Magnetic Resonance and Medical Imaging lect 7

4th year /Medical Physics

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Net Magnetization

A patient placed in an MRI system consists of a multitude of proton spins. Many of these protons attempt to align with the external field and precess at the Larmor frequency (as in Figure).

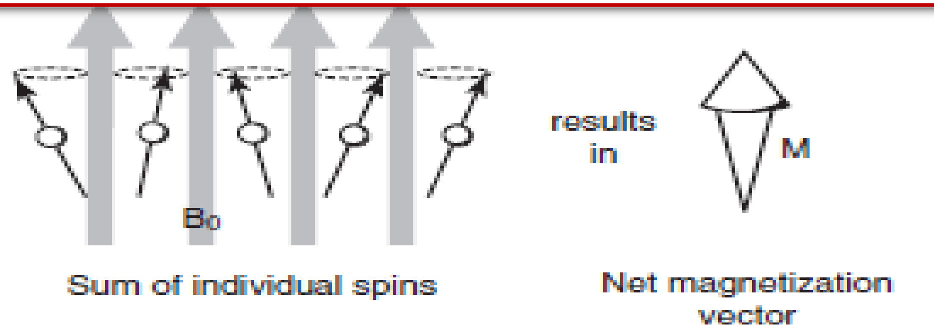

FIGURE 4-2 The protons aligned with the external magnetic field precess randomly at the same frequency. This results in the net magnetization represented by the vector *M*.

Although all the protons shown are oriented in an upward direction, the exact direction to which they point at any instant is slightly different because they are at random positions in their precession. The net result is that the individual magnetizations sum to a net magnetization (M) parallel to the direction of the external magnetic field.

Equilibrium

- In the preceding situation, the net magnetization does not precess but is a vector of constant magnitude pointed in the direction of the external magnetic field, which is the Z direction. Because they are randomly oriented, the horizontal or X and Y components of all the individual nuclear spins are out of phase, and therefore there is no net magnetization in the XY plane.
- This state of the net magnetization is called equilibrium. The proton spins are said to be at equilibrium with the external magnetic field. The magnitude of the net magnetization at equilibrium along the Z-axis, symbolized as M_0, is determined by several physical factors.
- The more protons available for alignment, the larger M_0 will be. The number of nuclei available that do align is determined by the intensity of the external magnetic field. Finally, a large gyromagnetic ratio results in a large M_0. Therefore N (the number of nuclei available), B_0, and γ contribute to M_0.

Note :The larger the M_0, the stronger the MR signal will be.

- Unfortunately, the component of M along the Z-axis cannot be measured directly. It is much too weak compared with B_0 to be detected. Only components of the net magnetization vector in the XY plane, that is, M_{XY}, can be detected by the MRI receiving coil. There is no magnetization in the XY plane, M_{XY}.

- The nuclear spins are all randomly oriented in these directions; therefore it makes no sense to refer to stationary magnetization along either the X- or Y-axis. At equilibrium, no signal is received from the patient because the net magnetization vector, M, points only in the Z direction, MZ, and has no component in the XY plane, M_{XY} (Figure 4-3).

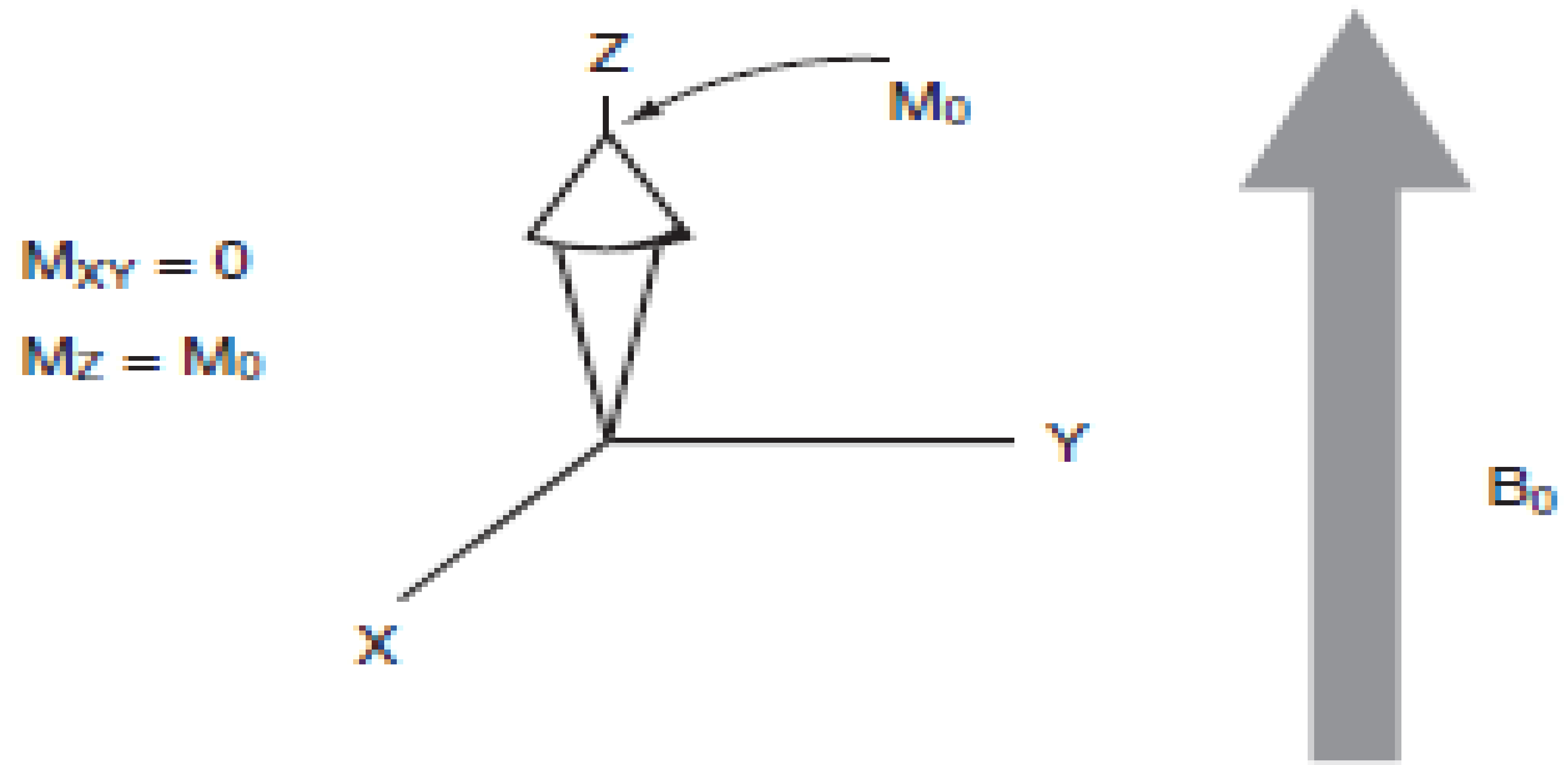

FIGURE 4-3 At equilibrium, there is no *XY* component to net magnetization, and the *Z* component is at its maximum value, M_0.

- For a signal to be received from a patient, the magnetization vector must be rotated from the Z-axis so that it has some nonzero component in the XY plane.
- This rotation follows a pulse of radiofrequency (RF) tuned to the nuclei's Larmor frequency. If the RF is not at this frequency, the nuclei do not absorb energy, and the net magnetization is not rotated. For typical magnetic fields and nuclei of interest, such as hydrogen, the Larmor frequency corresponds to electromagnetic radiation in the RF range.
- Thus if the MRI technologist sends a pulse of RF tuned to the precessional frequency of hydrogen, some hydrogen nuclei absorb energy from the RF, and the magnetization vector flips away from the Z-axis (Figure 4-4).

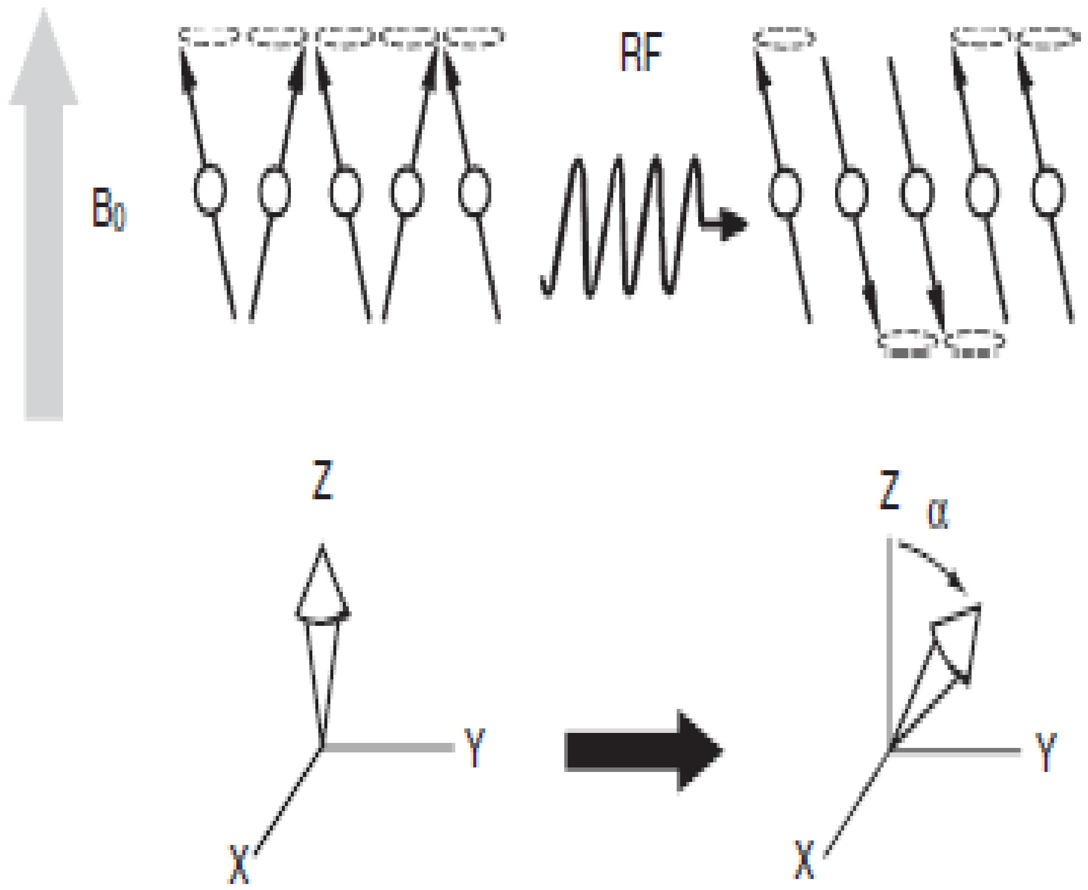

FIGURE 4-4 A radiofrequency *(RF)* pulse at the Larmor frequency causes the net magnetization vector to flip through the angle α.

Flip Angle

- The net magnetization vector has been rotated an angle α from the Z-axis because individual nuclei have absorbed RF energy and are now in a high-energy state.
- The high-energy state is opposite the direction of the external magnetic field. As long as the RF is energized, the net magnetization vector continues to rotate
- . The net magnetization vector can be rotated to any angle by application of a designed time/ intensity RF pulse.

Radiofrequency Pulses

Hard and Soft Pulses

The angle through which the net magnetization vector is rotated is controlled by two factors. The speed of rotation is controlled by the strength of the RF pulse. A strong RF pulse rotates net magnetization rapidly, whereas a weak RF pulse rotates it more slowly.

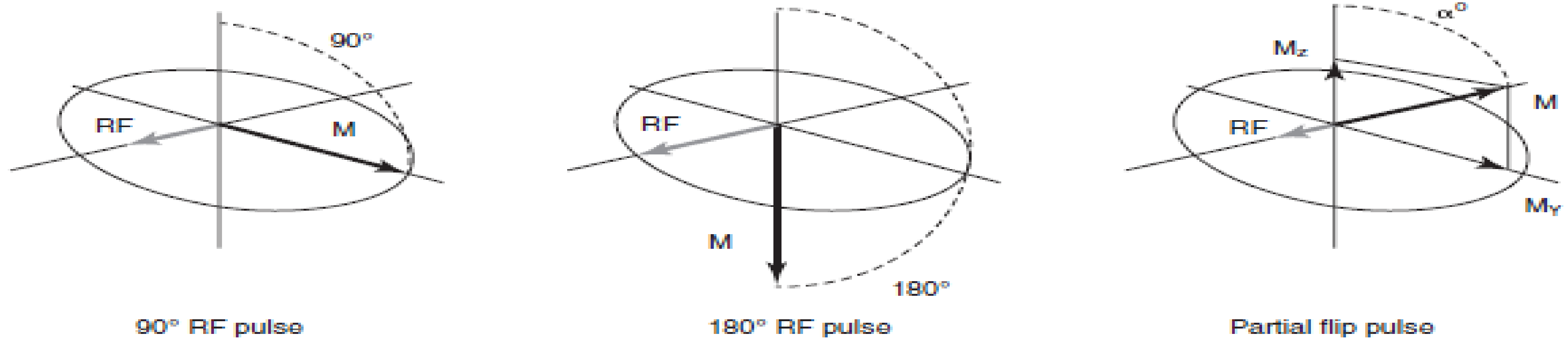

FIGURE 4-5 In MRI, *90°* and *180°* radiofrequency pulses are often used to saturate and invert the magnetization, respectively. Smaller flip angles may be used for fast imaging creating a signal-producing component *(M_y)* with a left-over longitudinal component *(M_z)*.

The final angle of rotation is controlled by the duration of the RF pulse. It is the product of these two factors—the RF pulse intensity and duration—that determines the final angle of rotation.

Note:

Strong, very short RF pulses are called hard pulses; weaker but longer RF pulses are called soft pulses.

Thus, for example, a 90° RF pulse can be achieved by either a strong RF pulse of short duration or a weak RF pulse lasting a longer time. Regardless, the duration of even the longest RF pulse used in practice is still very short, rarely exceeding 10 ms ; this is the reason for calling the burst of RF radiation a pulse

XY Magnetization

- Regardless of whether the RF pulse is hard or soft, what is important is how far the net magnetization vector has been rotated- the flip angle.
- For this reason, both hard and soft pulses are most commonly labeled not by their strength and duration but by the angle through which they rotate the net magnetization vector. Net magnetization can be rotated through any angle.
- A 90° RF pulse and 180° RF pulse are most often used in MRI (Figure 4-5). A 90° RF pulse rotates the net magnetization vector from equilibrium onto the XY plane. Similarly, a 180° RF pulse rotates the net magnetization vector from equilibrium to the-Z-axis. Many fast MRI techniques use so-called "partial flip" or alpha (α) pulses. The alpha pulse is identified by a rotation angle less than 90° (e.g., a 10° RF pulse, a 30° RF pulse).

The use of **RF** pulses in **MRI** produces an XY component to the net magnetization. When the net magnetization vector is rotated, M_Z shrinks and $\mathbf{M_{XY}}$ grows. As previously mentioned, the net magnetization in the XY plane ($\mathbf{M_{XY}}$) is the only magnetization that can be detected as an **MR** signal from the patient.

Note : Spins are saturated after a 90° RF pulse so that Mz = 0, Mxy = $\mathbf{M_0}$.

The net magnetization vector shown in Figure 4-6 has absorbed energy from an RF pulse and is no longer at equilibrium. The components of the net magnetization vector are different from those at equilibrium. MZ is smaller than M0 and MXY is no longer zero. When this occurs, the nuclear spins are said to be partially saturated. If the net magnetization were totally in the XY plane, then the spins would be saturated.

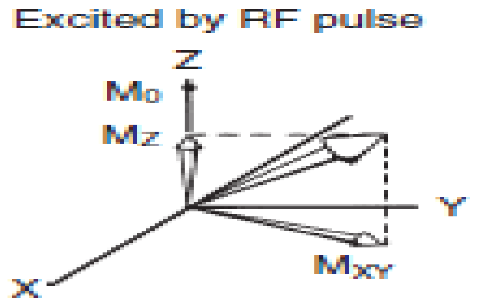

FIGURE 4-6 Flipping net magnetization from the *Z*-axis reduces M_Z and increases M_{XY}.

- Now, if the net magnetization is in one of these "off resonance" regions, then in the rotating frame the net magnetization vector does not remain stationary but rotates. If the spins are at a higher frequency they rotate counter-clockwise, and if they are at a lower frequency they will rotate clockwise. The magnetization vector precesses ,
- just as if it were an individual nucleus. This occurs because the individual nuclear magnetic moments that were precessing randomly were caused to flip in phase by the action of the RF pulse (see Figure 4-4). The frequency of the rotating frame is usually defined by the carrier frequency of the RF pulse for practical purposes. Thus if M_{XY} were looked at from above, it would be seen rotating at a frequency that is the difference between the Larmor frequency of the spins at their local position in space and the frequency of the rotating frame (Figure 4-7).

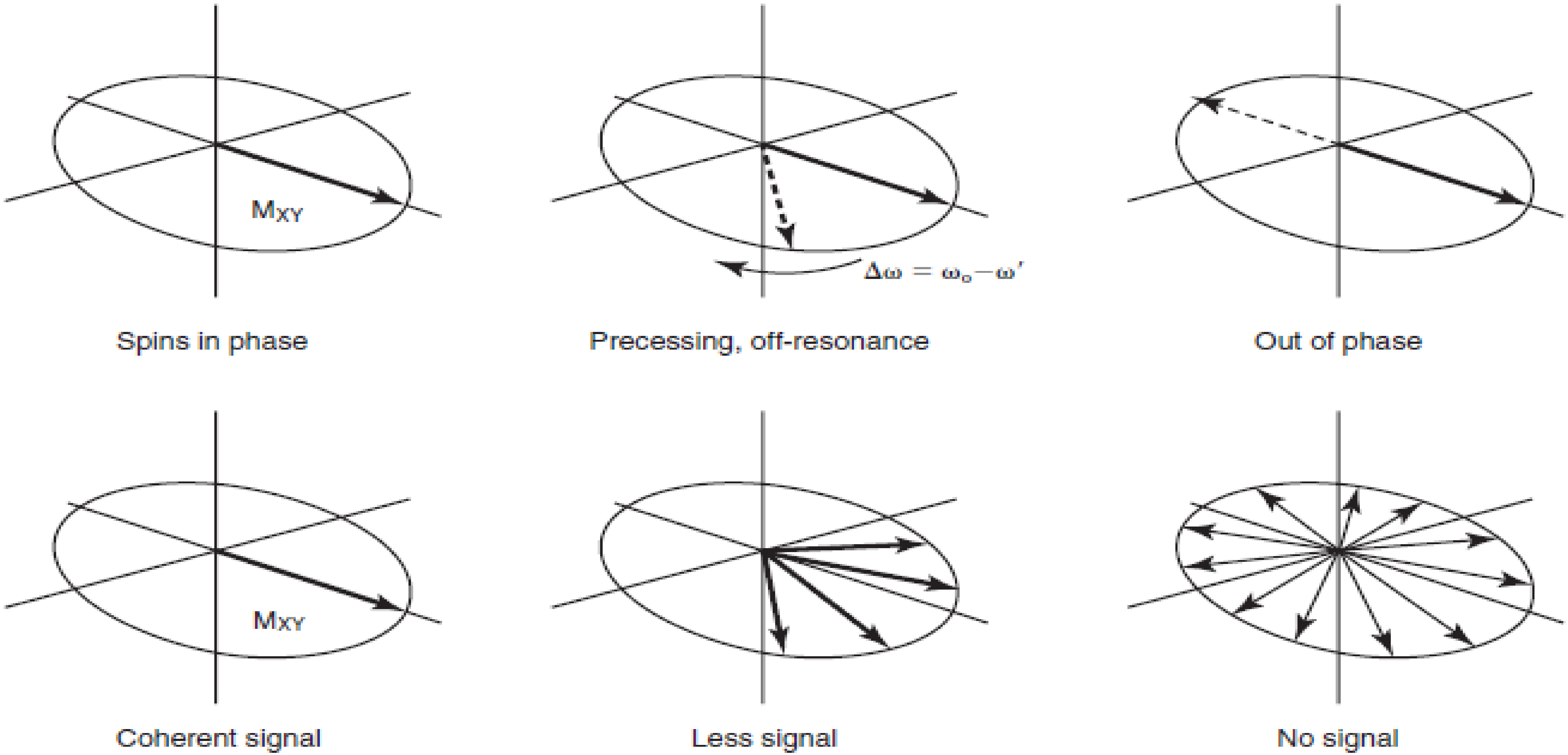

FIGURE 4-7 After a radiofrequency pulse that flips net magnetization from the Z-axis, the XY component, M_{XY}, precesses at a frequency that is the difference between its frequency, ω', and the Larmor frequency, ω_o. In the top row, the solid line represents on-resonance magnetization that does not move in the rotating frame. The dashed line represents off-resonance magnetization that precesses at an angular frequency of $\Delta\omega$. If there are groups of spins at a number of different frequencies they will all eventually dephase *(bottom row)*.

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Dephasing of XY Magnetization

- Nuclear spins can be influenced by the magnetic fields of other nearby atoms. If these fields add to or subtract from the external B_0 magnetic field, then the Larmor frequency of the spins will change.
- If the nearby atoms are moving past the nuclear spins, like a comet having a close encounter with a planet, the Larmor frequency will only change for a tiny amount of time, but after the magnetic atoms pass by, the nuclear spins will be left with a phase shift.
- A multitude of these types of interactions causes the net transverse magnetization to gradually dephase until there is no signal left at all (see Figure 4-7). We will discuss this process in more detail when we talk about T2 relaxation times in

Return to Equilibrium

- Immediately after RF excitation, the net magnetization vector seeks to realign itself with the external magnetic field. That is, the magnetization vector MZ slowly returns to its equilibrium position as the saturated nuclear spins individually give their energy back to surrounding nuclei in their local environment and return to their normal state of alignment with the external magnetic field.
- This is shown in (Figure 4-8) as the regrowth of M_Z along the Z-axis. The net result of these two motions, precession with dephasing and the return to equilibrium with B_0, are best thought of as two separate processes (Figure 4-9). The Z component gradually grows until it reaches its maximum value at equilibrium, M_0.
- However, in most tissues the XY component precesses and dephases until the net signal disappears at a rate that is at least ten times faster than the return of the Z component to equilibrium. Both of these changes in component magnitude, the shrinking of the XY component and MR signals, the spin echo and the gradient echo, are discussed later.

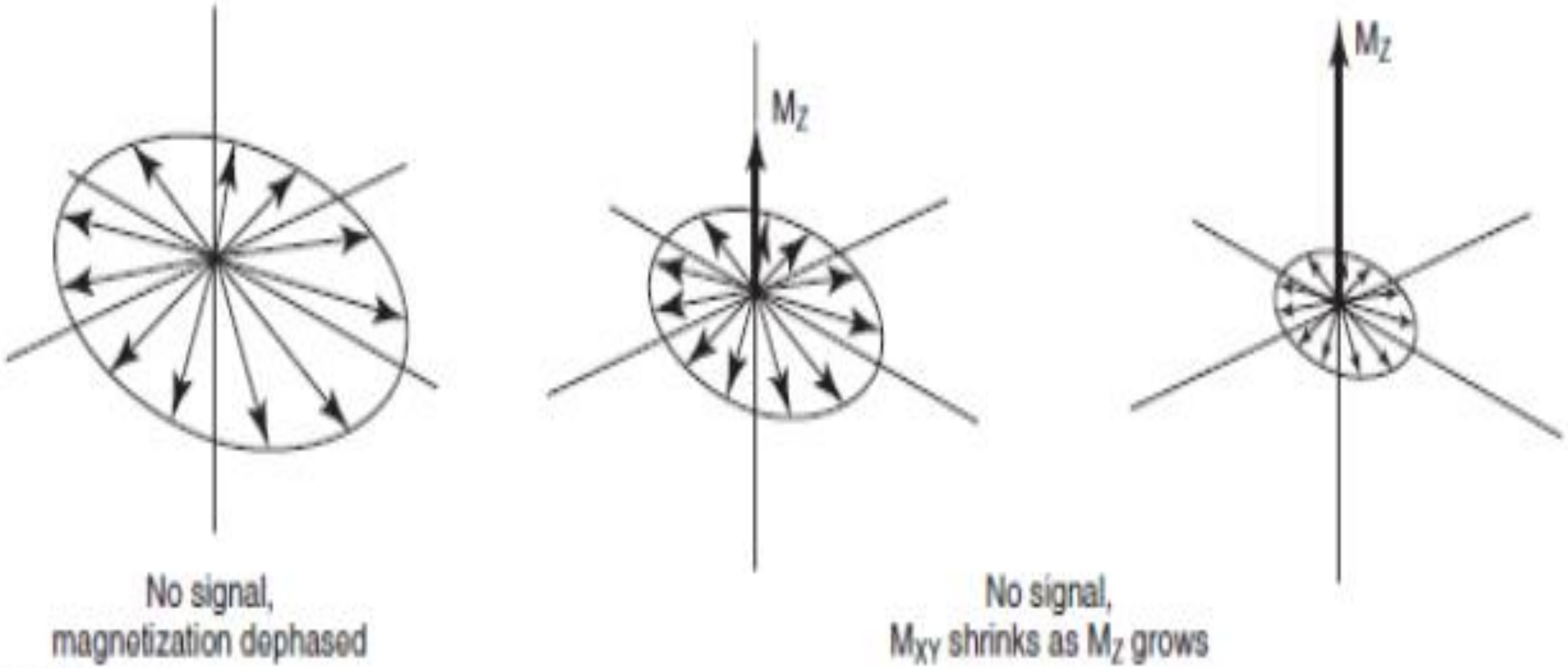

FIGURE 4-9 Relaxation of M_z occurs so slowly that the transverse magnetization is totally dephased and the signal is gone before noticeable recovery occurs. The rate of regrowth of M_z is controlled by the relaxation time, T1.

Free Induction Decay

- With all this complex motion of the net magnetization occurring, what can be observed? The only part of the net magnetization that can be observed is the XY component. As long as MXY precesses with spins in phase and is not zero, an oscillating signal is received.

- The strength of the signal received is proportional to the size of the XY component. As MXY dephases to a zero net value, the MR signal is reduced to zero. This decreasing MR signal, which is received after an RF pulse, is called a free induction decay (FID).

- The free induction decay is the primary MR signal. When the net magnetization vector is at equilibrium, there is no signal. The effect of the 90° RF pulse is to rotate the net magnetization vector onto the XY plane. At this point the signal decays exponentially. An oscillating MR signal is received from off-resonance spins, but the different frequencies in the XY component to the net magnetization vector begin to interfere with each other until there is no signal (see Figure 4-10).

- The oscillation of the signal is at the same frequency as the rotation of Mxy, namely, the Larmor frequency. As the net magnetization returns to equilibrium, the already dephased XY component shrinks concurrently, and the Z component increases.

- When MXY relaxes to zero, the MR signal is again zero. This sequence of events is shown in Figure 4-9 and, when repeated many times, constitutes the simplest MRI RF pulse sequence, which is called saturation recovery

Radiofrequency Pulse Diagrams

- In the macroscopic world, two events occur during an MRI sequence. First, an RF pulse, for example, a 90º RF pulse, is transmitted into the patient. The transmitted RF pulse is symbolized as RFt.
- Second, an RF signal symbolized as RFs is received from the patient. This signal is the FID, and these two events are diagrammed in Figure 4-11.
- There are two lines of information on the diagram. The horizontal axis in both cases is time. The top line, or RFt, is the RF signal transmitted into the patient. The bottom line, or RFs, is the FID, the MR signal received from the RF pulses transmitted into the patient are usually indicated on the RFt line by several ovals , as shown on the top line.

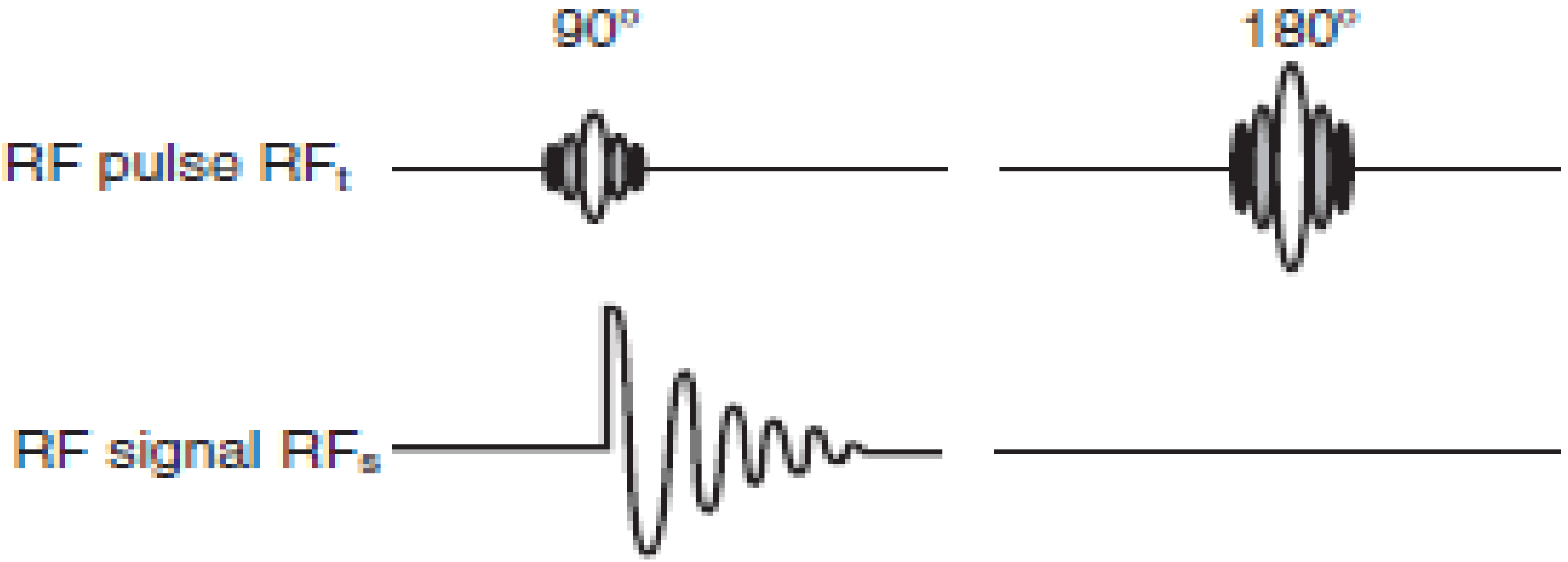

FIGURE 4-11 Simple radiofrequency (RF) pulse diagrams for a 90° and a 180° RF pulse. The top line represents the transmitted RF pulse (RF_t), and the bottom line represents the RF signal received (RF_s).

- The label above the smaller pulse indicates that it is a 90° RF pulse, and the label above the larger pulse indicates that it is a 180° RF pulse. After a 180° RF pulse, There is no FID because there is no XY component to the net magnetization.
- The signal from the patient is indicated by a plot of the intensity of the signal versus time. For the simple case given here, the diagram is correspondingly simple. In more complicated situations involving many pulses and signals, such diagrams are complicated but can be extremely descriptive.
- Additional lines are added to indicate excitation of the gradient magnetic fields necessary for spatial localization of the RFs. For now, it is sufficient to become familiar with this simple two line form of an RF pulse diagram. What about the amplitude and shape of the FID? The amplitude of the FID is equal to the amplitude of M_Z at the start of the RF pulse sequence.
- This amplitude is often equal to and always dependent on M_0, the equilibrium value. Therefore the amplitude of the FID is determined by the same parameters that influence M0, namely, the number of spins involved (the proton density), B0, and γ.