Lecture #5: Steady-State and advanced MRI Sequences

Louis Bouchard, Ph.D.
Assistant Professor
Department of Chemistry and Biochemistry
Member, BME IDP, CNSI
University of California, Los Angeles

This lecture and all of the figures presented are from the following paper:

The following paper is also a useful reference for steady-state MRI sequences:

This paper is more mathematical:

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Gradient-echo Sequences

RF-spoiled residual TM (eg. FLASH/SPGR/T1 FFE) → Residual TM refocused leading to steady state of TM and LM (eg. steady-state sequences)

Figure 1. Chart illustrates the two types of GRE sequences. **FLASH** = fast low-angle shot (Siemens Medical Systems, Erlangen, Germany), **SPGR** = spoiled gradient-recalled echo (GE Medical Systems, Milwaukee, Wis), **FFE** = fast field echo (Philips Medical Systems, Best, the Netherlands).

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Figure 2. Graphs show steady-state formation in GRE pulse sequences. In A, magnetization before application of an RF excitation pulse is shown. In B, the RF pulse tips the magnetization by 0°. In C, the resulting tipped magnetization has an LM that recovers and a TM that decays during the TR period. As seen in D, during the TR period, the TM can precess through a 180° phase shift in the transverse plane. In E, the succeeding RF pulse simultaneously tips a component of residual TM back along the +Z axis and a portion of LM into the transverse plane. In F, after several TR periods, this feeding of LM into TM and vice versa establishes a steady state of both LM and TM.
**Figure 3.** Signals produced in steady state. Once the steady equilibrium of LM and TM is reached, two types of signals are produced: The first signal is free induction decay (FID) \(S^+\), which is formed after excitation with the most recent RF pulse. The second component is spin echo (SE \(S^-\)), which is formed when residual echo from the previous RF excitation is refocused by the current RF pulse. \(\alpha\) = flip angle.

**Figure 4.** GRE sequences. \(\alpha\) = flip angle, \(G\) = gradient. (a) Spoiled GRE sequence. After the signal is acquired with reversal of the frequency-encoding (readout) gradient, residual TM is depolarized with a spoiler gradient so that it does not interfere with the next RF excitation. (b) Postexcitation refocused steady-state sequence. With this se-

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**Postexcitation Refocused Steady-State Sequence**

it does not interfere with the next RF excitation. (b) Postexcitation refocused steady-state sequence. With this sequence, instead of spoiling, residual TM is refocused with a gradient along the phase-encoding axis (phase reverter) such that a steady state of TM is achieved after a few TR periods. The difference in contrast between this sequence and a spoiled GRE sequence (a) is manifested only when TR is less than \(T_2\) and large flip angles are used. Slice-selection and readout gradients are not balanced. (c) Preexcitation refocused steady-state sequence. Time reversal

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**Preeception Refocused Steady-State Sequence**

selection and readout gradients are not balanced. (c) Preexcitation refocused steady-state sequence. Time reversal of both slice-selection and readout gradients (a,b) is done in this sequence, which consequently is called "bombed RSVP" by Siemens. As with a postexcitation refocused steady-state sequence, slice-selection and readout gradients are not balanced. TE is longer than TR, since the signal of the current RF excitation is refocused at the time of the subsequent excitation. (d) Fully refocused steady-state sequence. Gradients along all three axes (slice-selection,
Table 1: Features of Major GRE Sequences

<table>
<thead>
<tr>
<th>Feature</th>
<th>Steady-State Sequences</th>
<th>Preexcitation Refocused</th>
<th>Preexcitation Refocused</th>
<th>Fully Refocused</th>
</tr>
</thead>
<tbody>
<tr>
<td>Signal in</td>
<td>T1</td>
<td>T2*</td>
<td>T2 (n-1)</td>
<td>T2*</td>
</tr>
<tr>
<td>Refocusing</td>
<td>Phase-encoding</td>
<td>Phase-encoding</td>
<td>Phase-encoding</td>
<td>n-1</td>
</tr>
<tr>
<td>Image</td>
<td>T1</td>
<td>T2*</td>
<td>T2</td>
<td></td>
</tr>
<tr>
<td>Pulsing</td>
<td>Bright</td>
<td>Dark</td>
<td>Dark</td>
<td>Bright</td>
</tr>
<tr>
<td>Motion sensitivity</td>
<td>Sensitive due to long TE and acquisition window</td>
<td>Sensitive due to long TE and acquisition window</td>
<td>Sensitive due to long TE and acquisition window</td>
<td></td>
</tr>
<tr>
<td>Artifacts</td>
<td>Susceptibility</td>
<td>Movement, flow, susceptibility</td>
<td>Movement, flow, susceptibility</td>
<td>Movement, flow, susceptibility</td>
</tr>
<tr>
<td>Advantages</td>
<td>T2-weighted images are obtained</td>
<td>True T2-weighted images can be obtained</td>
<td>True T2-weighted images can be obtained</td>
<td></td>
</tr>
<tr>
<td>Major applications</td>
<td>Cartilage and meniscal evaluation, MR angiography</td>
<td>Cartilage and meniscal evaluation, MR angiography</td>
<td>Cartilage and meniscal evaluation, MR angiography</td>
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</table>

Figure 5. Natures of GRE sequences. (a) An axial 3D SPGR image (postexcitation refocused) shows the normal anatomy and various tissue interfaces. (b) A sagittal 3D GRE image shows the normal anatomy and various tissue interfaces. (c) A coronal 3D GRE image (preexcitation refocused) shows the normal anatomy and various tissue interfaces. (d) An axial 3D GRE image (postexcitation refocused) shows the normal anatomy and various tissue interfaces. (e) An axial 3D GRE image (preexcitation refocused) shows the normal anatomy and various tissue interfaces. (f) An axial 3D GRE image (postexcitation refocused) shows the normal anatomy and various tissue interfaces. (g) An axial 3D GRE image (preexcitation refocused) shows the normal anatomy and various tissue interfaces. (h) An axial 3D GRE image (postexcitation refocused) shows the normal anatomy and various tissue interfaces. (i) An axial 3D GRE image (preexcitation refocused) shows the normal anatomy and various tissue interfaces. 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(kk) An axial 3D GRE image (preexcitation refocused) shows the normal anatomy and various tissue interfaces. (ll) An axial 3D GRE image (postexcitation refocused) shows the normal anatomy and various tissue interfaces. (mm) An axial 3D GRE image (preexcitation refocused) shows the normal anatomy and various tissue interfaces. (nn) An axial 3D GRE image (postexcitation refocused) shows the normal anatomy and various tissue interfaces. (oo) An axial 3D GRE image (preexcitation refocused) shows the normal anatomy and various tissue interfaces. (pp) An axial 3D GRE image (postexcitation refocused) shows the normal anatomy and various tissue interfaces. (qq) An axial 3D GRE image (preexcitation refocused) shows the normal anatomy and various tissue interfaces. (rr) An axial 3D GRE image (postexcitation refocused) shows the normal anatomy and various tissue interfaces. (ss) An axial 3D GRE image (preexcitation refocused) shows the normal anatomy and various tissue interfaces. 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Table 2
Manufacturers’ Nomenclature for Major GRE Sequences

<table>
<thead>
<tr>
<th>Manufacturer</th>
<th>SpOiled GRE</th>
<th>Postrecitation Refocusedb</th>
<th>Precitation Refocusedb</th>
<th>Fully Refocusedb</th>
</tr>
</thead>
<tbody>
<tr>
<td>Siemens</td>
<td>FLASH</td>
<td>FISP</td>
<td>PSIF (reversed FISP)</td>
<td>True FISP</td>
</tr>
<tr>
<td>GE Medical Systems</td>
<td>SPGR, MPGR</td>
<td>GRASS, fast MPGR</td>
<td>SSFP</td>
<td>FIESTA</td>
</tr>
<tr>
<td>Philips</td>
<td>T1-FFE</td>
<td>FFE</td>
<td>T2-FFE</td>
<td>Balanced FFE</td>
</tr>
</tbody>
</table>

Sources.—References 1, 13, and 15.
Note.—FFE = fast field echo, FIESTA = fast imaging employing steady-state acquisition, FISP = fast imaging with steady-state precession, FLASH = fast low-angle shot, GRASS = gradient-recalled acquisition in the steady state, MPGR = multiplanar gradient-recalled, SPGR = spoiled gradient-recalled, SSFP = steady-state free precession.

*Steady-state sequence.

Figure 6. Joint imaging with a fast MPGR sequence in a 14-year-old girl who was undergoing steroid treatment for systemic lupus erythematosus. On sagittal (a) and coronal (b) fast MPGR images (postrecitation refocused steady-state sequence) of the elbow, changes of avascular necrosis are seen, with a large osteochondral defect (arrow) in the anterior part of the capitellum. Articular cartilage is seen as a bright structure surrounding the articular surface of bones (arrowheads in a).

Figure 7. Cardiac imaging with a true FISP sequence. True FISP images (two-chamber [a] and four-chamber [b] views) show the normal cardiac anatomy. Dark myocardium (arrowheads) and valve leaflets (arrow in b) are well appreciated against a background of bright blood. Atr = aorta, IVS = interventricular septum, LA = left atrium, LV = left ventricle, RA = right atrium, RV = right ventricle.

Figure 8. Assessment of myocardial viability. True FISP image (short-axis view) obtained 10 minutes after contrast material injection shows delayed enhancement in the interventricular (arrow) and inferoseptal (arrowheads) left ventricular wall, findings that are suggestive of nonviable myocardium. Because bright areas represent nonviable myocardium, it is said that “bright is dead” at viability imaging. Cardiac MR imaging has arguably become the new standard for the assessment of myocardial viability and scar. LV = left ventricle, RV = right ventricle.
Figure 9. Congenital heart disease in a 3-year-old boy. Axial FIESTA images obtained at the supracarinal (a) and carinal (b) levels show the left superior vena cava (SVC) opening into the coronary sinus. The patient also had interruption of the supracarinal inferior vena cava withzygous continuation. Pulmonary stenosis is seen as a bright jet in the main pulmonary artery (MPA). A = artery, Ac: Ao = ascending aorta, Di: Ao = descending aorta, LA = left atrium, LM = left pulmonary artery, RM = right pulmonary artery.

Figure 10. Cardiac valvular disease. True FIESTA image (four-chamber view) shows stenosis of the mitral valve with a jet (arrow) in the left ventricle (LV). The left atrium (LA) is dilated. Di: Ao = descending aorta, IVS = interventricular septum, RA = right atrium, RV = right ventricle.

Figure 11. Abdominal imaging with a balanced SSFP sequence. On a coronal true FISP image of the abdomen, the vessels and biliary system are bright. Note the calculus (arrow) in the neck of the distended gallbladder (GB), with prominence of the common bile duct (arrowhead) lateral to the portal vein (PV). Note also the movement artifact-free definition of the abdominal organs.

Figure 12. Fetal MR imaging with a FIESTA sequence. Static image shows a fetus in a sagittal orientation. Cine FIESTA sequences of the gravid uterus are used to study fetal movements.
Figure 13. Cranial nerve imaging with CISS. Axial CISS image of the posterior cranial fossa shows a normal facial nerve and eighth cranial nerve (VIII CN) and internal ear structures such as the cochlea and lateral semicircular canal (SCC).

Figure 14. Internal ear imaging with a 3D FIESTA-C sequence. Bilateral (a) and left-sided (b) maximum-intensity-projection images from 3D FIESTA-C data show the normal vestibule and cochlea. Post = posterior, SCC = semicircular canal.

Figure 15. Articular cartilage imaging with DESS in a 49-year-old woman with early signs of osteoarthritis. On this coronal DESS image of the left knee joint, articular cartilage is seen as an intermediate-signal-intensity line covering articular surfaces of bone in the lateral compartment (arrows). Note the loss of articular cartilage with reduction in the joint space in the medial compartment.