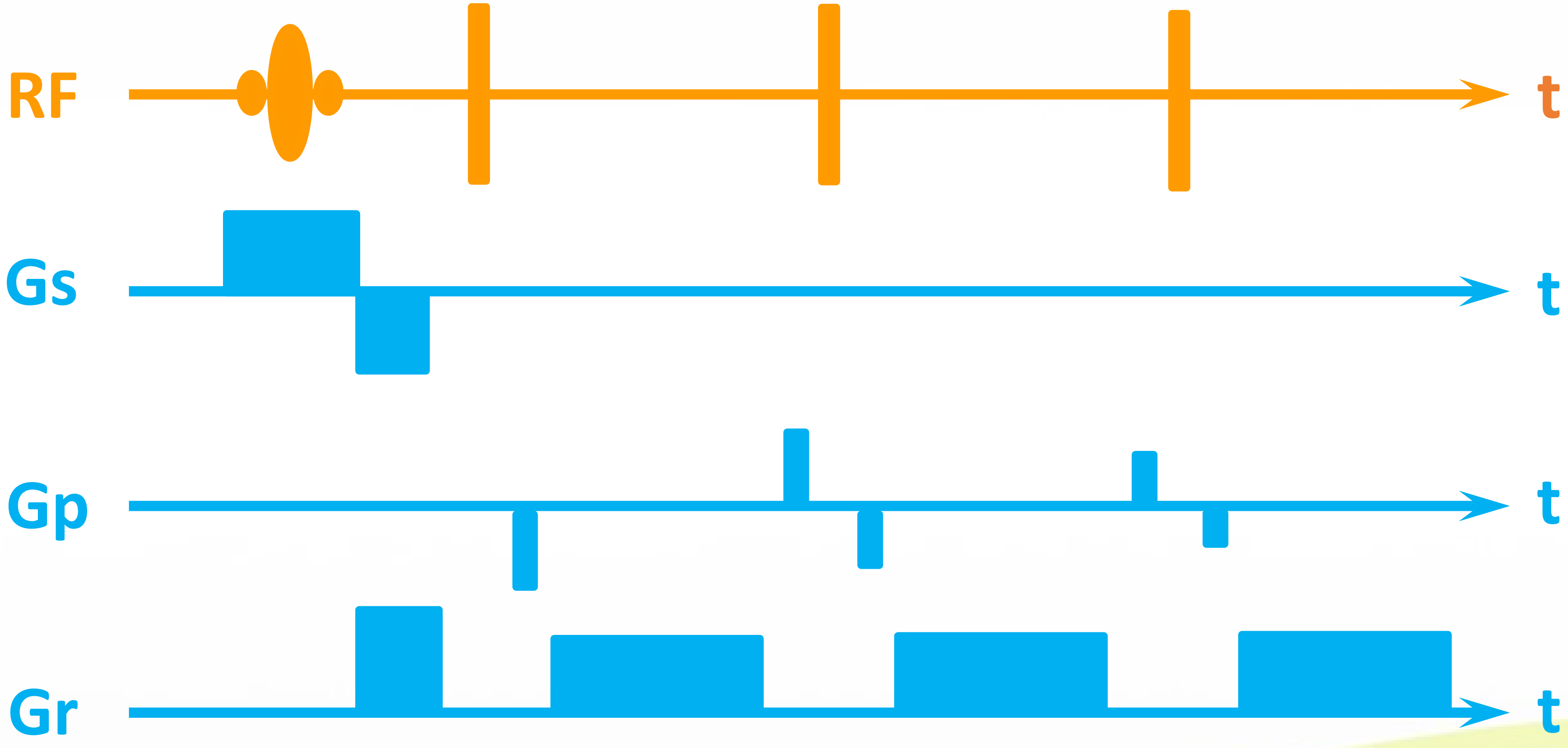


Pulse train of small flip angle

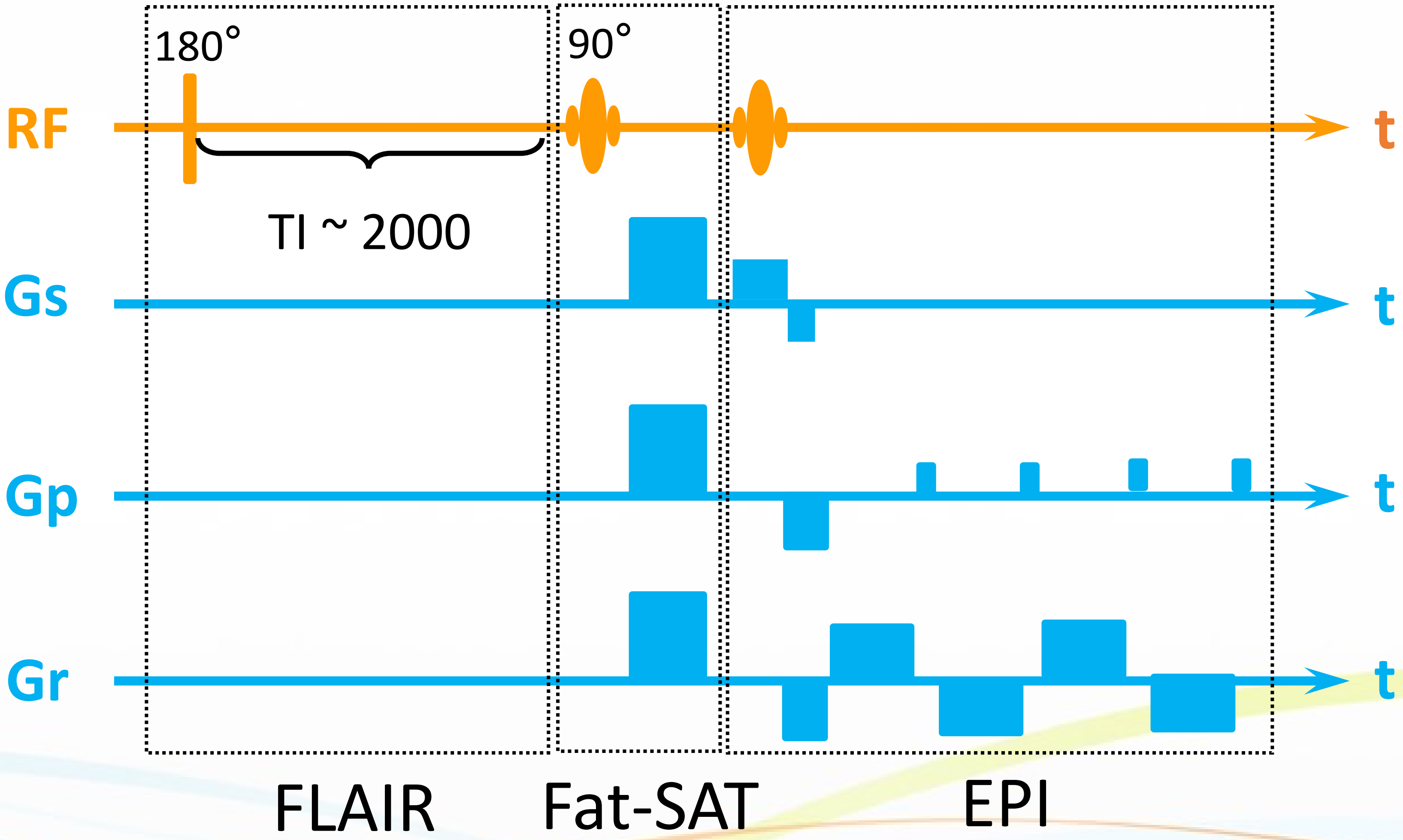
EPI



Fast spin echo (Turbo spin echo)



Magnetization prep. + fast acquisition



Example: FLAIR Fat-SAT EPI

Picker (Marconi → Philips)
IR + Fat-SAT + EPI
TI = 2000 msec
TE = 120
256x160

Note

- Fast gradient echo sequence has so many variants.
  - FISP, PSIF, trueFISP, DESS,… (Siemens)
  - GRASS, FIESTA,… (GE)
- We have only shown the simplified version!

Fast Scan: Fast Gradient Echo