8.1 Off-resonance

So far, B0 field has been perfectly homogeneous but it may be so because

1) Main field inhomogeneity
   - Super conductor (3 T, 50 cm diameter, 1 ppm (i.e 120 Hz))
   - Shim (passive iron shim, linear/higher order shims)

2) Susceptibility induced field variation
   - Magnetic susceptibility induces field inhomogeneity (a few ppm)
     e.g. air (paramagnetic) / water (diamagnetic) boundary, iron-loaded tissue (origin of SWI/fMRI)

3) Chemical shift
   - Electronic shielding effects shift the resonance frequency

     e.g. fat has 3.5 PPM shift w.r.t water (300 Hz at 3 T)

The deviation frequency from resonance is called off-resonance.

What happens if there is off-resonance?

Figure 8.1 Signal decay in FID

Let's model it. Remember signal equation?

$$\mathrm{s_r(t)} = \int_{vol} m(\boldsymbol{r}) e^{-i\omega_0 t} e^{-i2\pi k_r(t)\boldsymbol{r}} e^{-t/T_2(\boldsymbol{r})} \,\mathrm{d}V$$

What is $k_r(t)$?

Assume B_0 is deviated by $B_E(\mathbf{r})$ and set $\omega_E(\boldsymbol{r}) = \gamma B_E(\mathbf{r})$.

$$s_r(t) = \int_{vol} m(\boldsymbol{r}) e^{-i(\omega_0+\omega_E(\boldsymbol{r}))t} e^{-i2\pi k_r(t)\boldsymbol{r}} e^{-t/T_2(\boldsymbol{r})}\, dV$$

After demodulation of the resonance frequency

$$s_r(t) = \int_{vol} m(\boldsymbol{r}) e^{-i\omega_E(\boldsymbol{r})t} e^{-i2\pi k_r(t)\boldsymbol{r}} e^{-t/T_2(\boldsymbol{r})}\, dV$$

1) Ignoring gradients

$$s_r(t) = \int_{vol} m(\boldsymbol{r}) e^{-i\omega_E(\boldsymbol{r})t}\, e^{-t/T_2(\boldsymbol{r})} dV$$

The signal loses the phase coherence (i.e. “dephased”) and gives rise to destructive phase dispersion. This results in accelerated signal decay referred to T_2*. Hence $1/T_2^* = 1/T_2 + 1/T_2'$.

2) If gradients are included, the effect gets more complicated and depends on k-space trajectory

- Amplitude effects

  When special localization is performed, the field inhomogeneity within a voxel matters the most as compared to the whole volume in FID case

  The signal decay may induce additional weighting in k-space trajectory and may blur the resulting image

- Phase effects

  Assuming a delta function $^2\delta(x - x_0, y - y_0)$ as an object in 2D imaging

$$s_r(t) = \int_{slice} \delta(x - x_0, y - y_0)\, e^{-i\omega_E(x,y)t} e^{-i2\pi(k_x(t)x + k_x(t)y)} e^{-t/T_2(x,y)}\, dxdy$$

$$= e^{-i\omega_E(x_0,y_0)t} e^{-i2\pi(k_x(t)x_0 + k_y(t)y_0)}$$

In 2DFT case with Gy phase encoding and Gx readout, the signal equation after phase encoding and during readout becomes

$$= e^{-i\omega_E(x_0,y_0)t} e^{-i\gamma G_y y_0 t_y} e^{-i\gamma G_x x_0 t}$$

$$= e^{-i(\omega_E(x_0,y_0)+\gamma G_x x_0)t} e^{-i\gamma G_y y_0 t_y}$$

$$= e^{-i\gamma G_x(\omega_E(x_0,y_0)/\gamma G_x + x_0)t} e^{-i\gamma G_y y_0 t_y}$$

$$=e^{-i\gamma G_x (B_E(x_0,y_0)/G_x + x_0)t} e^{-i\gamma G_y y_0 t_y}$$

We can replace $x_0' = x_0 + B_E(x_0,\ y_0)/G_x$

This means that an impulse is shifted by field inhomogeneity/G_x in readout direction

Q: How do we minimize the displacement?

- Chemical shift effect

A large shift along readout direction (in 2DFT)
Distinct phase evolution over time (Water/Fat in-phase and out-of-phase)

Note that things are much more complicated in other trajectories.

8.2 Gradient Echo vs. Spin Echo

$$\mathrm{s_r(t)} = \int_{vol} m(\boldsymbol{r}) e^{-i(\omega_0+\omega_{off}(\boldsymbol{r}))t} e^{-i2\pi k_r(t)\boldsymbol{r}} e^{-t/T_2(\boldsymbol{r})}\,\mathrm{d}V$$

$$= \int_{vol} m(\boldsymbol{r}) e^{-i(\omega_0+\omega_{main\ field+suscep}(\boldsymbol{r})+\omega_{chem\ shift}(\boldsymbol{r}))t} e^{-i2\pi k_r(t)\boldsymbol{r}} e^{-t/T_2(\boldsymbol{r})}\,\mathrm{d}V$$

Let’s look at the phase evolution after demodulation

$$\varphi(\boldsymbol{r},t) = \omega_{main\ field+suscep}(\boldsymbol{r})t + \omega_{chem\ shift}(\boldsymbol{r})t + \gamma\int_0^t \boldsymbol{G}(\tau)\cdot\boldsymbol{r}\,d\tau$$

Q1: Explain the meaning of each term.

Q2: Why T2(r) is not included in the phase term?

This phase term induces signal drop out faster than T2 decay

Plot of FIDs from each off-resonance components

We can restore some of lost signal by generating “echoes”

Plot of the pulse sequence diagram to explain why we need to generate an echo

- Gradient echoes: undoing of phase shifts from gradient fields
- Spin echoes: undoing of phase shifts from field inhomogeneity and chemical shift

- Gradient echoes

When $\omega_{main\ field+suscep}(\boldsymbol{r}) + \omega_{chem\ shift}(\boldsymbol{r}) = 0$, the phase is solely controlled by the gradient fields

This gradient field induces systematic dephasing generating a faster signal drop out

The dephasing can be removed by rephasing the gradient field generating an echo

Plot gradient echo sequence (readout only) with an echo

This echo is called gradient-recalled echo

Another view of the gradient echo is crossing of the origin in k-space

Plot k-space and match the sequence diagram and k-space

Another view of the gradient echo is the zeroth moment is nulled in gradient

Q: Why do we acquire gradient echo instead of FID?