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SIGNA APPLICATIONS GUIDE

ECHO PLANAR IMAGING

BY

THOMAS SCHRACK

ADVANCED MR APPLICATIONS

GE MEDICAL SYSTEMS

MILWAUKEE, WI

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ACKNOWLEDGMENTS

The author would like to thank the many people who aided in the development and ultimate creation of this applications/users guide. Their help, patience, and guidance were crucial in answering the many questions and providing suggestions and comments.

Specific Thanks to:

Joe Maier, MS;
Fred Epstein, Ph.D.;
David Weber, Ph.D.;
Dick Prorok;
Linda Loehrer;
Tom McMahon; and
Susan Rock

The following institutions graciously provided images:

Waukesha Memorial Hospital – Waukesha, WI
St. Luke's Medical Center – Milwaukee, WI
St. Joseph's Hospital – Milwaukee, WI
St. Mary Corwin Hospital – Pueblo, CO
Universitätsspital Zürich – Zürich, Switzerland
The Mayo Clinic – Rochester, MN

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FOREWORD

This document is meant to be a complement to the primers *Echo Planar Imaging*, Weber, D. and *Echo Planar Imaging: Principles and Applications*, Weber, D. and Schrack, T. as well as *Introduction to Fast-Scan MR*, Wehrli, F. and *Applications Guide Volume Four*, Prorok, R. and Sawyer, A.

The acronym “EPI” has been mentioned in MR literature for some time now. For the most part, discussions of EPI (Echo Planar Imaging) have centered around dedicated research and very specific clinical applications, some of which are not yet used in routine clinical practice without the benefit of on-site physicists and research scientists. However, GE Medical Systems brings EPI to the forefront by making

it a clinical reality for most Signa users regardless of field strength and gradient configuration. The EPI sequence is remarkably flexible and easy to use. One button on the *Imaging Parameters* screen takes the user from a standard Spin Echo or Gradient Echo to a SE-EPI, GRE-EPI, or an IR-Prep EPI. The user is not limited to a single plane of acquisition, FOV, or resolution. The user is free to make whatever choices are compatible. However, with greater flexibility comes greater responsibility. Choosing the wrong parameters, like any pulse sequence, can mean images that are less than diagnostic. If ever there was a pulse sequence that required careful parameter selection, it is EPI. It can be the most unforgiving of pulse sequences.

While EPI brings to mind ultra fast imaging, it is NOT solely about speed. It is often about contrast as well. Used effectively, EPI will yield images with excellent contrast and resolution, both spatially and temporally. It can also provide images in times far shorter than any pulse sequence offered to date. Depending on field and gradient strength, sharp, clear images can be obtained even while a patient moves and breathes. Multi-phase cardiac images can be obtained with or without any gating. Getting these images, however, requires a full and complete understanding of the EPI pulse sequence.

This book is designed to serve two principle functions: **1** To provide the prospective user with an overview of the flexibility and utility of the EPI pulse sequence as implemented by GE Medical Systems; and **2** To provide the

user with a practical guide for using EPI in the clinical setting. To accomplish these two objectives, the guide provides a review of the principles of EPI, gives a detailed explanation of the set-up of the sequence on the Signa MR system, and lists suggested protocols for various anatomical regions. Again you should note that EPI is a sequence made available on most Signa systems across many field strengths and gradient configurations. Where possible, the suggested protocols are modified to account for this. However, with many possible combinations of field and gradient strength, it is not practical to list all possible protocol variations. The local GE Field Applications Specialists and Applications Support Specialists can provide more tailored protocols for a given system configuration.

REVIEWING THE BASICS

To understand fully the processes that make EPI a unique imaging sequence, it is useful to review some basics. By reviewing the concepts of *k*-space, gradient echo generation, and the Fast Spin Echo sequence, the reader gains perspective in understanding EPI as well. In fact, a careful look at these concepts reveals that the EPI sequence contains elements of all three and that understanding these basic

concepts makes understanding EPI far simpler. Note that this chapter is meant to serve as a basic review and is not intended to be a complete explanation of these three concepts. The review here goes over only the characteristics that will help in the understanding of EPI. For a more thorough and detailed review of these topics, suggested reading is provided at the end of each section.

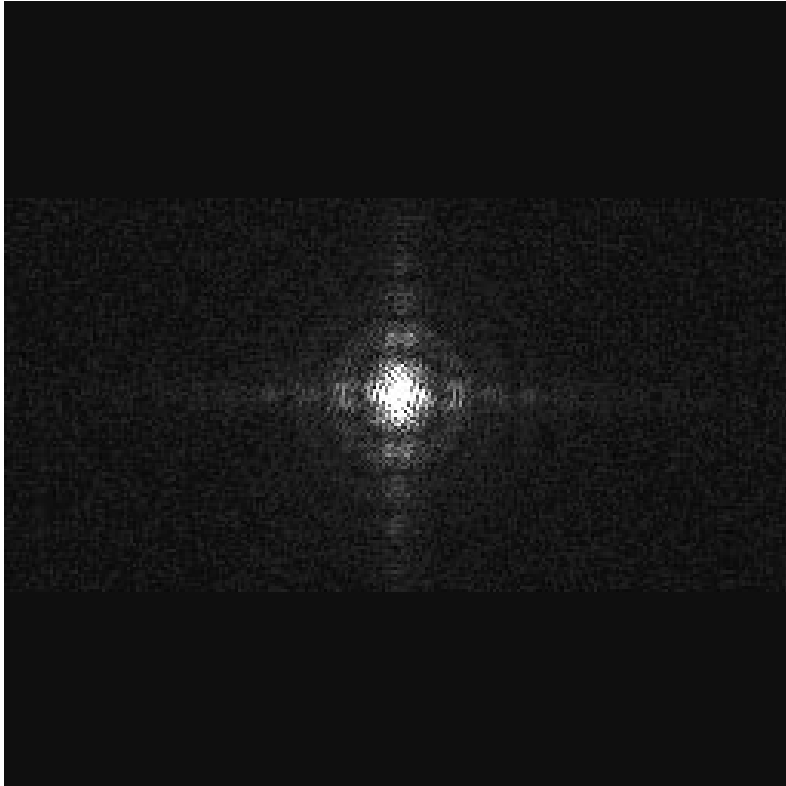


Figure 1: Raw data. Data that are acquired prior to undergoing Fourier Transform.

K-SPACE

“K-space” is a term that is mentioned often when referring to many pulse sequences, including EPI. In simple terms, k-space is the place which contains the raw MR data, that is, the data which is acquired by the pulse sequence which, after undergoing Fourier Transform, becomes the image. Each line of k-space is acquired under the frequency encoding (or readout) gradient and corresponds to one value of the phase encoding gradient.

The method in which k-space is filled has a direct effect on the image appearance. In a standard spin echo

sequence, for example, one line of k-space is filled for every TR period. One phase encoding step is executed followed by frequency readout, then one line of k-space is filled. K-space, for most standard sequences, is from the top down (figure 2). For a SE sequence that requires 256 phase encoding steps, the TR must be repeated 256 times for each image, one line of k-space for each phase encoding step. The k-space for a standard SE sequence is also filled in a sequential manner, meaning that the lines are filled left to right and top to bottom.

The amplitude of the phase encoding gradient is a determinant of the strength of the signal “echoed” back. The middle lines of k-space in any sequence, for example, have the lowest phase encoding gradient amplitude, dephasing the signal the least and therefore producing the strongest signal. The higher amplitude encoding steps, while producing little signal, provide spatial information about the image. Simply put, the more phase encoding steps, the sharper the image. Remember, the position of information within k-space does not correspond to the spatial position in the image; the information in the upper-right corner of k-space does not represent the upper-right corner of the image. Each line of k-space contains information about the whole image.

To have enough information to create and display a useful image, a certain amount of k-space filling is required. Generally at least 65% of available k-space must be filled. For most standard imaging, all of k-space is filled. We refer to this as one excitation or “1 NEX.” When only partial k-space has been filled, we refer to this as “partial NEX” usually annotated .75 or .5 NEX. Where scan time is defined as $TR \times NEX \times \text{Phase encoding steps}$, total scan time is reduced at the cost of SNR (since fewer lines of k-space are filled).

- For a more detailed discussion of k-space refer to the GE Medical Systems *Signa Applications Guide, Volume Four*.

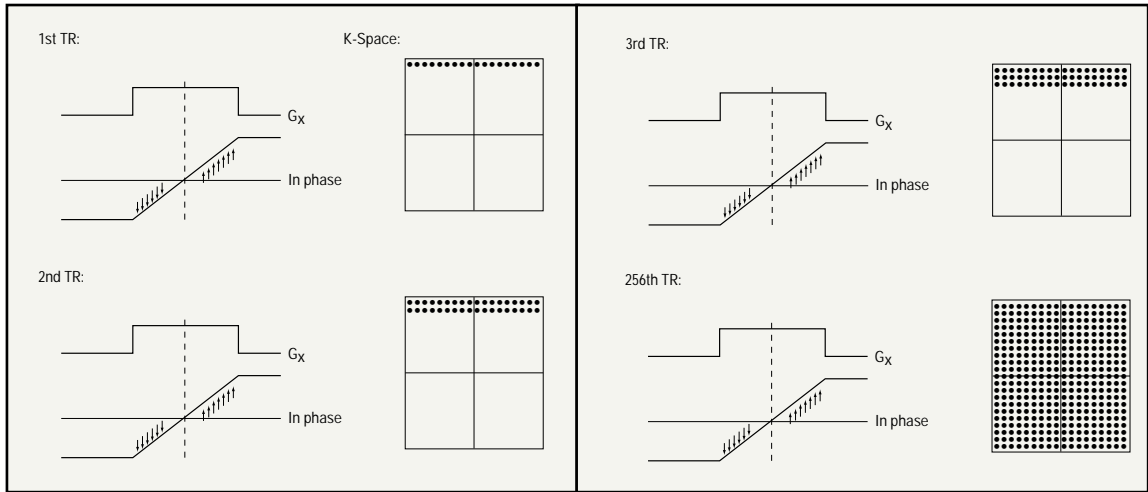


Figure 2: A specific number of samples of the echo is taken while the frequency encoding gradient is applied. As a result, in traditional spin echo and gradient echo sequences, one line of k-space is generally completed per TR.

POINTS TO REMEMBER

- In a standard pulse sequence, a single phase encoding fills one line of k-space.
- K-space does not have to be completely filled to produce an image.
- How k-space is filled has a direct effect on the appearance of the image.

GRADIENT ECHO IMAGING

As mentioned earlier, when collecting the required data to create an image, the standard spin echo pulse sequence fills one line of k-space per TR and that TR must be repeated for each phase encoding step. When TRs reach 2 seconds, scan times become relatively long, approximately 8 minutes or longer. A method of producing contrast in much shorter times is to drastically reduce the TR and generate the required echo using a gradient reversals rather than a 180 degree RF refocusing pulse (figure 3). By applying the frequency (readout) gradient with negative polarity, the spins are initially dephased immediately following excitation. The gradient is then reversed, rephasing the spins into an echo at the center of the readout window at the time of the TE.

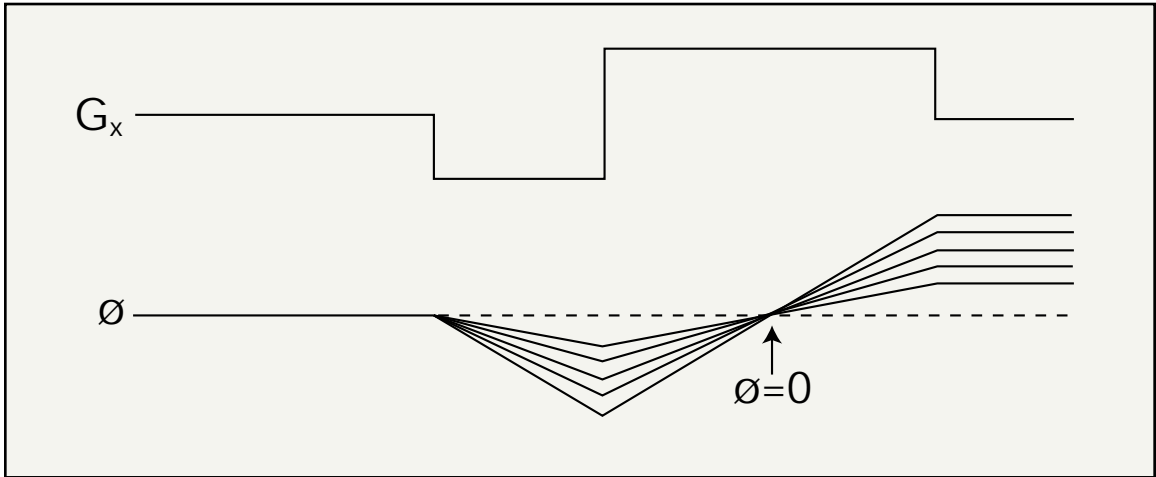


Figure 3: Principle of gradient echo. During the period of the dephasing lobe of the readout gradient, the spins lose phase which they gain back after sign reversal of the readout gradient. During this period, the signal is sampled. Note that all spins are back in phase at the center of the readout gradient.

Because a gradient can be applied faster than an RF pulse, gradient reversal can refocus a spin faster than applying an RF pulse. Hence the TR of a gradient echo pulse sequence can also be shortened reducing scan time. However, when TRs become shorter than the tissue T1, tissue saturation builds up quickly. If insufficient time is given for longitudinal relaxation (T1 relaxation), the longitudinal magnetization of the spins remains small and therefore little signal is produced in the refocused echo. To reduce the saturation effects, the flip angle of the excitation pulse is reduced with the TR. The flip angle chosen has a direct effect on the image contrast. All factors remaining the same, low flip angles favor proton density weighting; higher flip angles favor T1 contrast for short T1 tissues like fat, and T2* for long T2 tissues like cerebral spinal fluid. (In all instances, increasing the TE increases

T2* effects.) Also because there are far fewer RF pulses being utilized in a gradient echo sequence, the amount of heat build-up in the body, or Specific Absorption Rate (SAR), is reduced allowing for more slices per TR.

It is important to note, however, that the T2 information produced in a spin echo sequence is not the same as that produced in a gradient echo sequence. What is actually being rephased into an echo is different for the two. In a spin echo sequence, the 180 degree RF pulses correct for dephasing caused by extrinsic effects which disrupt the local magnetic field. For example, chemical shift and local field inhomogeneities. These effects cause dephasing termed T2' (prime). "True" T2 is dephasing that is intrinsic to the molecular environment of the spin. The combination of T2 and T2' yield T2*(star) contrast.

On a relative scale, spin echo sequences produce images that have little $T2^*$ contrast. On the other hand, gradient echoes do not correct for $T2'$ and thus the contrast produced (in the long TE exam) is $T2^*$. Because the $T2^*$ of a tissue is always shorter than its $T2$, the TE needed to produce the similar effect is usually shorter in a gradient echo sequence versus a spin echo.

The rapid dephasing caused by $T2^*$ effects is exacerbated in areas where there are marked changes in magnetic susceptibility. Magnetic susceptibility is

defined as the degree to which a tissue becomes magnetized. A large magnetic susceptibility is found in the water-filled tissues. Areas of low magnetic susceptibility are found in such areas as air and compact bone. When these regions of high and low susceptibility are adjacent to one another a great variation, or gradient, in magnetic field causes the spins along the boundary to dephase rapidly. Note the dephased areas in the gradient echo images compared to the same area in a spin echo image (figure 4).

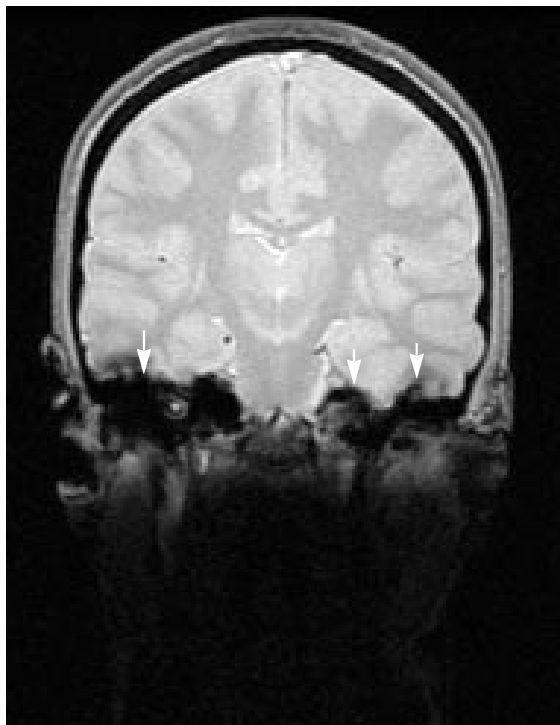


Figure 4: Figure A is a coronal spin echo image in the region of the IACs. Figure B is the same region only acquired using a gradient echo sequence. Note the areas of dephasing around the petrous ridges and the air-filled sinuses due to T2* effects.

POINTS TO REMEMBER

- Gradient echoes can be produced much faster than RF refocused echoes.
- Gradient echo pulse sequences produce less SAR and therefore allow more slices per TR.
- Gradient echo images generally have more T2* contrast than their spin echo counterparts.
- Gradient echo images are sensitive to susceptibility effects such as those near tissue-air interfaces.

- For more information on gradient echo imaging, refer to GE Medical Systems booklet: *Introduction to Fast MR*.

FAST SPIN ECHO

Fast Spin Echo is an imaging technique that is designed to make imaging much faster, as compared to standard spin echo, by acquiring more than one line of k-space per TR. To understand Fast Spin Echo, think back to the standard spin echo and think of a series where four echoes are selected instead of one. In this sequence four 180 degree RF refocusing pulses are played out. The phase encoding gradient is still applied only once and the data from each echo (TE1, TE2, TE3, and TE4) are placed in four separate k-spaces producing four separate images.

Typical scan times for T2-weighted images are relatively long for these sequences. For example, a series with a 2000msec TR, 256 phase encoding steps, and 1 NEX would take approximately 8 1/2 minutes. However, if a

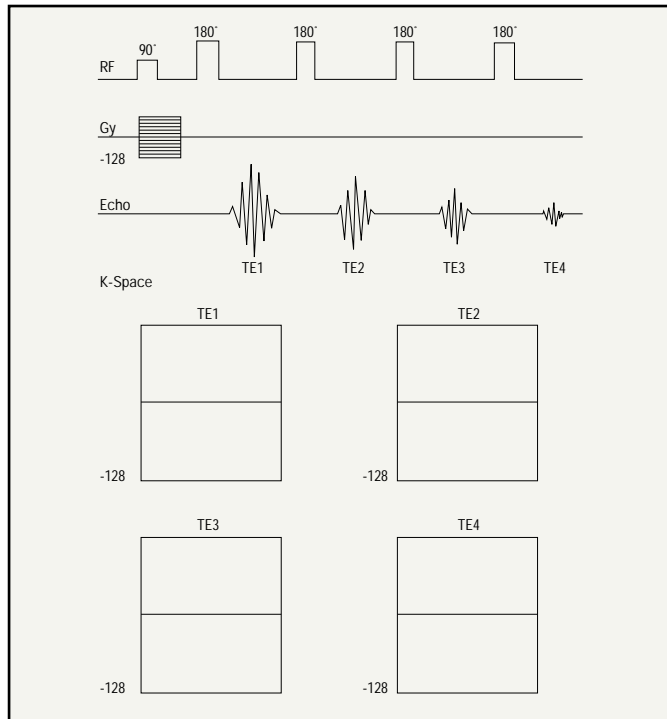


Figure 5: Traditional MEMP and VEMP sequence complete one phase encoding (line of k-space) per TR. The number of phase encodings selected determines the number of times it is necessary to repeat the MR experiment (TR).

different phase encoding gradient was played out for each echo instead of once for each TR, then four lines of k-space would be filled requiring the TR to be repeated only 64 times instead of 256. This reduces the scan time four-fold to just more than 2 minutes. Of course only one image is obtained instead of four. In essence, the data that creates 4 images is used instead to create one image, only four times faster. In a Fast Spin Echo scan, the more echoes selected the fewer times the TR needs to be repeated and the more the scan time is decreased.

In a FSE sequence, the number of echoes selected is referred to as the **echo train length** and the distance in time between each echo is the **echo spacing**. Because the image contains information from all the echoes the TE is referred to as an **effective TE**. The effective TE is obtained by varying the

phase encoding gradient in such a way that the middle phase encoding steps, and therefore the middle lines of k-space and greatest SNR, are collected “around” the selected TE.

The image displays contrast closest to that of the selected TE since the middle phase encoding steps occur at or near the same time with regard to TE. Remember that the echoes are acquired while T2 decay is occurring and therefore each line of k-space yields a different amount of T2 decay. This variation in signal information undergoes Fourier Transform which results in blurring of the image. The amount of blurring typically worsens when the TE is short. This is due to the middle lines of k-space being collected during the most rapid period of T2 decay and thus the greatest variation in T2 information within k-space. Also, the longer the ETL the longer it

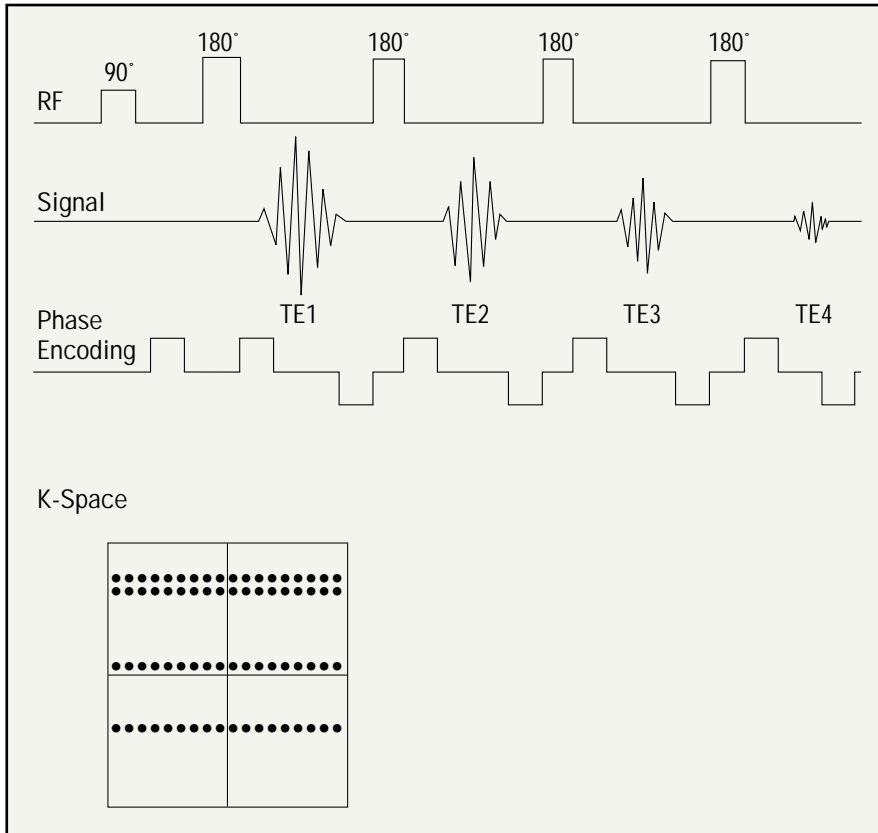


Figure 6: FSE sequence. Echo train of 4 fills four lines of k-space.

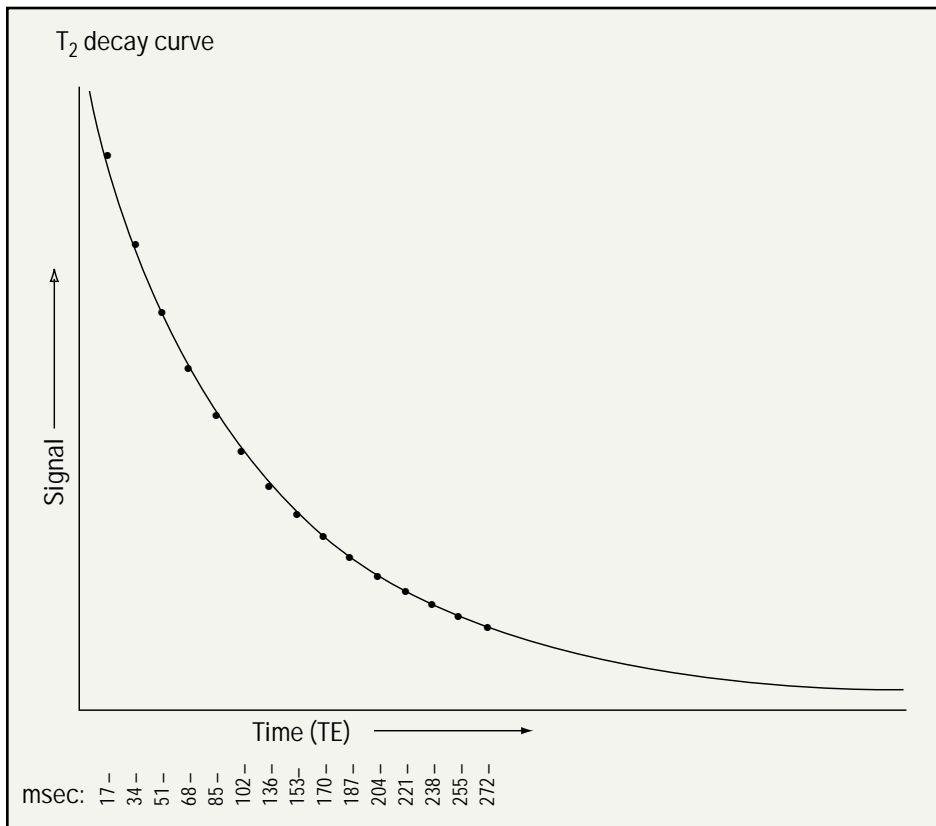


Figure 7: T₂ decay variation in FSE.

takes to collect the phase encoding data within the TR. The longer the ETL, the greater the T2 variation.

Note in figure 7 that if the effective TE had been shorter, then the T2 variation between the middle phase encoding steps would be large and contribute highly to image blurring. However, if the effective TE had been longer and the middle lines of k-space were collected during the less rapid descent of the decay curve, the T2 variation would have been far less and therefore the image blurring would also be less.

The amount of magnetic susceptibility effects in the image is also greatly influenced by the series of 180 degree RF pulses. A single 180 degree RF refocusing pulse corrects for dephasing caused by T2' effects. The degree of correction is dependent on the time from the refocusing pulse to the TE time (τ). In FSE, this time is short

thus inhibiting decay from T2' effects. This makes FSE relatively insensitive to magnetic susceptibility effects regardless of effective TE.

The number of slices per TR is also greatly affected by the ETL. If, for example, an ETL of 12 and a TR of 2000msecs permits 10 slices per TR, increasing the ETL to 24 will permit only 5. This occurs simply because the extra 10 RF pulses in the echo train use time within the TR, leaving little time to acquire more slices. The increase in RF pulses also increases SAR which contributes to this decrease in slice availability. So while the scan will take half the time, it also yields half the slices. If more than the 10 slices are needed for anatomical coverage than a second acquisition will be required. Figure 8 illustrates an example of a FSE sequence with a 4 ETL and one with a 6 ETL and the resultant loss in slice availability within a given TR period.

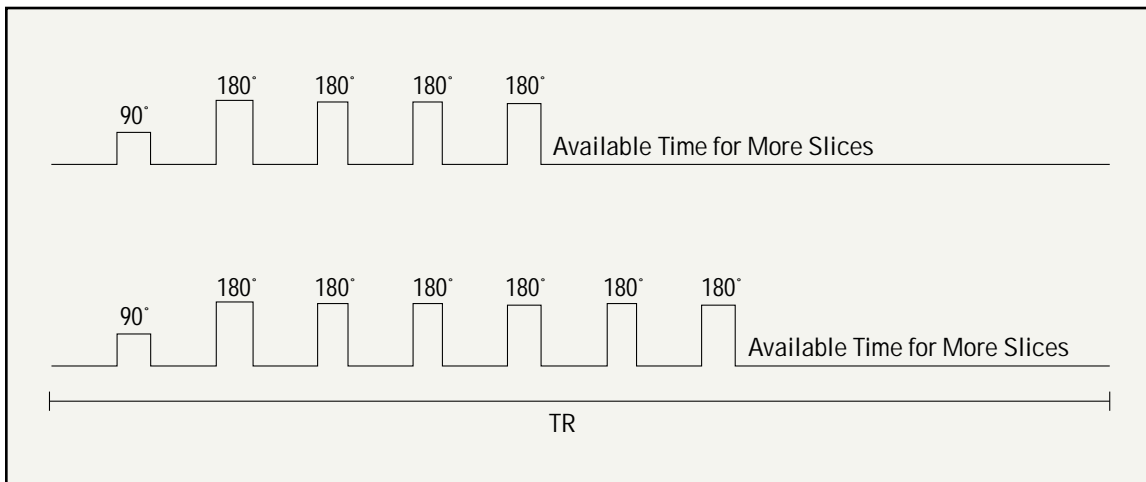


Figure 8: Echo train length effects on available slices per TR.

POINTS TO REMEMBER

- FSE uses a method of collecting more than one line of k-space per TR, which reduces scan time compared to standard Spin Echo.
- FSE uses a “train” of RF pulses to produce an equal number of echoes, each of which is phased-encoded using different gradient amplitudes.
- The middle lines of k-space are “centered” around the selected TE; this “effective TE” provides the desired contrast.
- Increases in ETL result in greater differences in the amount of T2 decay between each line of k-space and contribute to image blurring.
- FSE is very effective at reducing T2* effects by correcting for T2' effects.
- Increases in ETL decrease scan time but also decrease slice availability within the TR.

- For a more detailed discussion of Fast Spin Echo imaging refer to the GEMedical Systems *Signa Applications Guide, Volume Four*.

Now that the basics of k-space, gradient echo formation, and Fast Spin Echo are understood, these concepts can be used to explain the basic principles of Echo Planar Imaging. In the section that follows, the points made above serve as a foundation for an overview of EPI.

PUTTING IT ALL TOGETHER

THE EPI PULSE SEQUENCE

This chapter uses the concepts detailed earlier to explain the principles of the EPI pulse sequence. Note that this section is a complement to *Echo Planar Imaging and Echo Planar Imaging: Principles and Applications*. Reviewing these two primers is highly recommended for a complete understanding of the EPI sequence.

THE PULSE SEQUENCE

In the most simple terms, EPI can be thought of as a FSE sequence with a gradient-echo twist. Just like FSE, EPI utilizes an echo train to produce numerous echoes within a TR period to fill k-space rapidly. EPI, however, produces these echoes in a manner very

similar to a standard gradient echo sequence. In viewing a diagram of the EPI sequence, one sees that the beginning, or left side, of the sequence is exactly that of a standard Spin Echo or Gradient Echo sequence. (An EPI sequence can be either a SE-EPI, GRE-EPI, or IR-Prepared.) However, the second, or right side, of the sequence has marked similarities as well as differences to Fast Spin Echo.

Note that instead of a series of 180 degree RF pulses, EPI uses a series of oscillating gradient reversals. The differences between EPI and a standard GRE are: **1** EPI uses more than one gradient echo within a TR; and **2** EPI uses gradients that have both a positive and negative polarity to produce both “odd” and “even”

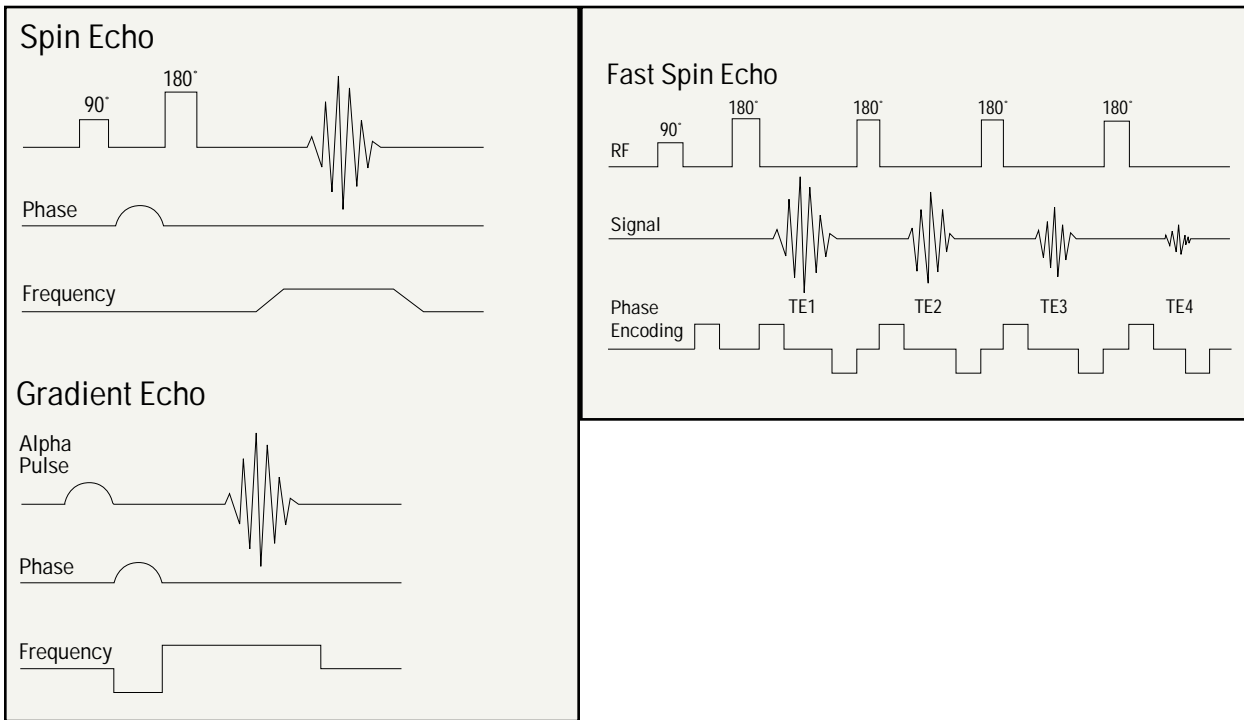


Figure 9A: EPI pulse sequences. Standard Spin Echo, Standard Gradient Echo, Fast Spin Echo sequence with 4 ETL, Spin Echo EPI with a 7 ETL, Gradient Echo EPI with a 7 ETL. Note, EPI echo train is expanded in these illustrations for teaching purposes.

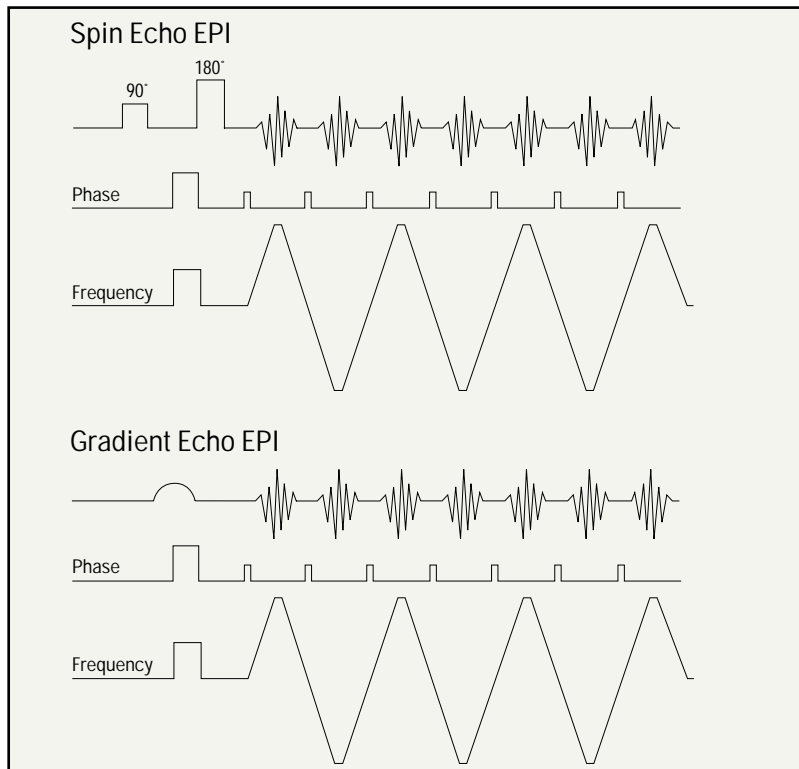


Figure 9B: EPI pulse sequences. Standard Spin Echo, Standard Gradient Echo, Fast Spin Echo sequence with 4 ETL, Spin Echo EPI with a 7 ETL, Gradient Echo EPI with a 7 ETL. Note, EPI echo train is expanded in these illustrations for teaching purposes.

The method in which the k-space is filled is also different for EPI. In standard SE sequences, k-space is filled sequentially and from left to right. After one line of k-space is filled the next line is played out in the same direction. In EPI, however, the lines are filled more efficiently. The k-space collection starts in one direction sweeping continuously from one side to the next. This represents the readout of one of the frequency gradient's oscillations, either in the positive or negative direction. The phase encoding gradient corresponds to the transition from one line to the next. The line is then filled sweeping in the opposite direction and corresponds to the reversed polarity of the next frequency gradient oscillation.

The differences between EPI and FSE can be seen in the echo train. Just as with standard SE vs. GRE, a gradient echo can be produced far faster than a RF spin echo. The same is true for EPI and FSE. A train of gradient echoes takes far less time to play out than a train of RF pulses. It also generates far less SAR. This means that for the same ETL, EPI offers more slices per TR compared to FSE. Moreover, because the gradient echoes can be played out faster, more of them can be utilized within a given TR. This means that for the same number of slices an EPI sequence can be performed much faster than FSE. However, EPI is not without its own hurdles.

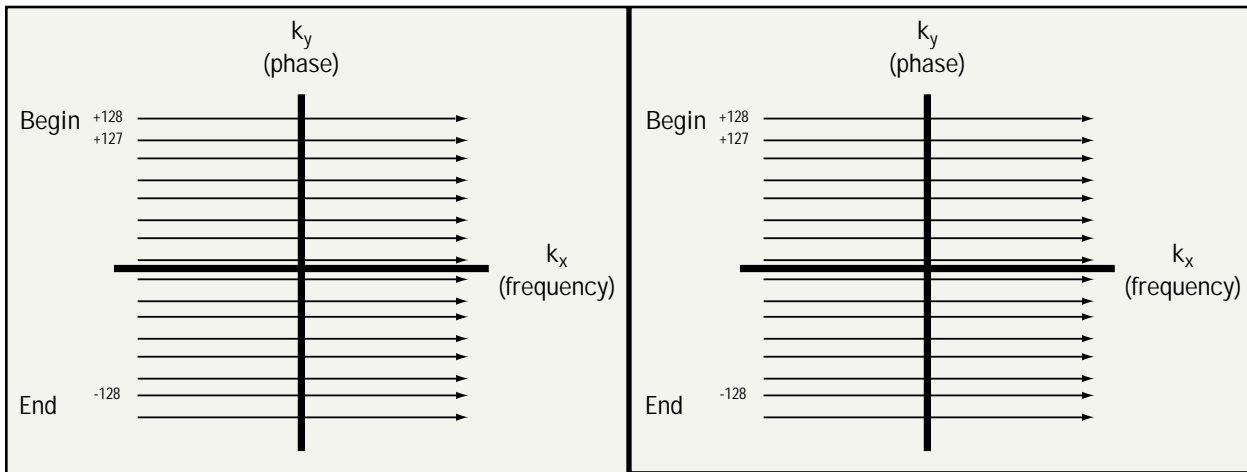


Figure 10: K-space filling in a conventional pulse sequence (left). K-space filling with EPI (right).

Just as a standard GRE is sensitive to magnetic susceptibility effects (also called “off-resonance” effects), EPI, with its series of gradient echoes, is even more susceptible. Two types of off-resonance effects must be dealt with in EPI: ① off-resonance effects of fat spins; and ② off-resonance effects of water spins.

Spins will accumulate a phase shift under the EPI readout gradient. Fat spins, having a precessional frequency 220 Hz (at 1.5T) away from water spins, accumulate a chemical shift-related phase shift equal to 220 Hz x the ETL time. (The ETL time is the time needed to play out the entire echo train in a single TR.) This shift between the fat and water spins can therefore be significant. Furthermore, the chemical shift artifact is seen in the phase direction rather than the frequency direction as with other sequences. Figure 11 shows

2 EPI images: one with no fat suppression, one with fat suppression.

It is because of the chemical shift artifact that EPI images are ALWAYS fat suppressed. The method used for automatically suppressing the fat signal is discussed in more detail later in this document.

Another artifact in EPI deals with off-resonance water protons. As with standard GRE sequences, areas near tissue-air interfaces experience small inhomogeneities in the local magnetic field. Areas with highly magnetized tissues adjacent to areas with low magnetization cause disruptions in the local field. Water protons in these areas consequently accumulate a phase shift. Unfortunately, you cannot simply suppress the water signal as you would the fat, after all, if both water and fat are suppressed there would be

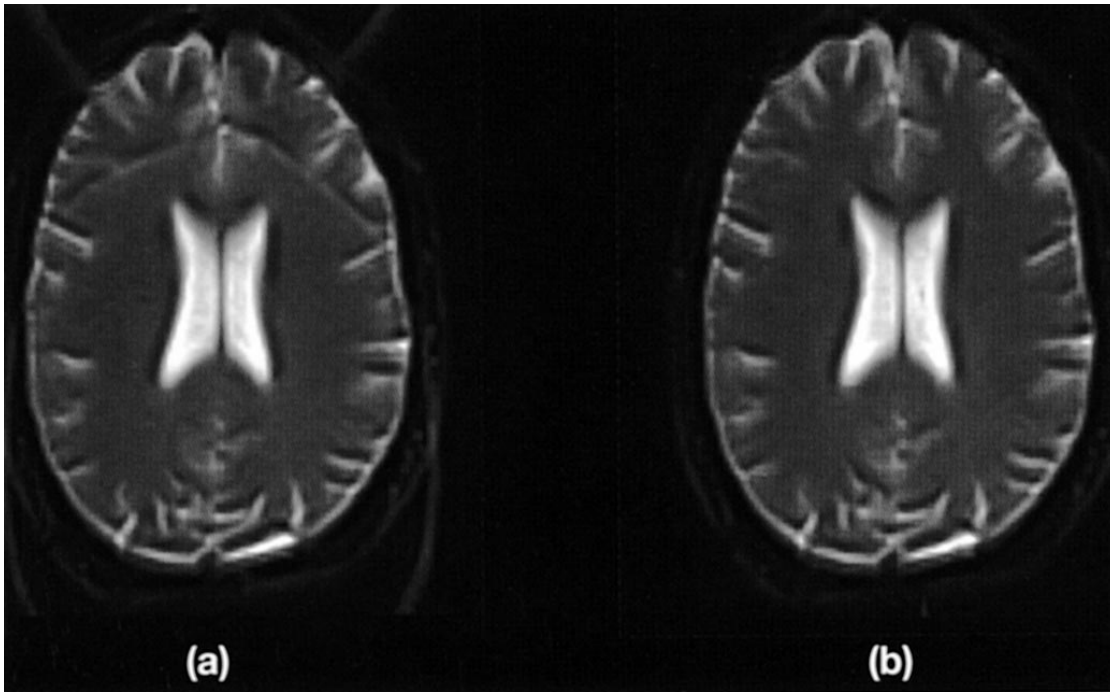


Figure 11: Comparison of (a) an image acquired without any type of fat suppression versus (b) the same EPI acquisition with fat suppression. The subcutaneous fat signal in (a) is shifted approximately 1/4 of the field-of-view, resulting in a significant artifact.

nothing left to produce a signal! These areas of interface will produce a “bending” or distortion in the image. These geometric distortions can be insignificant or completely detrimental depending on the parameters selected and the particular gradient sub-system being used. Figure 12 illustrates an extreme example of geometric distortion.

Keep in mind that geometric distortions can be controlled effectively but never fully erased. Susceptibility effects, and therefore geometric distortions, are a fact of life with EPI. Controlling the amount of distortion is explained in detail in the next chapter.

CONTRAST

The contrast of an echo planar image is “set up” by the particular root sequence selected, SE, GRE or IR-Prep. For example, a SE-EPI will display contrast similar to a standard fat-suppressed SE image with the same TR and TE time. Likewise, a GRE-EPI will produce contrast similar to a standard fat-suppressed GRE with the same TR, TE, and flip angle. As mentioned above, FSE, with its series of 180 degree RF refocusing pulses, is fairly insensitive to T2' effects and yields an image that is strongly T2-weighted (for a long TR, long TE sequence).

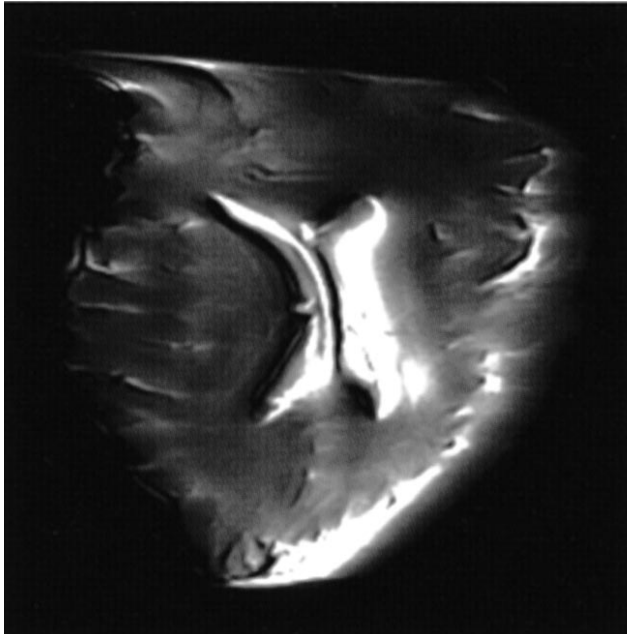


Figure 12: Single-shot EPI image with an echo train length of 256, acquired on a conventional MR scanner (10 mT/m gradient amplitude, 17 T/m/sec gradient slew rate). This extremely long echo train time has allowed the off-resonance water signal at the tissue-to-air interface to accumulate significant phase errors. The result is extensive geometric distortion along the phase encode direction.

This is demonstrated in figure 13 in SE, SE-EPI, and FSE images of the brain. Note the similar contrast characteristics between the SE and SE-EPI image compared to the FSE image. The area of the globus pallidus has much darker contrast on the SE and SE-EPI images due to its inherent iron content. The iron, being naturally ferromagnetic, produces T2' dephasing. The

FSE sequence corrects for much of that dephasing making the globus pallidus much brighter. A SE-EPI is far more sensitive to these T2' effects. Therefore, pathologies and anatomies that cause disruptions in the local magnetic field have a higher potential for contrast visualization on an EPI image. (See figures 14 and 15.)

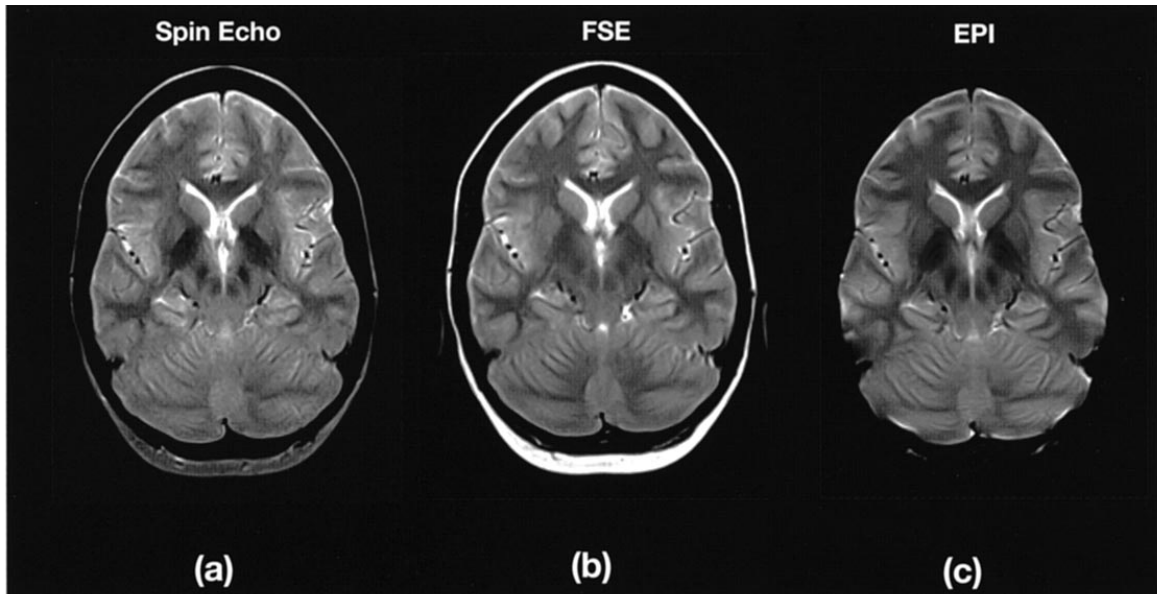


Figure 13: Comparison of oblique-axial images from (a) Spin Echo T2 (TR/TE = 2500/80 msec, 8:30 scan time). (b) FSE T2 (TR/TE = 2500/80, ETL = 12, 3:50 scan time), and (c) EPI T2 (TR/TE = 2500/80, 16 shots, 2:03 scan time).

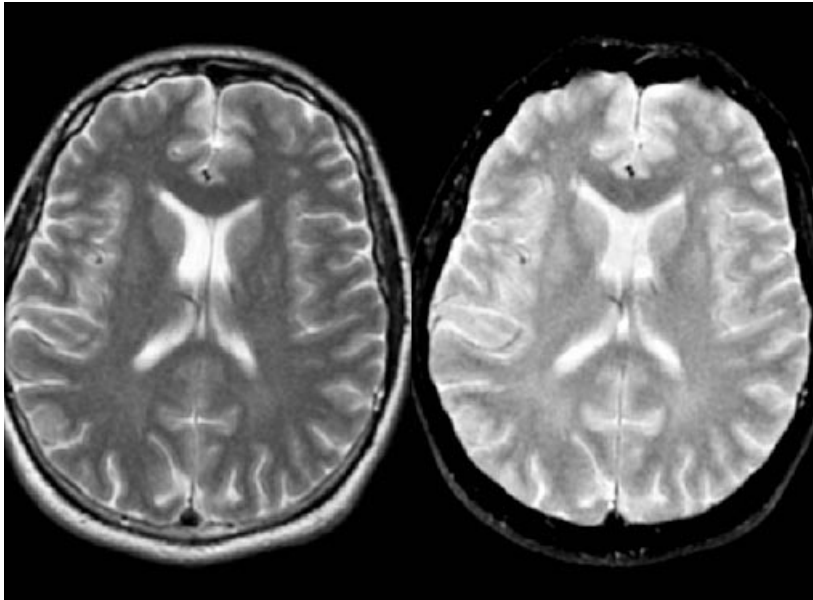


Figure 14: Contrast differences due to susceptibility sensitivity. The image on the left is a FSE (TR: 3000msec, TE: 84msec) while the image on the right is an EPI image (TR:2560msec, TE:80msec). Note that while the parameters are very similar the contrast of the images is different. The EPI image demonstrates more sensitivity to changes in the white matter than the FSE in the anterior aspects of the brain.

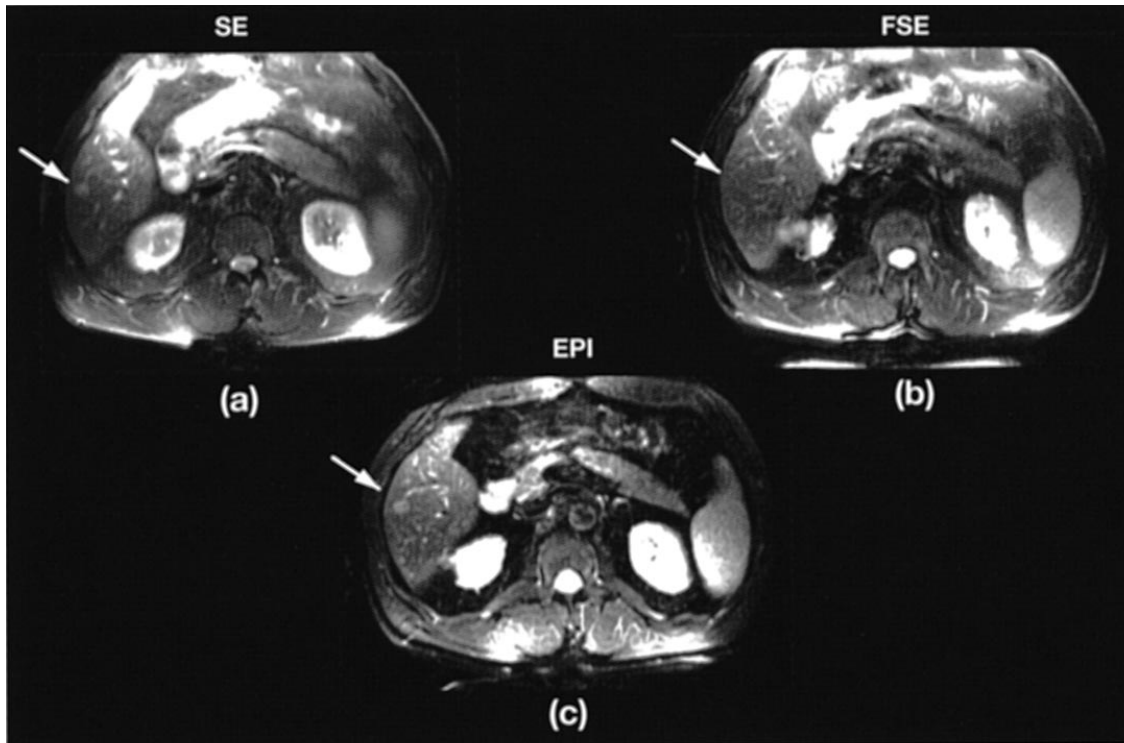


Figure 15: Comparison of a T2-weighted liver exam with (a) Spin Echo, 8 minutes; (b) Fast Spin Echo, 20-second breath-hold; and (c) EPI, 18-second breath-hold.

SIGNAL-TO-NOISE RATIO

EPI images can be inherently low in SNR, due mainly to the wide receive bandwidths used. (The role of bandwidth is discussed in detail later.) Just as with standard GRE, $T2^*$ decay means that tissue dephasing will occur more rapidly than $T2$ alone. However this does not mean that the images produced with EPI must have low SNR. With proper use of surface coils and other parameters such as FOV, TR, TE, NEX, and slice thickness; proper balances of SNR, resolution, and scan time can easily be obtained. At 0.5T, EPI images of high diagnostic quality are possible as evident in the image below. Keep in mind that for the same parameters, EPI may yield less SNR than other pulse sequences.

It should now be clear from the first two chapters that EPI has much in common with other pulse sequences,

and differences as well. The next chapters will explain in more detail the individual characteristics of EPI.

POINTS TO REMEMBER

- Like FSE, EPI collects multiple lines of k-space per TR for decreased scan times.
- Unlike FSE, EPI uses gradient pulses instead of RF pulses to produce echoes.
- Since gradient echoes can be produced faster than RF echoes, EPI can offer greater slice efficiency per TR and greater decreases in scan time.
- EPI is very sensitive to off-resonance effects and thus is ALWAYS fat-suppressed.
- EPI produces geometric distortions to some extent that can be controlled through proper parameter selection.
- EPI offers speed and contrast.

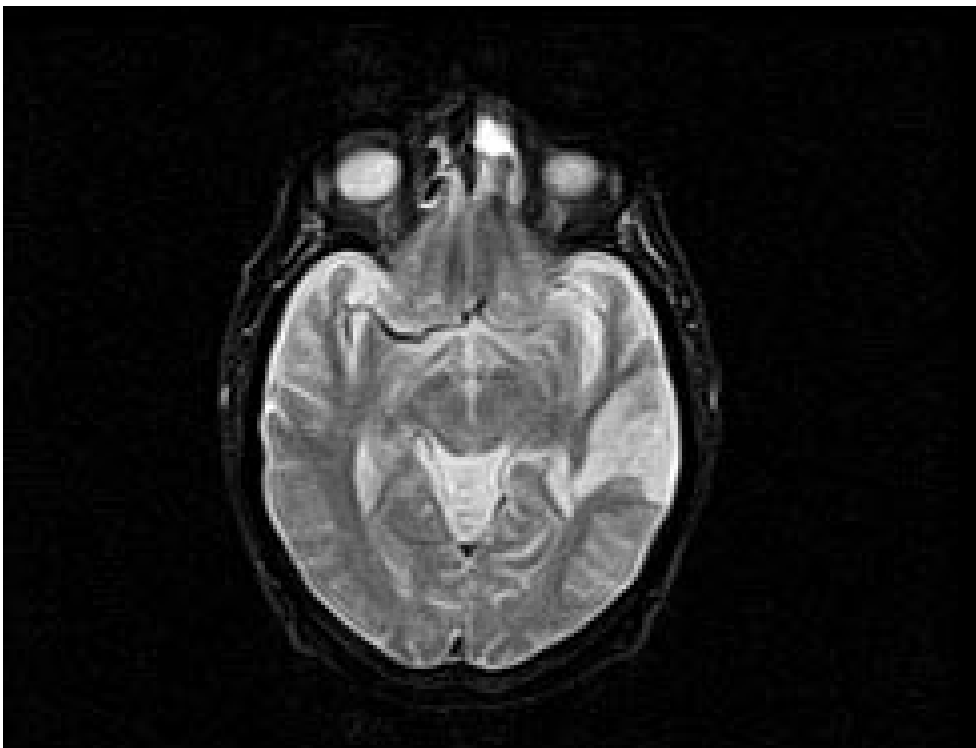


Figure 16: Multi-shot EPI image done at 0.5T. The exam was acquired in 16 shots, TR:4000, TE: 80eff, +/-32kHz, 224x224 matrix, FOV:32x24, 2 NEX. Scan time: 2:12.

THE NAME OF THE GAME

ECHO SPACING

To any Fast Spin Echo user, “echo spacing” is a familiar term. Controlling it has a direct effect on image quality. For EPI, control of the echo spacing is paramount in producing images of high diagnostic value.

For EPI, echo spacing (ESP) is defined as the time from the middle of one readout gradient pulse to the middle of the next (figure 17). In FSE, the shorter the ESP the better the image quality will be with regard to image blurring. Unlike FSE where ESP controls the degree of image blurring, in EPI the ESP has an extreme effect on the amount of geometric distortion. (ESP does affect image blurring, but its affect is negligible because the ETL

time is far shorter in EPI.) Average echo space times for FSE are in the 10msec range (depending on selected parameters). In EPI, however, these times are much shorter, from 250 micro-seconds to 2000-3000 micro-seconds. Remember this simple rule:

In EPI, shortening ESP is extremely important. Whatever the operator can do to shorten the ESP, the more geometric distortion is reduced.

There are numerous ways to shorten the ESP.

Before we discuss methods for reducing ESP, a clear understanding of WHY shortening ESP improves image quality is useful.

As mentioned in the previous chapters, water spins found in areas near high magnetic susceptibility accumulate a phase shift as the echoes are sampled across the echo train. This shift is manifested by geometric distortions in the phase encoding direction of the image. The areas most prone to these distortions are regions of tissue-air interface. The longer it takes to sample the echo, the more time water spins have to accumulate shift. In reducing geometric distortions, the less time the frequency gradient is “on” sampling the signal, the less distortions will appear. The period of sampling is typically during the “flat-top” of the readout gradient (assuming ramp sampling is not done. Ramp sampling is

discussed in detail later.) The shorter the flat-top the more geometric distortions are reduced. However, as with most selections in MR, changing one parameter to improve an aspect of image quality usually degrades others. Finding the best balance of geometric distortion, SNR, spatial resolution, and scan time ensures the highest image quality. The table which follows is a guide to finding this balance.

Two important characteristics for reducing ESP are: ① Gradient Performance; and ② Receive Bandwidth. They are discussed in detail next. Certainly other parameters, such as the number of shots, has a direct effect on ESP. They are also detailed in the following chapter.

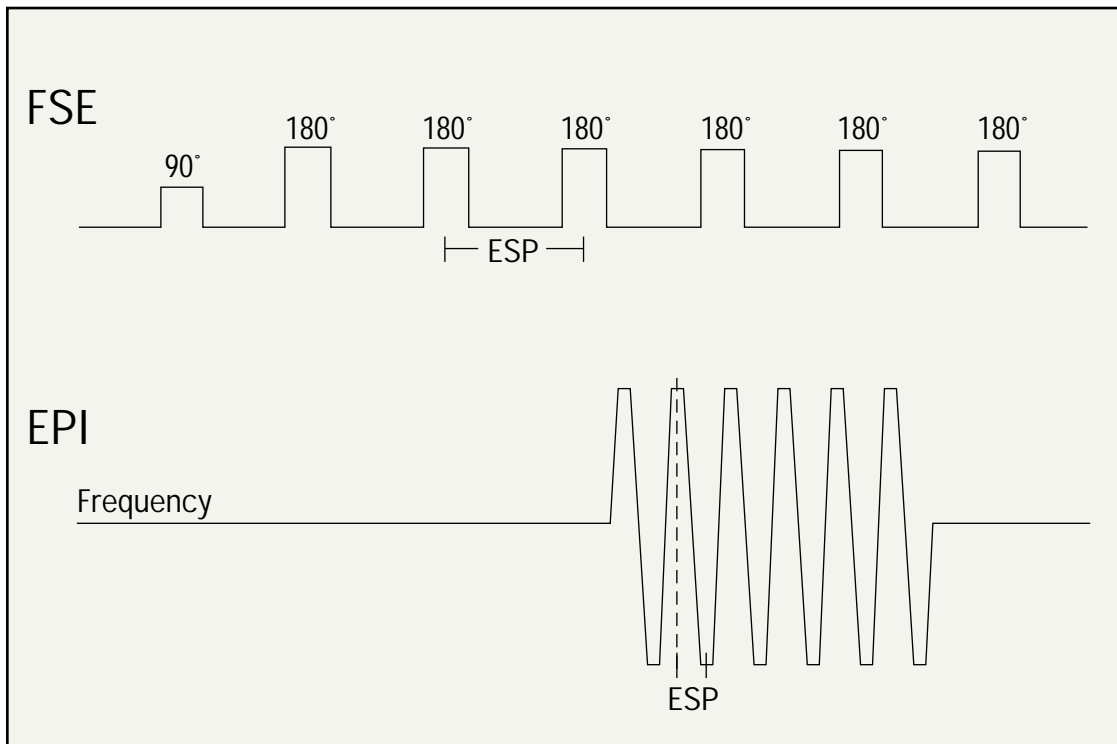


Figure 17: Echo spacing for FSE and EPI.

PARAMETERS	I	M	A	G	E	E	F	F	E	C	T
	ECHO SPACING		SNR		RESOLUTION		SCAN TIME		GEOMETRIC DISTORTION		
↑ GRADIENT SLEW RATE	↓		—		—		—			↓	
↑ RECEIVE BANDWIDTH	↓		↓		—		—			↓	
↑ # OF SHOTS	↓		↑		—		↑			↓	
↑ FREQUENCY ENCODING STEPS	↑		↓		↑		—			↑	
↑ PHASE ENCODING STEPS	—		↓		↑		—			—	
↑ FREQUENCY FOV	↓		↑		↓		—			↓	
↑ PHASE FOV	—		↑		↓		—			↑	
↑ RAMP SAMPLING	↓		—		—		—			↓	
↑ FIELD STRENGTH	—		↑		—		—			↑	

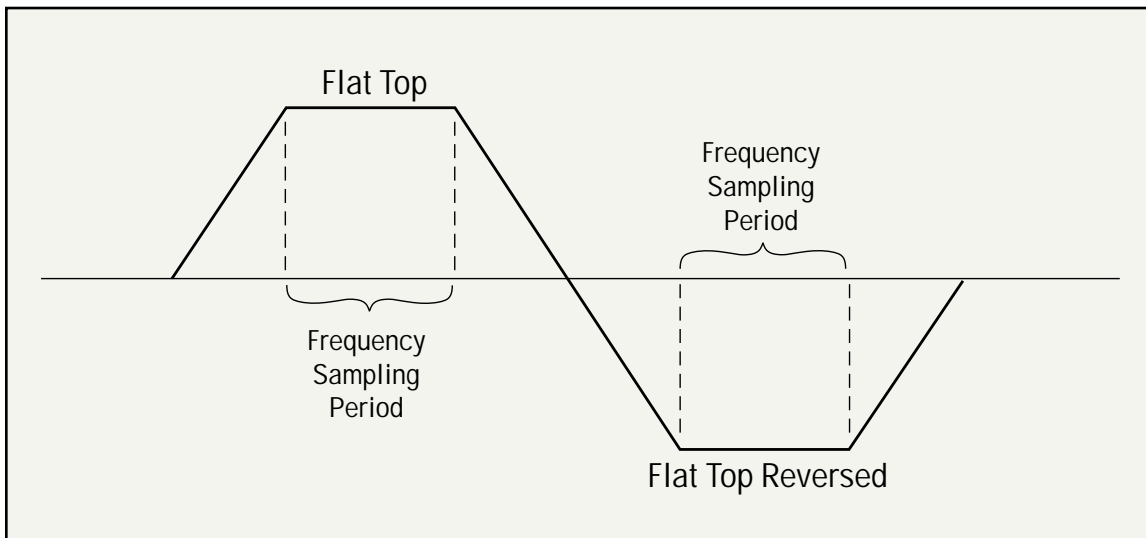


Figure 18: Flat-top gradient

GRADIENT PERFORMANCE

One of the most effective methods of reducing ESP is through “brute force” gradient power. It is surely one of the most important factors to consider BEFORE equipment purchase because high performance gradients can play a large role in improving system performance across all pulse sequences, not just EPI. For the purposes of this document, however, we will restrict our discussion of gradient power to the advantageous effects on EPI.

Gradient performance is usually thought of in three ways: ❶ gradient amplitude; ❷ gradient rise time; and ❸ gradient slew rate.

Gradient amplitude is simply how “high” the gradient field variation can be. Figure 19 illustrates two gradients with differing amplitudes. The variation of gradient A from zero to peak is twice that of gradient B. Note, however, that

A takes longer to reach its peak amplitude. Because gradient B has a shorter rise time (the time to reach peak amplitude), gradient B maintains a shorter ESP even though gradient A has a greater amplitude. (Assuming the desired resolution can be met by both gradient systems.) Certainly A holds advantages over B in minimum FOV and slice thickness. Moreover, if the resolution requirements are such that gradient B cannot obtain the same area under the gradient, then it must remain on longer, lengthening the ESP. Since frequency resolution is a function of the area under the gradient and not the flat top duration, gradient amplitude by itself will affect ESP in this case. If the desired frequency resolution for the image can be met by both gradients (that is, maintain the same area), the higher amplitude gradient holds no advantage over the lower amplitude gradient in terms of ESP. What is really needed to take advantage of the higher amplitude is a higher slew rate.

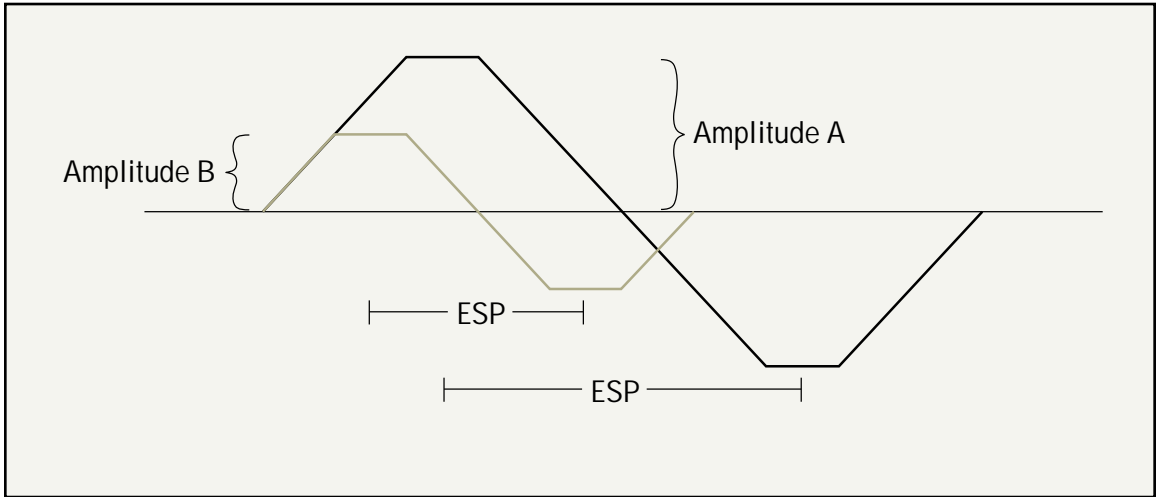


Figure 19: Gradient A and B

Slew rate is the **rate** of ascent or descent of a gradient from zero to its maximum amplitude, either negative or positive. It is determined by dividing the amplitude (usually in milli-Tesla/meter) over the rise time (in μ secs). In conventional MR systems of the past where the gradient amplitude is 10 mT/m and the rise time is 600 μ secs, the calculated slew rate is 17 mT/m/sec. Figure 20 illustrates two gradients with the same amplitudes but different slew rates.

While the two gradients will have the same performance with regard to FOV and slice thickness, Gradient A has a much shorter ESP. For the same parameters, the image obtained using gradient A will be of higher quality

than gradient B in terms of geometric distortion. Also note that the required time to play out all the gradients will take less time for gradient A, leaving more time to acquire more slices within the TR. So not only will the image quality be better, one can obtain more slices at the same time. Likewise, if contrast requirements permit, the user can select a shorter TR if the extra slice coverage is not needed, providing better image quality in less time. In simple terms, MR systems with higher slew rates have less geometric distortions in EPI images, all other parameters remaining the same. The chart on page 51 lists several Signa systems and their individual slew rates.

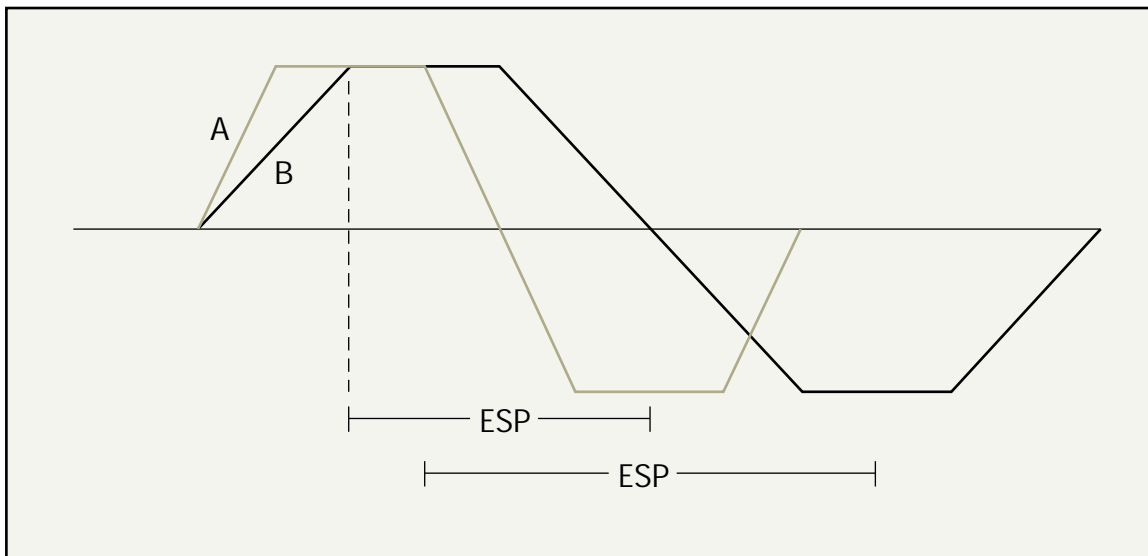


Figure 20: Note gradient A, with faster slew rate, has a shorter ESP versus gradient B, with a slower slew rate. Also note, both gradients have the same amplitude.

MR SYSTEM	SLEW RATE
Signa RP (1.5T, 1.0T, .5T)	17 mT/m/sec max amp: 10mT/m; rise time: 600 μ sec
Signa Horizon (1.5T, 1.0T)	20 mT/m/sec max amp: 22mT/m; rise time: 1150 μ sec
Signa Horizon HiSpeed (1.5T, 1.0T)	77 mT/m/sec max amp: 22mT/m; rise time: 284 μ sec
Signa Horizon EchoSpeed (1.5T only)	120 mT/m/sec for EPI only max amp: 22mT/m; rise time: 184 μ sec 77 mT/m/sec for all other sequences

POINTS TO REMEMBER

- Controlling echo spacing (ESP) is extremely important in reducing geometric distortion with EPI.
- The shorter the ESP, the smaller the geometric distortions.
- Parameters affecting ESP may also affect other image characteristics such as SNR, resolution, and scan time.
- While EPI can be used on any system and gradient configuration, to perform fast high resolution EPI, a gradient system that utilizes both high gradient amplitudes and slew rates is necessary.
- High gradient performance (high amplitudes and slew rates) affect ALL pulse sequences, not just EPI.

RECEIVE BANDWIDTH

The receive bandwidth (RBW) plays an important role in determining the ESP in an EPI sequence. For one, it is user-selectable and flexible. Secondly, its selection has a direct and formidable relationship on ESP. The basic rule:

The wider the RBW, the less the ESP and therefore, the less the geometric distortion at the cost of SNR.

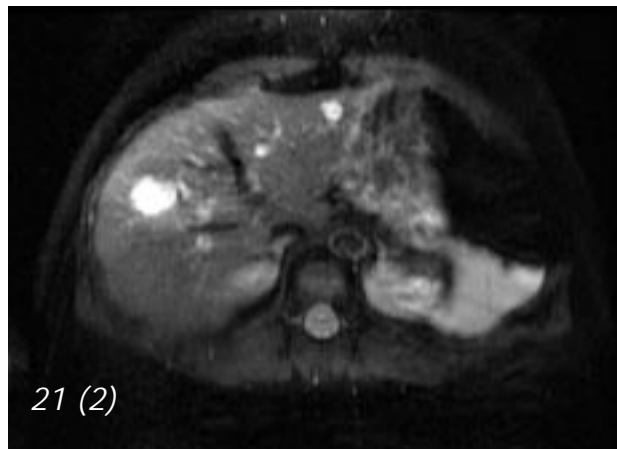
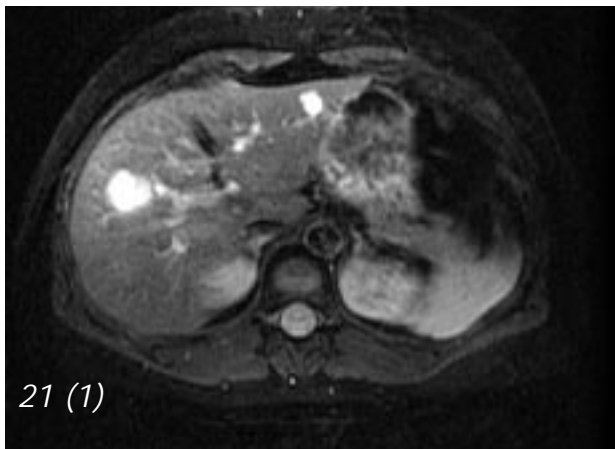
For example, an image using a RBW of +/- 32kHz will have twice the geometric distortion as one using +/- 62.5kHz. The images in figures 21 (1) and (2) illustrate this point very well. The image on the top is an abdomen acquired with a +/-62.5kHz RBW while the image on the bottom with

+/-32kHz. Note the increase in geometric distortion in the image using +/- 32kHz.

To understand the role between RBW and ESP, recall the basic principle of selecting a variable bandwidth. The receive bandwidth determines a range of frequencies that will be sampled by the frequency encoding gradient. To have enough image data to create and display an image, a balance must be struck between the range of frequencies sampled and the time needed to sample them. Stated in simple terms, the more frequencies that are sampled, the less the time needed to collect the data. If the bandwidth selected “sees” a wide range of frequencies, then the frequency encoding gradient need only be on for a short time. Conversely, if a narrow range of frequencies is being sampled, the frequency encoding gradient must be on longer to collect the required data. Figure 22 provides a graphic example.

The graphic illustrates that by increasing the BW, the amount of time at the flat top of the gradient reduces significantly. Shortening the duration of the flat top reduces the ESP dramatically and thus geometric distortion. Of course, upon closer look, one also sees that SNR is adversely effected as well.

As the range of frequencies to be sampled is increased, the system samples more of the inherent noise along with the generated echo signal. Since the same amount of signal is sampled, but more of the noise is sampled, the signal-to-noise ratio falls. As the bandwidth is narrowed, the receiver samples less noise and, again, the same amount of signal. Thus, the SNR increases. While using wide RBWs is imperative for successful EPI, gaining the SNR back also gains importance. For all field strengths, proper utilization of surface coils, including phased array coils, is extremely important.



Figures 21 (1) and (2): Effect of receiver bandwidth on geometric distortion. 21 (1) was done using a $\pm 62.5\text{kHz}$ RBW while figure 21 (2) was done using $\pm 32\text{kHz}$ RBW. Note the decrease in geometric distortion in the area of the air-filled bowel in figure 21 (1) using a $\pm 62.5\text{kHz}$ RBW. Both images were acquired using 8 shots, TR:2000, TE:60, 256x128, 1 NEX, 15 slices in 18 seconds. Also note that the expected loss of SNR in figure 21 (1) is compensated for by use of the Torso Phased Array coil.

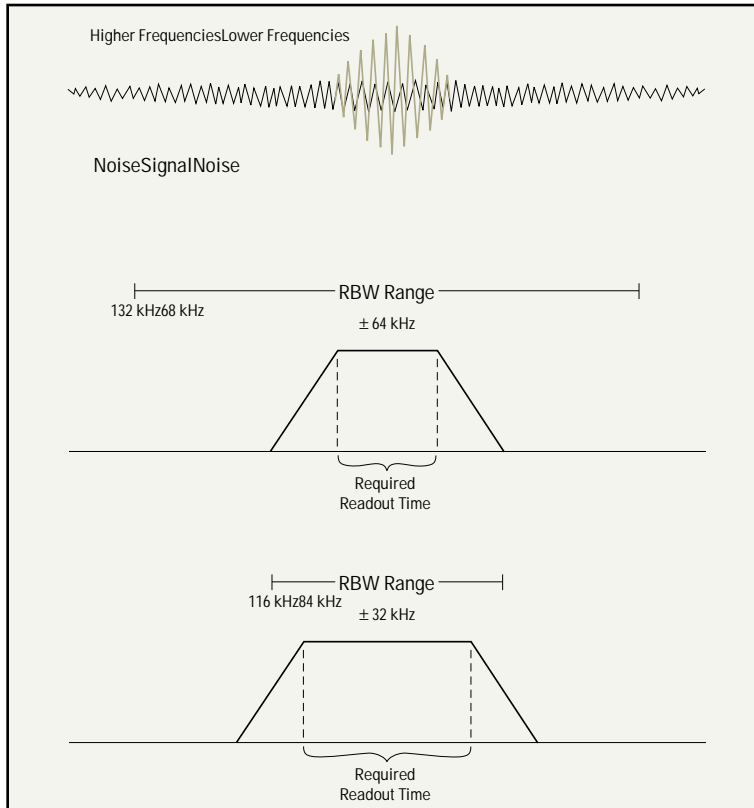


Figure 22: Bandwidth effects on gradient flat top duration. RBW values are examples only.

RECEIVE BANDWIDTH AND THE FAST RECEIVER (ECHO SPEED ONLY)

When we speak of “narrow” RBWs for EPI, we typically speak of bandwidths around $\pm 32\text{kHz}$ – fairly wide bandwidths for other sequences. In fact, $\pm 32\text{kHz}$ is typically the most narrow of RBWs used in EPI! Bandwidths of $\pm 62.5\text{kHz}$ are far more common.

To perform rapid EPI that is both high resolution and relatively free of geometric distortions, bandwidths greater than $\pm 62.5\text{kHz}$ are often required. The standard receiver hardware that is common to all MR systems is not capable of “keeping up” with data that are sampled with frequency encoding gradients that turn on and off so fast. In fact, the upper limit in kilohertz that the standard receiver can handle is $\pm 62.5\text{kHz}$. Beyond this point a faster receiver is required.

The Fast Receiver is a standard part of all Horizon EchoSpeed systems. This single channel receiver is capable of handling data that uses RBWs of up to $\pm 500\text{kHz}$. (Note: Because the Fast Receiver is single-channel only, use of Phased Array coils is not compatible.) Above $\pm 62.5\text{kHz}$, the Fast Receiver *automatically* turns on. It must be noted, however, that as wider RBWs are used, field-of-view limitations will be seen. For example, a RBW of $\pm 180\text{kHz}$ requires a minimum FOV of 40cm in the frequency direction. While this can be detrimental to resolution, it certainly gains back SNR lost by using such wide bandwidths. In fact, EPI images using such wide RBWs rarely suffer from SNR loss due to the FOV requirements. Resolution of the image can be regained through proper matrix selection that is discussed later in the document.

POINTS TO REMEMBER

- The receive bandwidth (RBW) plays an important role in determining ESP.
- The wider the RBW, the less time the frequency gradient must be “on” to sample the echo.
- Generally, the wider the RBW, the shorter the ESP which decreases geometric distortions.
- RBWs higher than +/- 62.5kHz require a “fast receiver” to process the data. The Fast Receiver is standard on the Horizon EchoSpeed only.
- Proper utilization of surface coils, including Phased Array coils, is necessary where very wide RBWs are used.

SETTING UP THE EPI SEQUENCE

THE MEANING BEHIND THE BUTTONS

This chapter explains the meaning behind certain parameter selections when setting up an EPI sequence. Like any Signa pulse sequence, EPI is flexible enough to allow for a wide range of selections. This section is dedicated to making sure the correct selections are made and explaining what makes them correct. This section can be used alongside the scanner while building an EPI protocol or used as a reference for future protocols. To make it as easy and organized as possible, this chapter is divided into the sections that are found on the scanner itself. While certain sections are short, others are longer depending on the particular

selections that can be made and the relative importance to the success of the EPI series.

FLAVORS OF EPI: SPIN ECHO,
GRADIENT ECHO, OR IR-PREP

EPI can be either Spin Echo (SE-EPI), Gradient Echo (GRE-EPI), or IR-Prep (IR-EPI). Determining which to use is critical and depends solely on the contrast required. Recall the earlier chapters where the differences in the sequences are discussed. In deciding which sequence to select, use the same process as if one were prescribing a Spin Echo versus a Gradient Echo – the same rules apply with EPI. A SE-EPI will yield similar contrast to a fat-saturated

SE. A GRE-EPI will yield similar contrast to a fat-saturated GRE. An IR-EPI yields contrast similar to fat-suppressed IR.

For contrast similar to Gradient Echo, choose GRE-EPI. Like GRE, it is sensitive to magnetic susceptibility effects. Anatomy and pathology that increase magnetic susceptibility can be more visible using GRE-EPI. In fact, GRE-EPI is more sensitive to the effects than GRE alone due to EPI's series of gradient pulses. For this reason, GRE-EPI may be the sequence of choice for performing certain applications requiring detection of minute contrast changes over time. For these experiments, minor changes in the local magnetic field are caused by changes in blood oxygen level to affected regions of the brain.

- For more on blood oxygen level imaging, refer to *Echo Planar Imaging: Principles and Applications*.

IMAGING OPTIONS:
FOR EPI, SIMPLY SELECT IT

To designate a Spin Echo or Gradient Echo sequence as EPI, select **EPI**. For IR-EPI select the IR-Prep option, as well.

COMPATIBLE IMAGING OPTIONS

Listed below are the compatible imaging options for EPI:

FLOW COMPENSATION

Use **Flow Comp** any time that the region of interest may be degraded due to flow motion. Flow Comp is applied in both the phase and slice-select direction. Note the selection of Flow Comp will increase the minimum TE just as with SE or GRE.

GATING

Gated EPI is a powerful option for imaging the heart. EPI gating can be done either peripherally or by using an ECG, with ECG being the preferred method for imaging the heart across multiple cardiac phases. The gating parameters are selected in the same manner as any standard Spin Echo or Gradient Echo. Note that **Multi-Phase** is also selectable permitting multiple cardiac passes in a single breath-hold. Lastly, gating can be used to reduce pulsatile motion artifacts such as with CSF flow.

MULTI-PHASE

The **Multi-Phase** button is selectable for repeated imaging of single or multiple locations within a series, just as the

Fast Gradient Echo sequence. This option is used primarily for applications requiring detection of minute contrast changes over time requiring multiple scans over a region of interest.

VARIABLE BANDWIDTH

The importance of Variable Bandwidth (**VB**) is well understood as detailed in the previous chapter. Regardless of whether the option is chosen or not, Variable Bandwidth selections are always available. If the option is selected, **VB** is annotated along with other selected imaging options and the numerical value of the bandwidth is displayed with the other timing parameters. If **VB** is not selected, no imaging option annotation for **VB** appears, only the value of the bandwidth itself.

EXTENDED DYNAMIC RANGE

Extended Dynamic Range (EDR) performs the same function in EPI as any other compatible pulse sequence. Just as with other pulse sequences, EDR can be used to provide slight boosts in SNR.

GRAPHIC PRESCRIPTION

Graphic Prescription (GRx) functions the same in EPI as any other compatible pulse sequence.

POINT TO REMEMBER

- No Phase Wrap, POMP, Fast, Respiratory Compensation, Respiratory Triggering, and Classic are not compatible with EPI.

USER CV PAGE (ECHO SPEED ONLY)

Ramp Sampling: ___	1 = on 0 = off	For EchoSpeed systems, the selections of Ramp Sampling and Burst Scan Time are available. These options appear on a special user page.
Burst Scan Time, secs: ___	0 = off (1-30)	

RAMP SAMPLING

All gradient waveforms used on GE Signa MR systems use trapezoidal waveforms meaning they rise or fall to a given amplitude and then “flatten out” for a required amount of time before reversing back in the other direction. Figure 23 illustrates the difference between a trapezoidal and sinusoidal waveform.

For a trapezoid frequency encoding gradient the sampling of the spins occurs under the flat top of the gradient. The time duration of the flat top is

dependent on the number and the bandwidth of frequency samples taken. The role of receiver bandwidth is discussed in the earlier sections of this guide. However, the number of samples taken also has a direct effect on the duration of the flat top. Recall that the duration of the flat top has a direct effect on the ESP. For example, a selection of 256 frequency samples has half the flat top duration as a selection of 512 samples, all other parameters remaining the same. Therefore, a selection of 512 frequency samples increases the ESP considerably.

A method for reducing the flat top duration without changing the number of frequency samples is to collect, or sample, the echo while the gradient is rising and falling (ramping either in the negative or positive direction.) This is referred to as **Ramp Sampling**. In Ramp Sampling, the **echo sampling** begins as the gradient starts to rise and continues during the flat top and while it falls. Because sampling does not wait until the maximum gradient amplitude is reached, the time duration of the flat top decreases dramatically **increasing the effective slew rate greater than 120mT/m/sec.**

Reducing this duration in turn reduces ESP which decreases geometric distortions in the image while maintaining resolution. One can also take the reverse approach as well, increasing the frequency resolution while maintaining the same ESP.

Note in figure 25 that spins being sampled during the ramp experience different gradient readout magnetic fields and therefore have different encoding values. However, because the changing value of the magnetic field under the ramp is predictable and consistent, the receiver bandwidth is continually modified to correct for this shift. By maintaining the area under the gradient, spatial resolution is maintained while ESP is shortened. Doubling the area under the gradient doubles resolution.

Using Ramp Sampling does not come without cost, however. Because of the dynamic signal bandwidth, the Fast Receiver collects a wider range of frequencies automatically. While this receiver bandwidth might lead one to think that the SNR of such a range precludes its use, the actual “effective” receive bandwidth seen in the image is

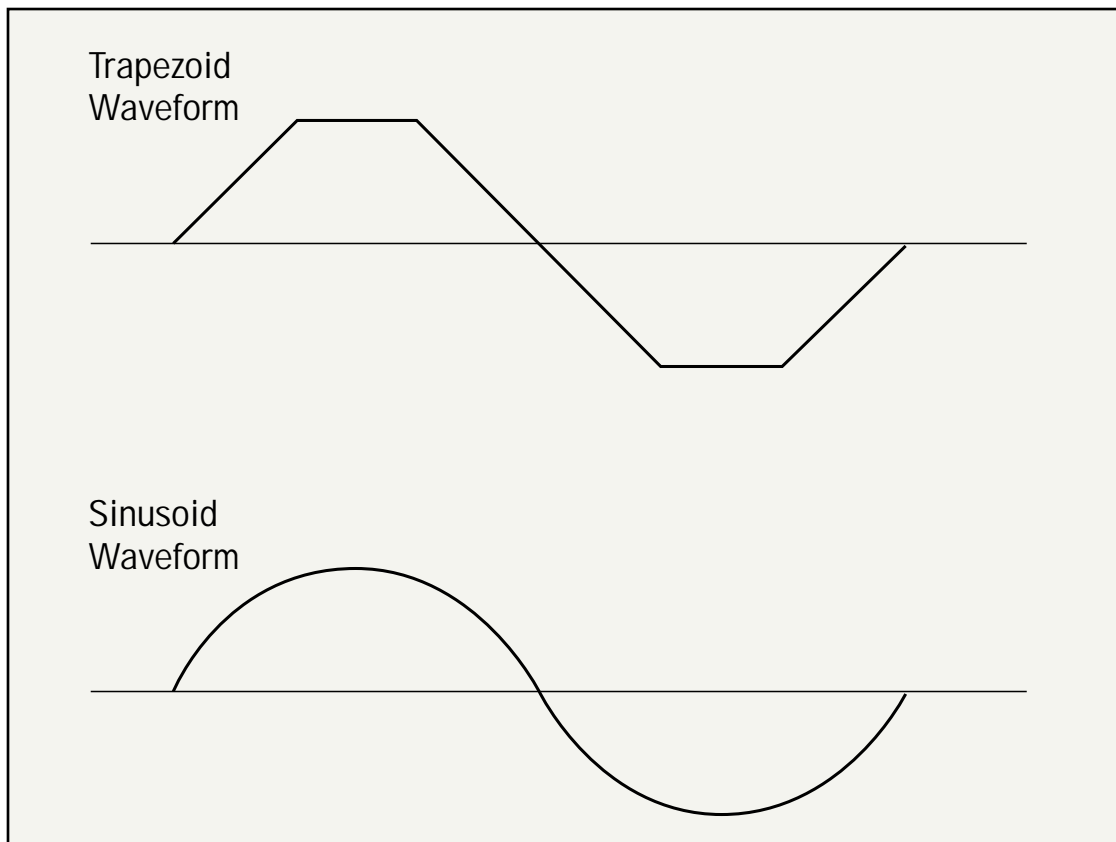


Figure 23: Trapezoid versus sinusoid waveform.

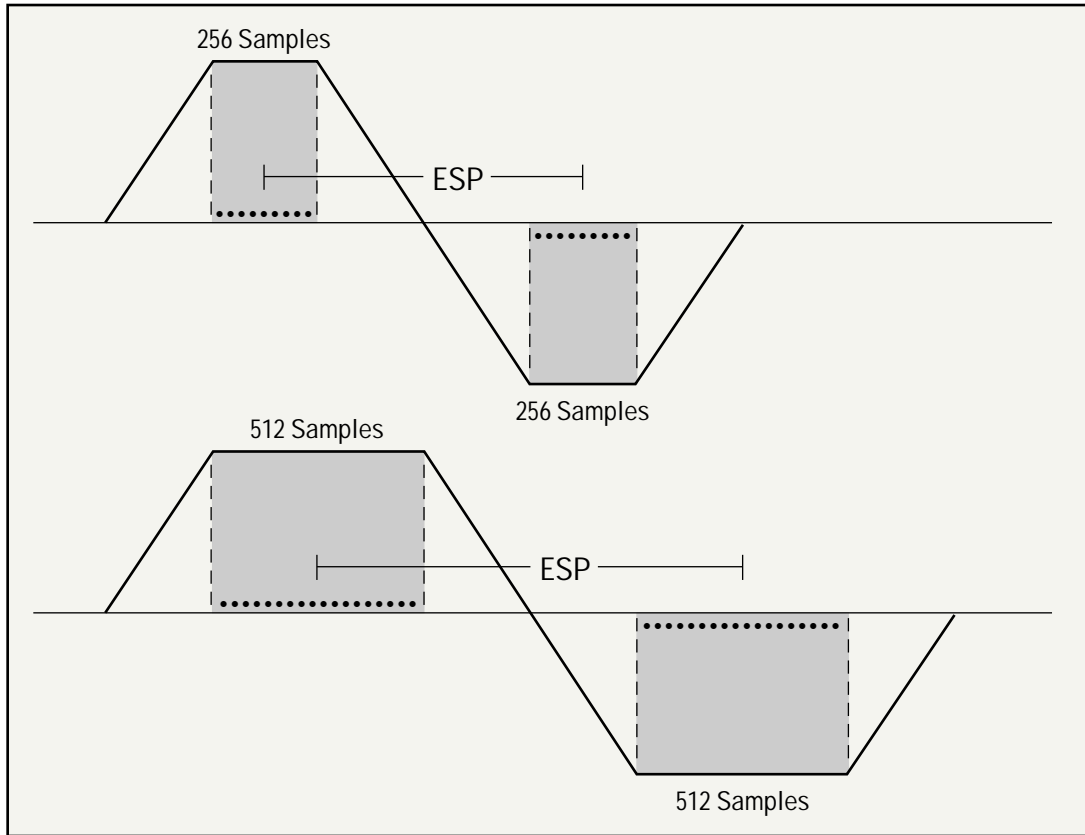


Figure 24: 256 gradient vs. 512 gradient

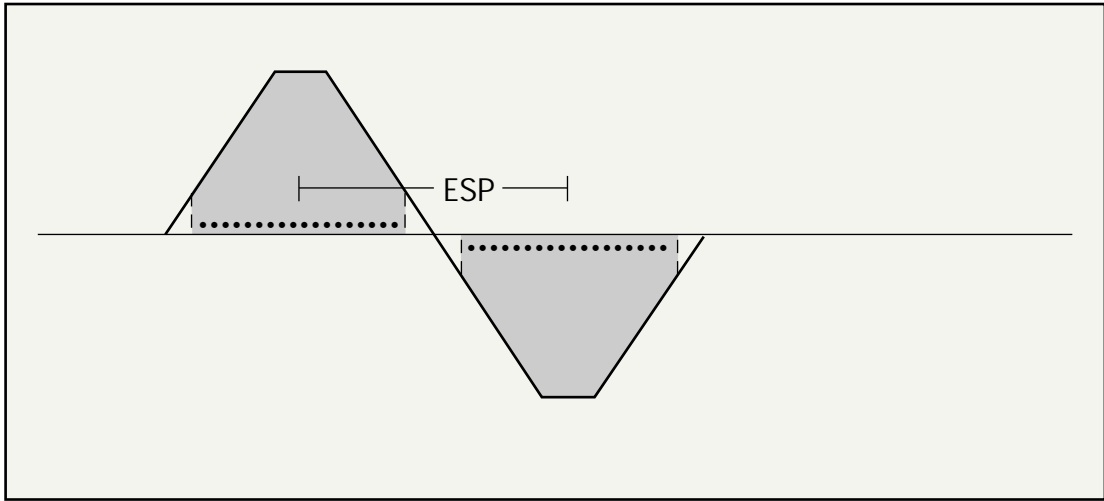


Figure 25: Data acquisition with ramp sampling.

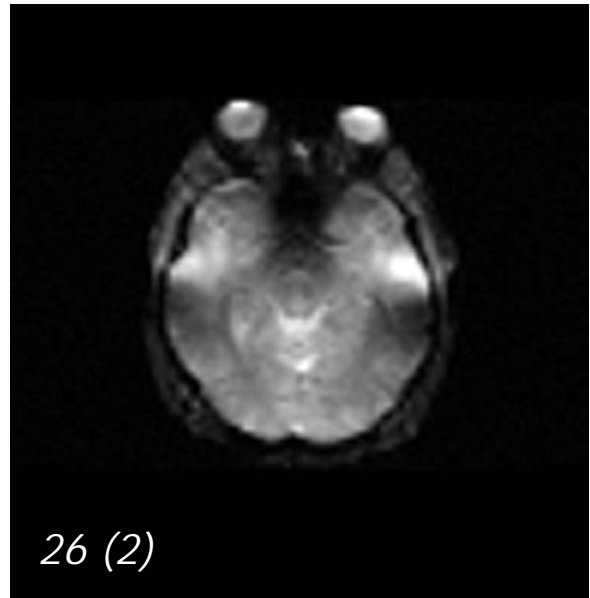
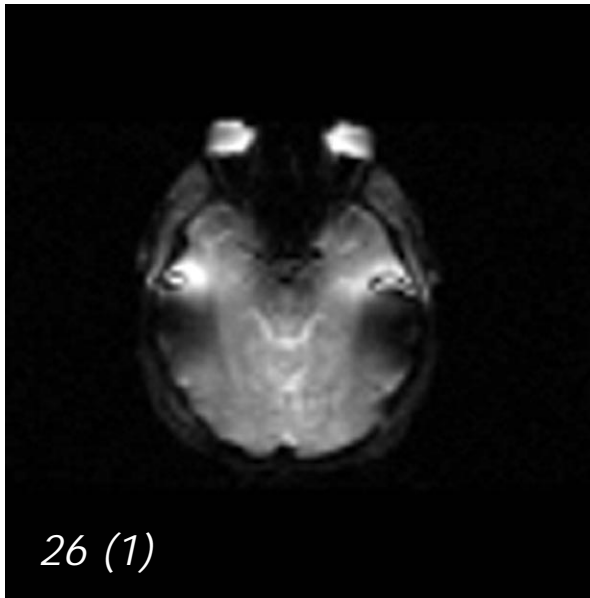
much narrower. In fact, when using ramp sampling, the system takes control of the RBW automatically and annotates the effective RBW. To the right are two images, one acquired with Ramp Sampling and one without. Ramp sampling will have its greatest benefit when ESP must be reduced to its absolute minimum at the cost of all other considerations.

Because of the wide bandwidth limitations of Ramp Sampling, it is recommended that it be used only for EPI acquisitions where geometric distortions are required to be minimized to the greatest extent possible such as with single-shot imaging and cardiac EPI studies. For example, the region of the mediastinum and heart, which has high magnetic susceptibility, is surrounded by the air-filled lungs which have low magnetic susceptibility, creating a large tissue-air interface highly

sensitive to geometric distortions. In most clinical scenarios, ramp sampling is utilized for snapshot imaging.

POINTS TO REMEMBER

- Ramp Sampling collects frequency information while the frequency gradient is rising and falling as well as along the “flat top.”
- Ramp Sampling reduces the ESP by reducing the time duration of the flat top of the gradient.
- The “effective” receive bandwidth displayed in the image is narrower than the actual sampling bandwidth and is a function of FOV, frequency matrix selection, and # of shots.
- Ramp sampling should be used when ESP must be reduced as much as possible.
- Ramp Sampling can increase the effective slew rate beyond



Figures 26 (1) and (2): Effects of Ramp Sampling on geometric distortion. Image 26 (1) was acquired without using Ramp Sampling. Note the distortions in the area of the petrous ridges. Image 26 (2) uses the exact parameters except for the use of Ramp Sampling. Note the reduction in distortions due to the reduced ESP through the use of Ramp Sampling. The ESP of image 26 (1) is 832 microseconds, image 26 (2) is 576 microseconds.

BURST TIME

For certain applications, the Signa system will allow the user to override the default gradient duty cycle to gain higher, but temporary, performance in slices per TR. Entering a time from one to 30 seconds on this line turns the Signa “Burst Mode” on. The time selected must be at least one second **greater** than the scan time of the acquisition but can be no longer than 30 seconds. The benefit of Burst Mode is to acquire more slices within a TR. Moreover, Burst Mode is a “scalable” option, meaning the smaller the burst time, the greater the slice efficiency. As an example, a burst time of 5 seconds offers greater slice efficiency than a burst time of 30 seconds. (A 5 second burst time offers the greatest slice efficiency.) However, because the gradients have been driven harder than the permitted duty cycle, there may be a required “cool down” period immediately following the

acquisition that may be equal to up to twice the scan time. A practical application for using Burst Mode is any time the desired TR does not provide the needed slice coverage. As an example, above are 16 images acquired in 2 seconds using a 5 second burst time.

SHOTS	OTHER	1	2	4	8	16
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SINGLE-SHOT VERSUS MULTI-SHOT EPI

The number of shots is probably the most often mentioned EPI parameter and is the basic unit that determines the speed of the acquisition. It also has a great effect on ESP. The general rule:

The greater the number of shots,
the less the effective ESP.

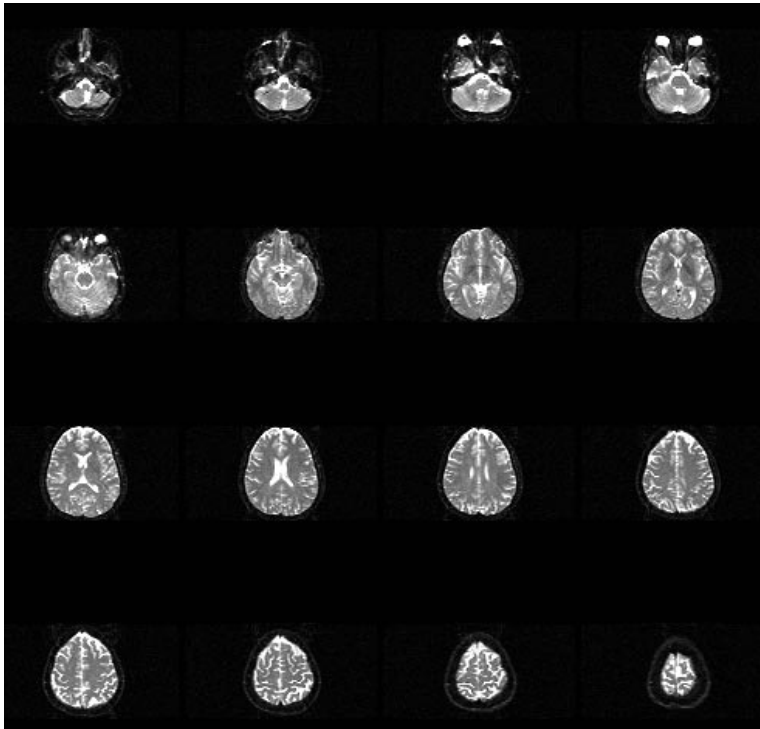


Figure 27: Sixteen axial images of the head done in 2 seconds. Single shot exam used a 2200 TR (though true TR is infinitely high), TE; 80eff, ramping sampling, burst time of 5 seconds, 128x128 matrix, FOV:36x18, .6 phase FOV.

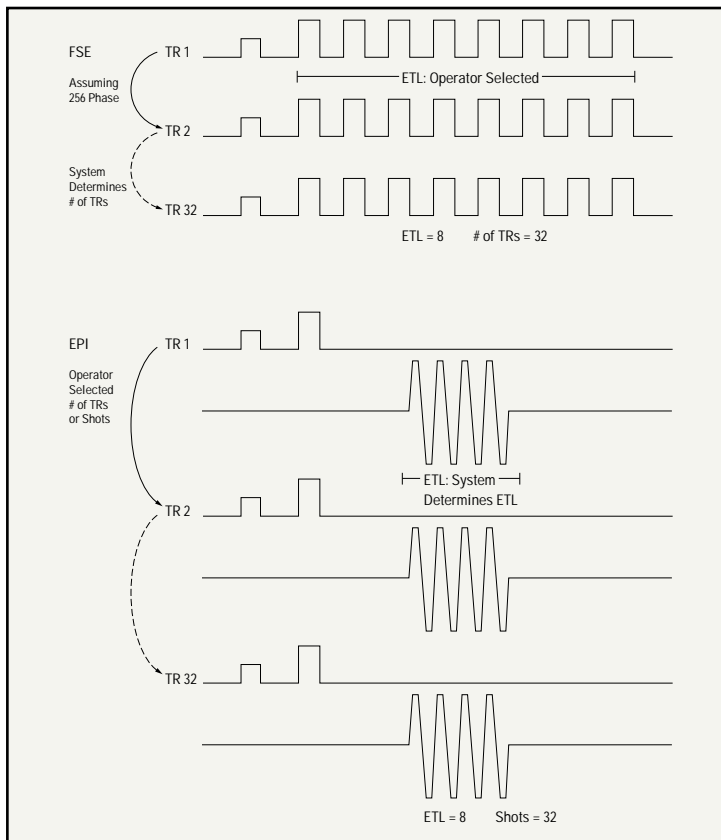


Figure 28: FSE ETL/TRs vs. EPI ETL/TRs

The number of shots selected is the number of TR periods that the sequence will repeat to obtain the image data. To understand “shots” think back to our review of Fast Spin Echo. In FSE, the basic unit for determining the acquisition speed is the Echo Train Length (ETL). The operator selects an ETL and the MR system determines the number of TR periods to be repeated. The longer the ETL, the fewer TRs need to be repeated and the scan time decreases. In EPI, the operator determines the number of TRs to be repeated and the MR system determines the ETL. (Recall that EPI, just as FSE, fills multiple lines of k-space per TR. FSE uses 180 degree RF refocusing pulses while EPI uses oscillating gradient echoes.) The fewer the number of shots selected, the longer the ETL, and the shorter the scan time. A *single shot* (or *snap shot*) means that ALL the required number of phase

encoding steps are performed within a single TR. For a series requiring 256 phase encoding steps, if only 128 phase encoding steps are collected in a TR, two TRs will be required to complete data acquisition. This then is a “2 shot EPI” sequence. Calculating the scan time for an EPI sequence is:

$$\text{scan time} = \text{TR} \times \# \text{ of shots} \times \text{NEX}$$

The number of shots selected has a dramatic effect on echo spacing. The general rule:

The more shots selected, the shorter the “effective” ESP.

An explanation of “effective” ESP follows in the next section.

EFFECTIVE ESP

In EPI, k-space for a multi-shot acquisition is filled in an interleaved fashion. An illustration of interleaved k-space for a 2 shot acquisition is depicted on the next page.

Figure 29 illustrates how the echo spacing between adjacent lines of k-space within the same TR is generally not affected by the number of shots. However, with each additional shot, the lines of k-space are “interleaved” with the existing lines, thereby reducing the effective ESP between echoes of each shot by a factor of two in this example. To illustrate it another way, one could picture the interleaving in the manner depicted on page XX.

In Figure 30, the gradients of the first shot display a “true” ESP, that is the time from the middle of one echo to the middle of the next. When

the next TR period is played out, the phase encoding gradient forces the lines of k-space to interleave so that the echoes from successive TRs are placed adjacent to each other. The time from the middle of one echo to the middle of the next echo from the next TR period is the effective ESP. As was stated before, the shorter the ESP (as well as effective ESP), the more geometric distortion is reduced because the interleaved lines of k-space become closer together as more shots are added. Keep in mind, however, that increasing the number of shots decreases the ETL which increases overall scan time. A small number of shots compared to a large number results in increased geometric distortion, assuming all other parameters remain the same, but in a shorter scan time. Finding a balance between speed and acceptable geometric distortion is critical to the success of the EPI sequence.

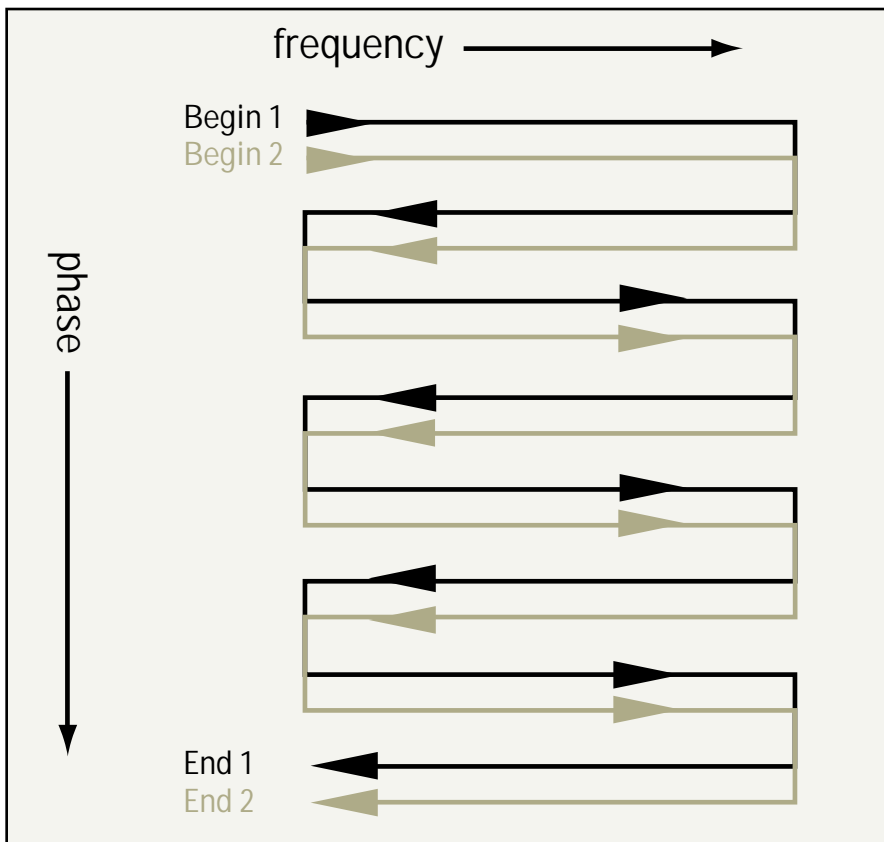


Figure 29: Interleaved k-space

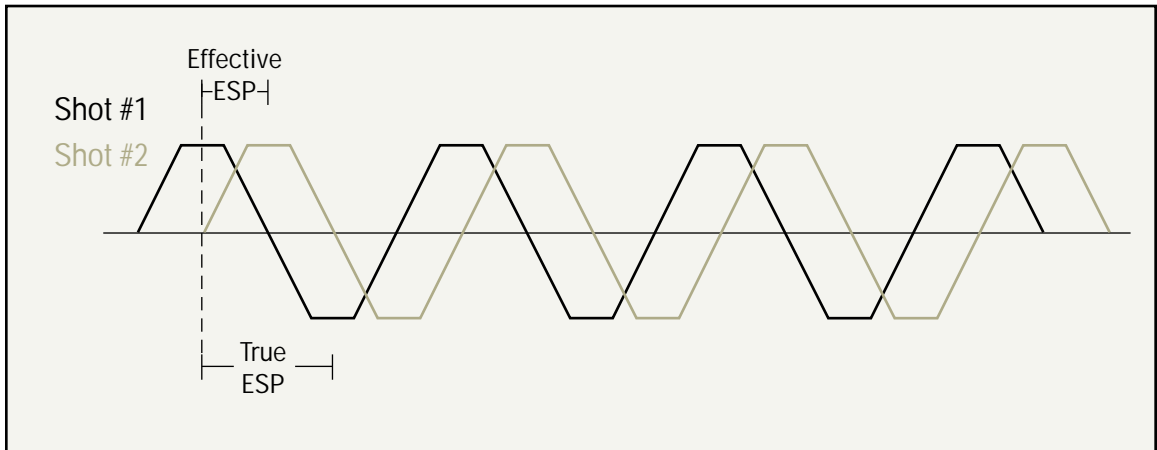


Figure 30: Gradients interleaved from one shot to another

The annotation for ESP is found on the series text page under the prescan options. The value of ESP is in units of microseconds.

Page 77 contains a table of approximate effective ESPs for various numbers of shots in microseconds. The assumed parameters are +/-62.5kHz receive bandwidth, 24cm FOV, and 256x256 resolution while the EchoSpeed assumes Ramp Sampling.

POINTS TO REMEMBER

- The number of shots selected determines the number of TR periods to be repeated. This in turn determines the echo train length (ETL).
- A "single" or "snapshot" EPI sequence is one in which all the required phase encoding steps are collected within one TR period.
- The fewer the number of shots, the shorter the scan time.
- Multi-shot EPI fills k-space lines in an inter-leaved manner. The interleaved k-space yields a reduced "effective" ESP.
- The fewer the number of shots, the more the effective ESP increases which increases geometric distortions, all other parameters remaining the same.

SYSTEM CONFIGURATION					
	16 shots	8 shots	4 shots	2 shots	1 shot
Horizon (+/-62.5 kHz)	eff ESP 320	eff ESP 512	eff ESP 896	eff ESP 1728	eff ESP 3328
Horizon HiSpeed (+/-62.5 kHz)	eff ESP 224	eff ESP 368	eff ESP 736	eff ESP 1472	eff ESP 2944
	4 shots	2 shots	1 shot	1 shot	1 shot
EchoSpeed with Ramp Sampling	256x128; 24 FOV eff ESP 384	256x128; 24 FOV eff ESP 704	128x128; 40 FOV ESP 576	128x128; 24 FOV ESP 768	256x128; 24 FOV ESP 1344

TE	Other	Min	Min Full	20	60	100
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SELECTING TE (FRACTIONAL VS. FULL K-SPACE)

Selecting the TE is no more difficult than selecting the TE for any other Spin Echo or Gradient Echo sequence. Select the TE with regard to the desired amount of T2 (or T2*) contrast for the image. The longer the TE, the more T2 or T2* will be displayed in the image. But the TE selection plays another role as well: It determines if the sequence will utilize a full k-space filling or a fractional k-space filling (Partial Fourier Transform).

Recall that in standard sequences, Partial Fourier Transform in the phase direction is selected via the number of NEX. NEX less than one means that only a fraction of the k-space is filled in that direction thus reducing scan time.

EPI Sequences. In EPI the implementation of Partial Fourier Transform is similar to standard sequences with minor variations. First, it is the TE selection that determines if Partial Fourier Transform will be utilized in EPI. Any value of TE less than the minimum full value collects half the total of k-space lines possible plus the required overscans. Secondly, the benefit of filling only part of k-space is increased slices per TR and a shorter minimum TE, not shorter scan times. The annotation for using Partial Fourier Transform is displayed next to the TE value. TEs that are less than the minimum full value are annotated at effective TEs. (Recall that the annotation for other pulse sequences utilizing Partial Fourier Transform is .5 or .75 NEX.) For TEs greater than the minimum full value, no “effective” annotation is displayed. The annotation is not the same in EPI as compared to standard

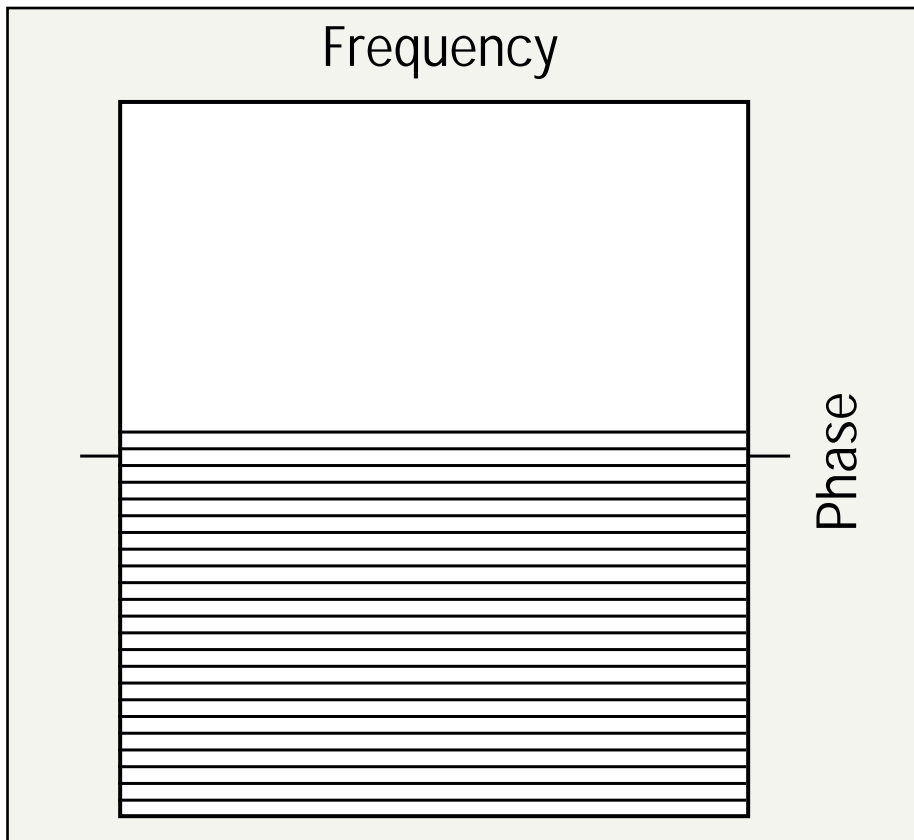


Figure 31: Partial k-space in the phase or "y" direction.

sequences because partial k-space filling is utilized often in EPI, even when using more than 1 NEX. For multi-NEX studies the k-space is partially filled for each excitation. To prevent the NEX annotation from always being displayed as “.5 NEX” even when multiple NEX are used, the annotation is moved to the TE and the NEX is annotated as whatever the operator selected.

- For more information on fractional NEX, refer to the GE Medical Systems *Signa Applications Guide, Volume Four*.

POINTS TO REMEMBER

- With EPI, the TE selection controls the amount of k-space that is filled. This is different from other sequences where NEX controls the amount of k-space filling.
- EPI sequences that use less than the full k-space in the phase direction, are annotated with an effective TE. TE values with no effective annotation indicate all of k-space was filled.
- The benefits of filling partial k-space in EPI sequences are increased slice efficiency and shorter minimum TEs.

Effective TR	Other	300	500	800	1000	2000

SELECTING TR

As with TE, select the TR according to the desired contrast. Higher TRs are less T1-weighted and, depending on the TE, more Density or T2 (or T2*) weighted. Higher TRs also yield higher SNR due to greater T1 relaxation between excitation times. Where the TR selection requires some further explanation is with regard to snapshot EPI.

Recall that with multi-shot EPI, more than one TR period is used to collect the required data. Since lines of k-space are being filled over numerous TRs, the amount of relaxation must be the same for each period, just as with standard sequences. This ensures that the T1 effect for each line of k-space is constant. To make sure the very first

TR interval collects data that has the same signal properties as those that follow, a series of “set-up pulses” is applied to ensure that when the first TR period is launched the spins have reached the same T1 equilibrium and relaxation characteristics as those that follow. Without the set-up pulses, the magnetization vectors of the spins during the first TR period will be infinitely high. As the first 90-180RF pulses are applied the spins become partially saturated and the vectors will be different. The set-up pulses are essentially the same sequence of pulses as those that are used during data acquisition. The only difference is that no data is collected during the set-up pulses.

But what if there is only one TR period?

In a single shot EPI sequence, the TR, regardless of what is selected, is effectively infinite. Since there will be

no TR periods played out after the first, there is no need for set-up pulses. The magnetization vectors are at their maximum when the sequence begins. For single shot EPI, the TR is only used to determine number of slices.

POINTS TO REMEMBER

- The TR selection has a direct effect on image contrast.
- As with most sequences, “set-up” pulses are used in multi-shot EPI sequences to ensure proper amounts of longitudinal magnetization are present before data acquisition begins.
- For single, or snapshot EPI sequences the TR is effectively infinite.

Prescan
Options

AutoShim

Phase Correction

AUTO SHIM

AutoShim should always be used and is defaulted “on” anytime EPI is selected.

AutoShim performs an automated 3-plane gradient shimming as part of prescan. It is designed to ensure the best possible uniformity in the magnetic field.

While having as homogeneous a field as possible is important for all MR imaging, it is particularly important anytime spectral differences between fat and water are being manipulated. The most common example of this is using ChemSat to suppress fat signal in the image. Recall that EPI is *always* fat suppressed. While EPI does not use ChemSat (it uses another method to be discussed later in this section), its fat suppression technique requires a very homogeneous magnetic field.

PHASE CORRECTION AND THE ROLE OF THE “REF SCAN”

The Phase Correction button will appear for either FSE or EPI sequences, however its function is different. For FSE sequences, the Phase Correction button replaces the “FSE Optimization” CV Page from previous software revisions. It is designed to correct for phase shifts that occur during the echo train as well as for certain aliasing artifacts that can occur in FSE.

- For more information on Phase Correction with Fast Spin Echo, refer to the *Horizon Scan Reference Guide*.

For EPI, Phase Correction serves another purpose: it launches the “referencescan” (or simply “ref”) immediately following prescan. In short, the “ref scan” corrects for misaligned echoes under the readout (or frequency) gradient.

Figure 32 illustrates the problem. In a “perfect” MR system, all the generated gradient echoes would refocus in the center of the readout gradient. However, the echoes are actually misaligned to some degree under the readout gradient. But, since the shift is constant from one echo to the next, meaning the amount each echo is off center is the same for all, the misalignment can be corrected during reconstruction.

During the reference scan, the system collects data from the slices. The data collection is almost exactly like the sequence to be run. It uses the same number of shots, the same TR, and TE. However, the main difference is that no phase encoding is done. The data are collected and the amount of shift in the echoes is determined and then a correction algorithm is generated that is used for the image data as it is reconstructed.

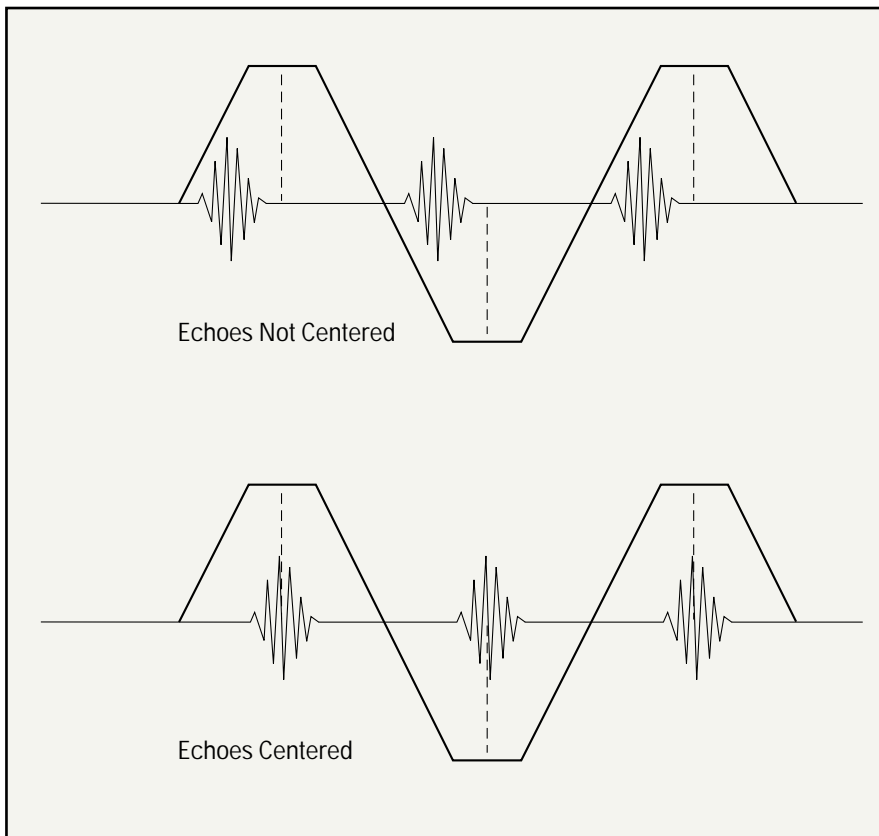


Figure 32: Phase shifts for reference scan

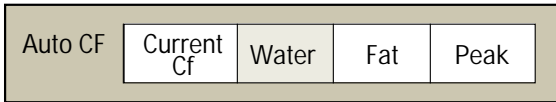
The reference scan is launched after a successful prescan (assuming **Phase Correction** has been selected). During the reference scan the message “ref in progress” is displayed in the reconstruction message window. After the calculations are done the message “ref complete” appears. The scan will now proceed as normal.

It should be noted that the reference scan process is completely automated. The user can select either **Prescan**, **Prep for Scan**, or **Scan**. The system will launch prescan, then, assuming the prescan is successful, the “ref”, and finally the scan. If **Manual Prescan** is initially selected, the “ref scan” must be launched manually by typing **ref** into the scan control bar.

The reference scan is an extremely important element of obtaining a successful EPI series. It should be used on every EPI sequence. The **Phase Correction** button is defaulted on any-time EPI is selected.

POINTS TO REMEMBER

- AutoShim is very important with EPI sequences. It is recommended that it be used for at least the first EPI sequence in any plane.
- Phase Correction launches the “ref scan” following a successful prescan. The ref scan calculates the required corrections in the placement of echoes underneath the frequency gradient. All EPI scans should be run using Phase Correction.



CENTER FREQUENCY

Since EPI is always fat suppressed, **Water** should always be the center frequency selection. If AutoShim is not being utilized and the center frequency for the previous series is determined by the user to be the correct frequency, then **Current CF** can be used to shorten the prescan time. If AutoShim is being used, the **Current CF** button is not selectable because the system needs the “freedom” to adjust the center frequency during shim manipulations.

POINTS TO REMEMBER

- Always center on water for EPI sequences.
- Current CF may be used to shorten prescan time if the previous series used the correct center frequency for water and the new series has NOT changed any parameters that may alter the apparent water frequency.

Receive Bandwidth	Other	400	200	100	62.5
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RECEIVE BANDWIDTH

As discussed earlier in this guide, the receive bandwidth affects the ESP to a great extent. In general, a RBW of +/- 32kHz is narrow and is used only for sequences of 16 shots or higher, a RBW of +/- 62.5kHz is considered medium

and is recommended for sequences using between 8 and 4 shots. It is noted, however, that for non-EchoSpeed systems, $\pm 62.5\text{kHz}$ is the maximum RBW. In cases where single shot imaging is desired, these systems are limited to resolution matrices of no higher than 128×128 . For EchoSpeed systems, ramp sampling can be utilized to reduce ESP in single shot imaging. Recall that the system takes control of the RBW when ramp sampling is used.

EchoSpeed systems are limited to $\pm 62.5\text{ kHz}$ when using phased array coils. Also, RBWs of $\pm 62.5\text{kHz}$ and lower use the standard receiver while RBW higher than $\pm 62.5\text{kHz}$ use the fast receiver.

POINT TO REMEMBER

- The wider the RBW, the more narrow the ESP at the cost of SNR.

FOV	Other	18	20	24	30	40
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FOV

The FOV selected is another parameter that affects the ESP in an EPI sequence. The general rule:

The larger the FOV, the shorter the ESP, assuming all other parameters remain the same.

The area under the frequency encoding gradient is inversely proportional to the FOV. This means that as the FOV decreases the area under the frequency gradient must increase. For a fixed slew rate, the amplitude of the frequency gradient must increase to obtain smaller FOVs. All other parameters remaining the same, a sequence requiring a smaller FOV will require a longer rise time

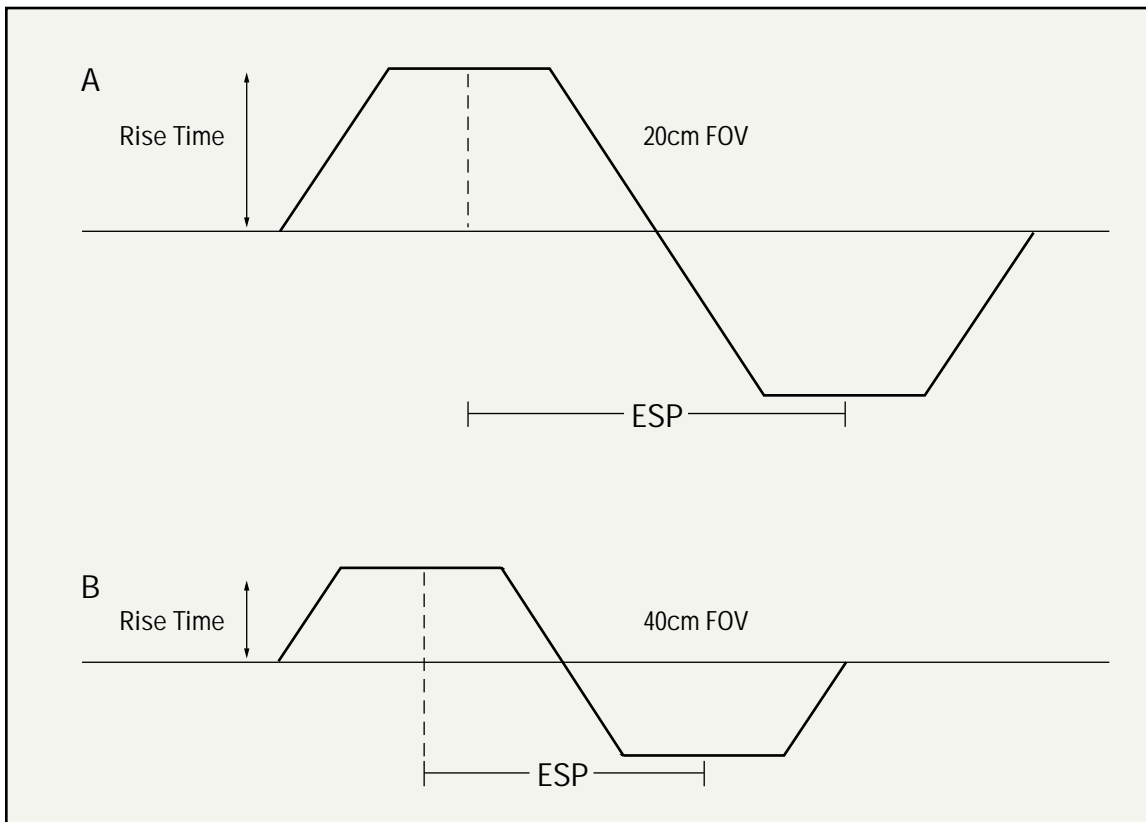


Figure 33: Effect of FOV on ESP.

to reach its peak amplitude. This increase in rise time translates into increased ESP. Figure 33 illustrates this point.

Note that gradient A with a 20cm FOV requires a longer rise time while gradient B requires half that time for a 40cm FOV. Since the rise and fall time for B is shorter than A, the overall ESP for B is shorter even though the flat top portion of both gradients is the same indicating the same number of frequency encoding steps. Of course, a balance between FOV resolution and ESP must be found to produce an EPI image that meets overall image quality requirements.

POINTS TO REMEMBER

- The area under the frequency gradient determines the FOV while the flat top determines the number of samples to be collected.
- The smaller the FOV, the more area under the frequency gradient is required, thereby increasing the rise and fall time of the gradient. This lengthens the ESP and therefore increases geometric distortion.
- The larger the FOV, the shorter the ESP will be at the cost of resolution, all other parameters remaining the same.



FAT SUPPRESSION, NOT SATURATION: THE ROLE OF SPATIAL/SPECTRAL PULSES IN EPI

As stated before, EPI sequences are always fat suppressed. However they are not fat saturated. There is no need to select Fat Sat to suppress the fat signal in EPI sequences. The selection of EPI as a pulse sequence automatically utilizes specialized spatial/spectral excitation pulses to suppress the fat signal. In essence, these pulses are designed to excite ONLY the water spins leaving fat spins unexcited and producing no signal. (Note: For EPI sequences on the 0.5T MR systems there are no spatial/spectral pulses used due to a chemical shift of only 73Hz between fat and water. Fat Saturation is required for EPI at 0.5T.)

The spatial aspect of these pulses refers to their slice-select nature. Each slice is spatially excited instead of the entire imaging volume as with Fat Saturation. The spectral nature refers the precise center frequency used in the pulse to excite only the water spins. It is this spectral aspect that requires a very uniform local magnetic field, therefore AutoShim should always be used, especially with anatomic areas far from isocenter. It is the combination of the spatial/spectral that make EPI images so heavily and uniformly fat suppressed. Note the complete void of fat signal in the orbits in Figure 33.

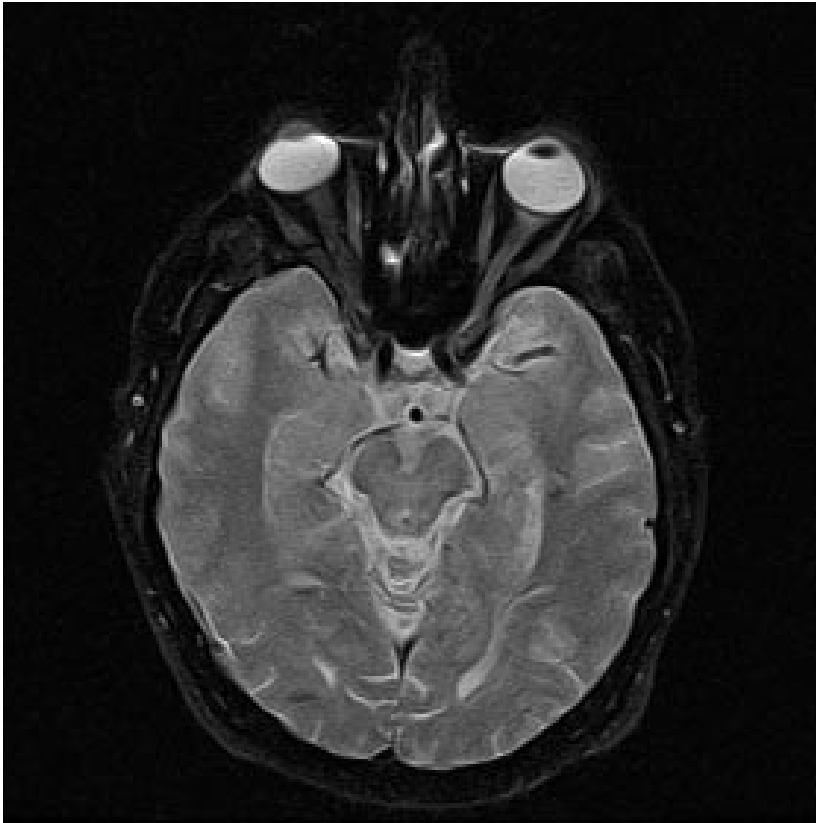


Figure 33: 1.0T 512 orbits

POINTS TO REMEMBER

- EPI images are fat suppressed, though not fat saturated, through the use of spatial/spectral excitation pulses.
- Spatial/Spectral pulses provide heavy and uniform fat suppression even far from isocenter. AutoShim is recommended.
- Spatial/Spectral pulses are used automatically for 1.0T and 1.5T EPI imaging. At 0.5T, Fat Saturation is used instead.

Frequency Matrix

Other	64	128	256
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Phase Matrix

Other	32	64	128	256	512
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FREQUENCY AND PHASE MATRIX

Generally EPI has been thought of as limited to medium-to-low resolution matrices due to ESP constraints (and thereby, geometric distortion constraints). Resolutions of 256x256 were commonly the upper limit for EPI. On the Signa MR system this is far from true. Resolutions of 512x512 are practical with EPI provided all other parameters are selected with care. The image on page 93 is a 512x512 EPI that was acquired over 16 shots with a 62.5kHz RBW.

Because the frequency encoding gradient is used to generate each echo train and its relationship to ESP is understood, the selection of the frequency matrix has a important a ffect on ESP as well. The general rule:

The larger the frequency matrix, the greater the ESP but the higher the resolution in the frequency direction.

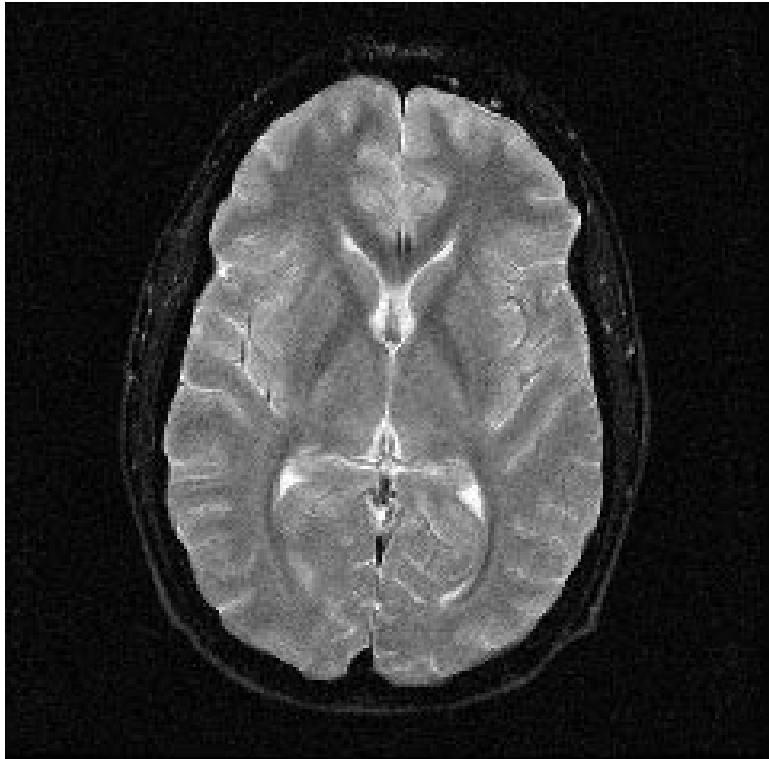


Figure 34: Axial T2-weighted head. Image was acquired using 16 shots. TR: 2850, TE: 80eff, 24 FOV, 512x512, 4 NEX. Scan time was 3:05.

Finding the right balance between resolution and ESP is important to the overall quality of an EPI image.

Generally, a selection of 256 frequency encoding steps is adequate for sequences utilizing 8 shots or higher and RBWs between $\pm 64\text{kHz}$ and $\pm 32\text{kHz}$. However, for sequences where ultra high resolution is required in only one direction, it is recommended that the 512 matrix selection be in the **phase direction** instead of the frequency direction as normally done with other sequences. Recall from chapter 2 that the longer the frequency encoding gradient must be on, the greater the ESP and therefore the greater the geometric distortions caused by off-resonance water protons. Hence it can be more advantageous not to increase frequency encoding steps depending on other parameters. Figure 35 illustrates the effect of increasing frequency

encoding steps on ESP. In this example, 8 frequency encoding steps are used and then the steps are doubled to 16. Assuming that the receive bandwidth remains the same, the ESP increases by a factor of two and therefore the geometric distortions increase as well. To prevent unacceptable increases in geometric distortion, increases in frequency steps should be balanced with increases in the number of shots and/or RBW to maintain short ESPs.

This principle of increasing phase encoding rather than frequency encoding is in contrast to other sequences where higher frequency steps are selected in order to maintain scan time yet still obtain high resolution. Since EPI scan time is equal to the $\text{TR} \times \# \text{ shots} \times \text{NEX}$, increasing the number of phase encoding steps does not directly increase scan time, provided the slice coverage is maintained. Since increasing the phase matrix will result

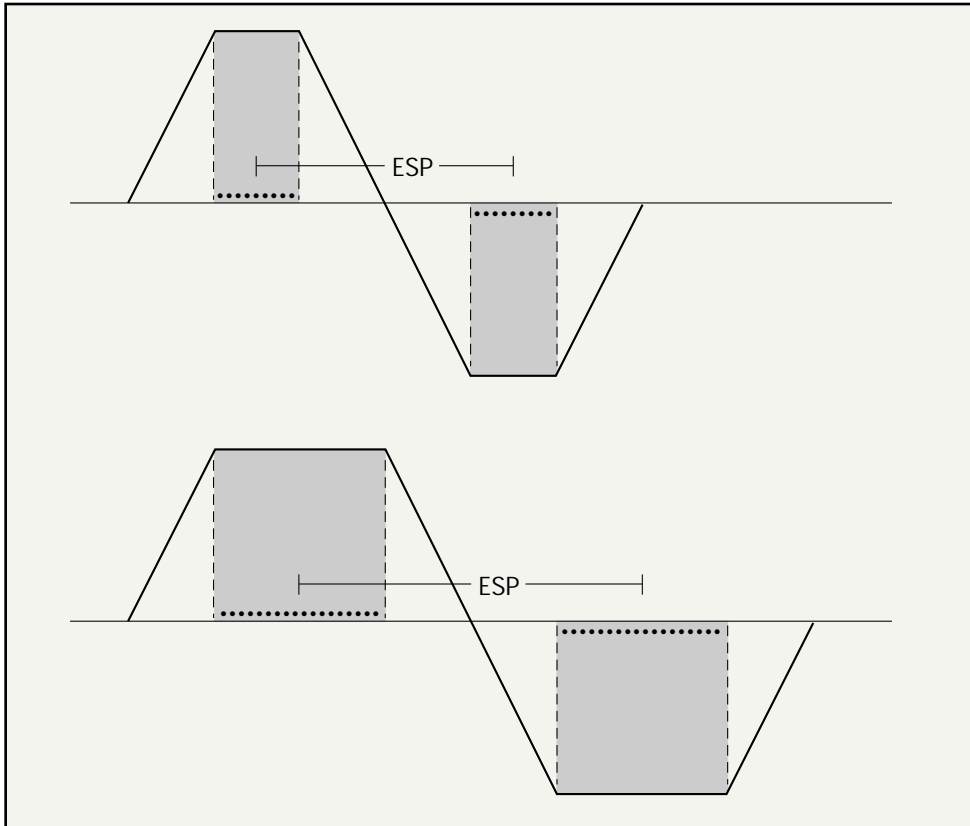


Figure 35: Effect of frequency encoding matrix on ESP.

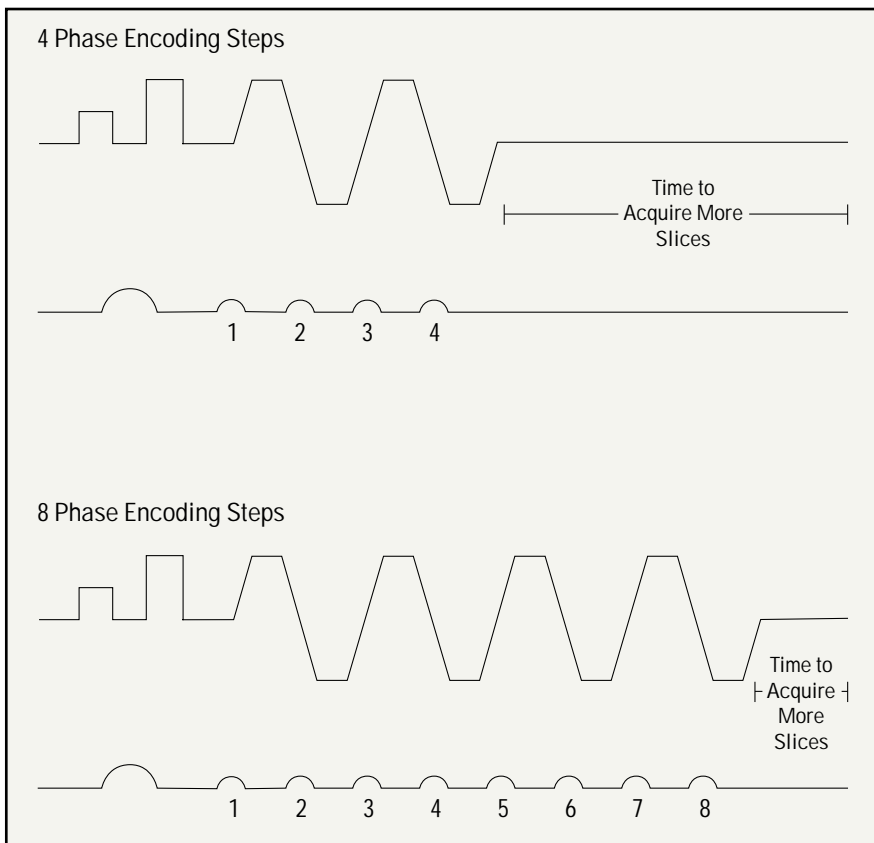


Figure 36: Effect of phase encoding steps on slices per TR.

in a longer echo train, the time allowed for exciting new slices decreases. To maintain the same slice coverage from 256 phase encoding to 512, for example, the TR may have to be increased resulting in an increased scan time. Figure 36 illustrates the loss of slices that will result from increasing the phase matrix. In this example, the first sequence uses 4 phase encoding steps that allow a certain time within the TR for more slices. Increasing the phase steps to 8, while causing no increase in ESP, takes up time within the TR resulting in a net loss in slices. If the loss in slices likewise results in a loss of required anatomic coverage, the TR will need to be increased to allow for adequate slice coverage.

Note that the first phase encoding step continues to be played out immediately after the excitation pulse just as with standard spin echo and gradient echo sequences. In EPI, the first phase encoding step is used to determine where in k-space the first line will be filled.

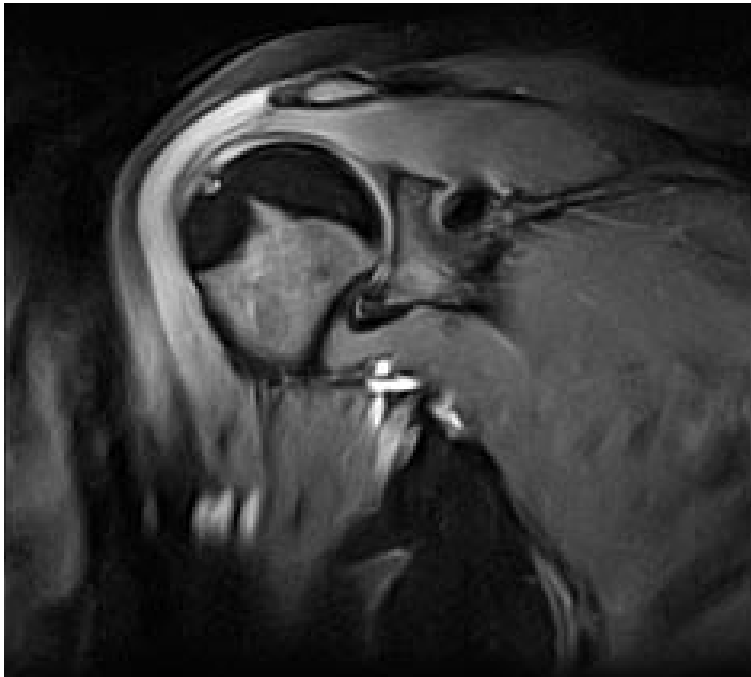


Figure 37: Proton Density oblique image of the shoulder using Multi-Shot EPI. Note the heavy fat suppression far from isocenter as well as strong contrast. Technique was 16 shots, 2000TR, 35TEeff, 20cm FOV, 4 NEX, 192x256 matrix. Note: 192 frequency. Scan Time: 2:10.

Finally, it should be noted that with EPI sequences, the user is allowed matrices as low as 32×32 . The reason such low resolution scanning is permitted is because certain EPI applications, such as those designed to detect minute blood oxygen levels, do not have high resolution requirements but do have high SNR requirements. Sequences using such low matrices also reconstruct faster than those of higher resolution matrices.

POINTS TO REMEMBER

- Increasing the frequency encoding steps increases ESP and ultimately geometric distortions.
- For most multi-shot EPI sequences, 256 frequency encoding steps provide a good balance between resolution and ESP. Increases in frequency steps should also include increases in number of shots or receive bandwidth to maintain short ESPs.
- Increases in phase encoding steps do not increase ESP nor scan time but do decrease number of slices allowed within the TR.

Phase	.62 FOV	1.0	.5
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PHASE FOV

The **Phase FOV** ratio offers the user more flexibility when using EPI. It provides a powerful method for increasing the phase resolution without increasing the ESP or decreasing the slices per TR.

First, the phase FOV ratio is not limited to 1.0, .75, or .5. By accessing the **Other** button, the user can select any decimal number lower than one. In the graphic above, .62 is entered as an example of this flexibility. The resultant image will be 62% of the selected FOV in the phase direction.

Second, and more important, is what occurs when a number less than one is selected. With other sequences, values lower than one cause the system to acquire only part of the phase

encoding steps selected. For example, if 256 phase encoding steps were selected and then a Phase FOV of .5, then only the middle 128 phase encoding steps are collected. The first 64 and last 64 steps are not collected. This results in shorter scan times while maintaining the selected resolution at the cost of SNR. In EPI, things work differently and in favor of resolution and not scan time.

With EPI, selections of phase FOV less than one cause the system to “squeeze” the FOV in the phase direction by the amount selected collecting all the phase steps but reducing the pixel size in the phase direction thus increasing the resolution in the phase direction. For example, if 128 phase encoding steps were selected then a .5 phase FOV, all 128 steps are collected but since the FOV is halved in the phase direction the pixel size is also halved resulting in doubled pixel resolution in the phase direction. The image would have half the FOV in the

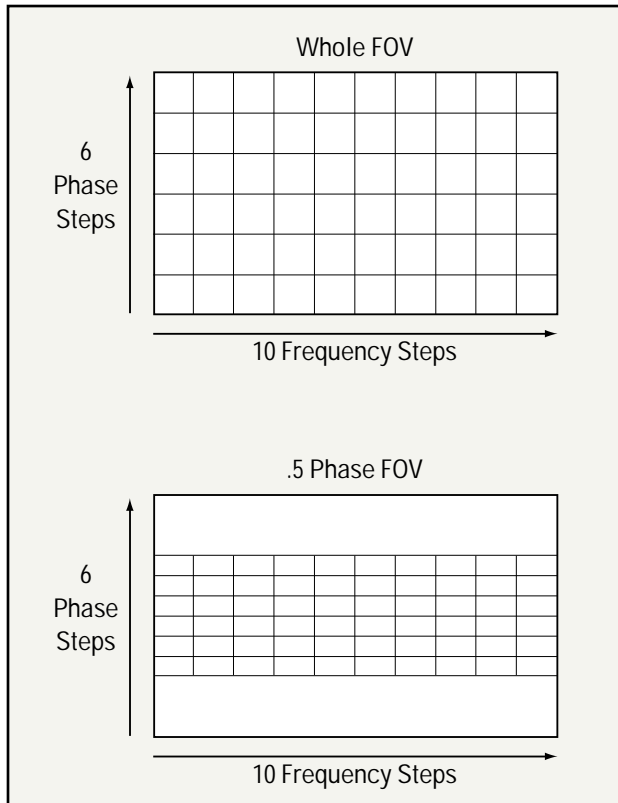


Figure 38: Decreases in phase FOV result in higher resolution in the phase direction.

phase direction but would have the resolution of 256 phase encoding steps. If the original selections for frequency and phase had been 256x128 with .5 phase FOV, the image would display the resolution of 256x256. Figure 38 illustrates this point. In EPI, a reduced phase FOV, increases resolution while maintaining scan time.

Another benefit of smaller phase FOVs is that the degree of geometric distortion appears less since there is less “room” within the FOV for the distortions to displace. Of course, the decreases in phase FOV will also result in decreases in SNR, just as with other sequences. However, since the Phase FOV Other key accepts any value, the size of the FOV in the phase direction can be tailored to the anatomy.

POINTS TO REMEMBER

- The Phase FOV function can accept any value less than one.
- Selecting a value less than one decreases the FOV in the phase direction while collecting all the phase steps selected in the phase matrix.
- The pixel size is decreased effectively increasing the resolution in the phase direction while maintaining scan time.
- Decreases in phase FOV reduce the amount of geometric distortion.

Direction Frequency	A/P	R/L
------------------------	-----	-----

FREQUENCY DIRECTION AND PERIPHERAL NERVE STIMULATION

For EPI sequences, the frequency direction selections are determined in the same manner as with any other pulse sequence EXCEPT for certain imaging planes in the head coil. For axials, axial obliques, coronals and coronal obliques, the phase and frequency directions are automatically swapped for two reasons: geometric distortion presentation and to reduce the potential for peripheral nerve stimulation.

As the images in figure 39 demonstrate, when the frequency direction of an axial head image is left at the “normal” A/P direction, the geometric distortion around the petrous ridges are displaced in the R/L direction (the phase direction). Since the naturally

symmetry of the head is more an A/P direction, swapping the frequency direction to make phase A/P forces the geometric distortion into a more symmetrical presentation. Note that swapping the phase and frequency direction does not reduce the amount of distortion, but only changes its direction and its appearance.

The more important reason for these swapped phase and frequency directions in the head coil deals with reducing a phenomenon known as peripheral nerve stimulation. It must be stated as clearly as possible that peripheral nerve stimulation is NOT harmful and the potential for inducing peripheral nerve stimulation is kept within FDA-cleared limitation by software. Yet it can occur while imaging in any plane with any coil. Still, it may be considered a patient comfort issue and since the potential exists it should be discussed.

Peripheral Nerve Stimulation (PNS) has been described as a light

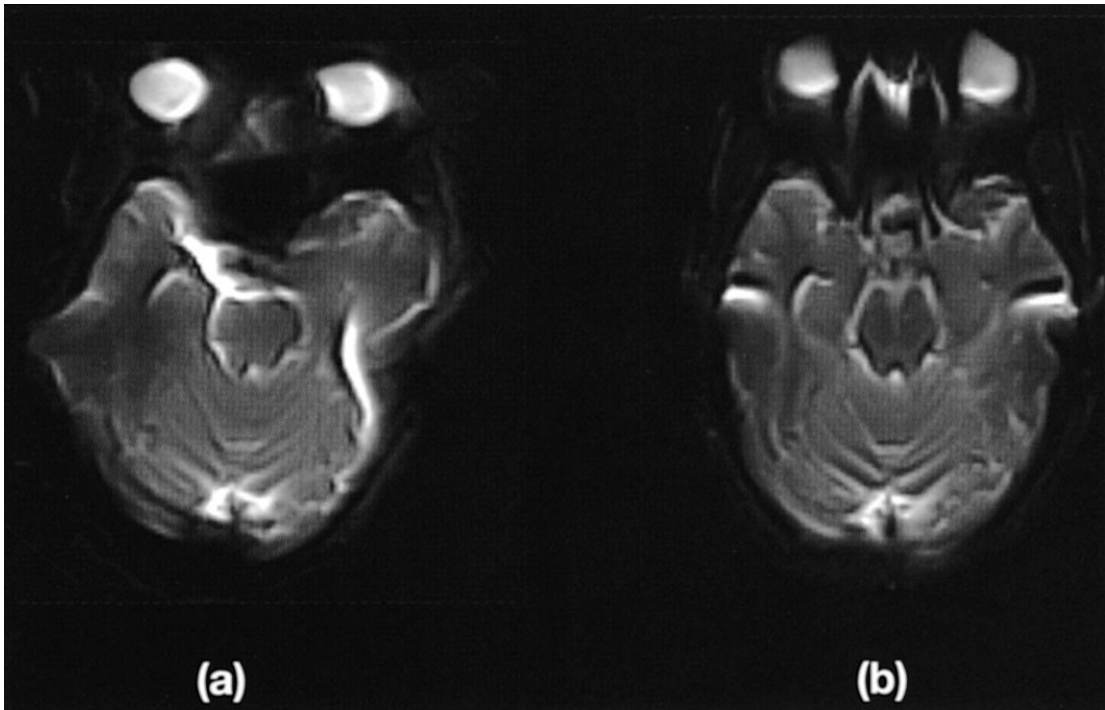


Figure 39: A comparison of two skull base images with (a) phase R/L and (b) phase (A/P). In general, whenever echo planar imaging is performed in a region with a natural axis of symmetry, the phase encode direction should be placed along that axis.

“touching” sensation felt on various areas on the skin surface. These areas will vary depending upon which gradient axis is being used and when. Some of the more common areas are the bridge of the nose, arms, chest, and upper abdomen. Also, hands clasped together increases the potential for stimulation. Keeping the hands from touching (“breaking the circuit” so to speak) will decrease the potential for inducing stimulation by ~45%.

Peripheral nerve stimulation is induced by very rapidly switching gradient fields. The rate at which these fields switch is given as a value of dB/dt , or the change in the local magnetic field divided by the change in time, in terms of Tesla per second, T/s . Conventional MR systems generally operate at dB/dt levels of $\sim 10\text{T}/\text{s}$. High performance gradient systems produce dB/dt levels of $45\text{-}60\text{T}/\text{s}$. At certain dB/dt levels the possibility of inducing stimulation of

nerves along the surface of the skin increases, depending on the length of time the gradient is actually switching. The point at which 50% of a population will experience PNS is the **PNS threshold**. The PNS threshold is a function of the dB/dt and the gradient ramp time. Ramp time is the time for a gradient to go from maximum value in one direction to the maximum value in the another.

The “Reilly Curve”¹ (figure 40) is a predictor of when the PNS threshold will be reached for a given dB/dt and ramp time. Note that as ramp times shorten, the “allowable” dB/dt increases. The Signa Horizon, Horizon HiSpeed, and Horizon EchoSpeed MR systems are all limited from operating above 66% of the PNS threshold by software. The chances of inducing PNS are exactly the same for ALL pulse

¹ Reilly, J.P., *Med. & Biol. Eng. & Comput.*, 1989; 27: 101-110

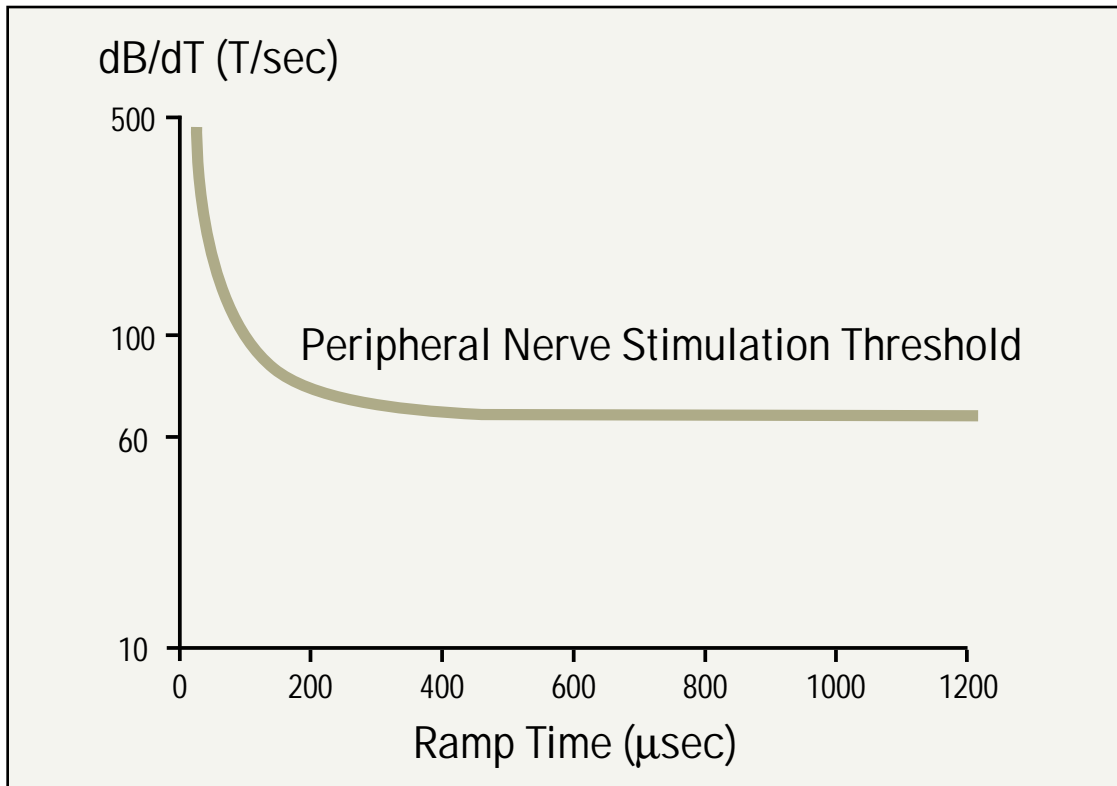


Figure 40: Reilly curve. Illustration of mean peripheral nerve stimulation threshold in Tesla/sec versus ramp time in msec.

sequences on the Horizon and Horizon HiSpeed systems. **Only on the Horizon EchoSpeed, where EPI sequences can utilize gradients slewing at 120 T/m/sec, can using EPI increase the potential for PNS above other pulse sequences. Even so, the potential remains low. Still, as low as the potential is, if any patient complains of uncomfortable sensations on the skin surface during any pulse sequence, the scan should be stopped and the incident reported to GE Medical.**

POINTS TO REMEMBER

- The phase/frequency directions are automatically swapped for axial, axial obliques and coronals and coronal obliques in the head coil.
- Keeping the phase direction A/P for axials (and like obliques) and S/I for coronals (and like obliques) makes geometric distortions less obtrusive and reduces the potential for peripheral nerve stimulation (PNS).

POINTS TO REMEMBER

- PNS is described as a light touching sensation felt during some sequences in which gradient fields switch back and forth rapidly.
- PNS is NOT harmful.
- While the potential for PNS is low, it exists for all sequences in all gradient configurations.
- Gradient systems with higher dB/dt levels have an increased potential for inducing PNS.
- The Horizon EchoSpeed system utilizes higher dB/dt levels during some EPI sequences.
- Signa MR systems are limited to operating at no more than 66% of the PNS threshold.
- Patients who complain of PNS during an EPI sequence should have the series stopped and replaced with another pulse sequence. If the PNS occurs with a non-EPI sequence, the patient should be removed from the magnet and the incident reported to GE Medical Systems.

COMMON ARTIFACTS AND THEIR REDUCTION

EPI can yield images of high contrast and/or extremely short scan times. It is flexible enough to be used with many field strengths, gradient configuration, or anatomic region. However, it is a very sensitive sequence and artifacts can be present if any parameter is selected incorrectly. In this chapter, some of the more commonly seen artifacts are presented with suggested actions to remove or reduce the artifact. Attention will also be given to determining artifacts that may be caused by improper parameter selection or physics.

PHYSIOLOGIC ARTIFACTS

Whether it is mis-tuned gradient hardware, a bad exciter board, or poor shim, system-related problems that cause artifacts in EPI images all exhibit themselves in the same basic manner: ghosting. While minor ghosting caused by such things as flow or patient motion is expected in any pulse sequence, severe ghosting is NOT a normal nor expected result in an EPI sequence. However, ghosting in an EPI image may not always be caused by a system problem. A carefully trained eye will aid in discerning if visible ghosting is caused by a system problem or physiologic motion. The next two pages contain examples of ghosting.

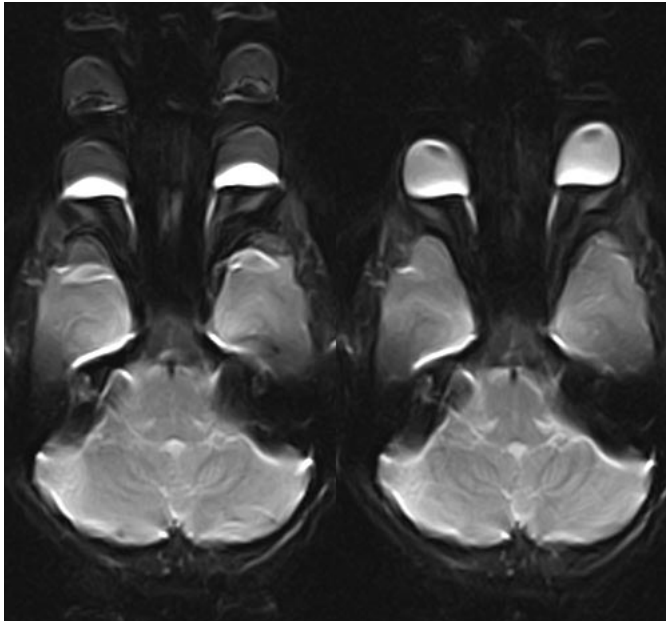


Figure 41: The importance of controlling eye motion is illustrated here. Both images were acquired using an 8 shots ± 32 kHz multi-shot EPI scan. The image on the left shows the artifact produced when the eyes are moving. The image on the right was done with the eyes held as still as possible. In order to reduce the potential for PNS, the phase direction runs A/P in axial and coronal planes in the head coil, thus motion artifacts will also run A/P.

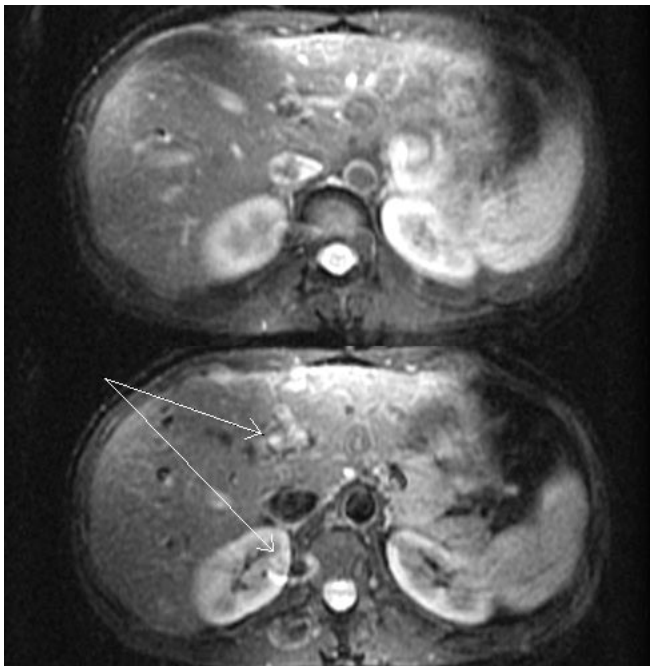


Figure 42: Demonstrates liver imaging with and without Flow Compensation. Both images are 8 shots EPI scans using a 2000TR and 80TE. The top image uses Flow Comp and Saturation pulses in the inferior and superior direction. The bottom image uses only the saturation pulses. Note the increase in flow artifact from the inferior vena cava in the bottom image.

SUSCEPTIBILITY ARTIFACTS

Artifacts caused by magnetic susceptibility effects can be reduced through changes to parameter selection. Recall that EPI is extremely sensitive to susceptibility effects. Metal and air in the region of interest are the two biggest causes of susceptibility artifacts. Moreover, the susceptibility effects exhibit themselves as geometric distortions in the image and these distortions can be controlled by reducing the ESP. Note, that depending on the degree of susceptibility, it may not be possible to eliminate the artifact completely. Note the EPI image of a patient with braces. Even with multiple shots (and therefore a short effective ESP) and being far into the most homogeneous section of the anatomy, the susceptibility effects of the braces cause massive artifacts in all the images.

The air-filled cells of the petrous ridges can be particularly prone to geometric distortions. However, as seen in the images in figure 44, these regions can be made relatively free of distortions by increasing the number of shots.

The abdomen (figure 45) may present a different set of obstacles. Bowel air can be particularly troublesome if large amounts exist and may produce extensive geometric distortions. Increasing the number of shots to reduce the ESP (and therefore the distortion) will increase the scan time – possibly beyond reasonable breath-hold times. In these cases, weigh the benefits of EPI, speed, and contrast against the possibility of geometric distortion.

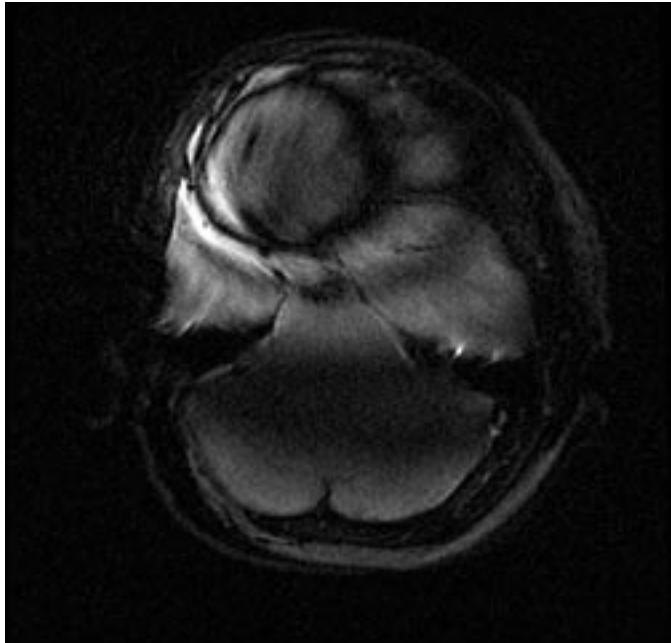


Figure 43: Note the artifact caused by metal even in slice locations where the metal is not imaged. In this case the patient had braces on the teeth of the upper jaw. The metal causes such a large inhomogeneity in the local field that all the images in the data set are rendered useless. Images were acquired using 16 shots with a RBW of $\pm 32\text{kHz}$.

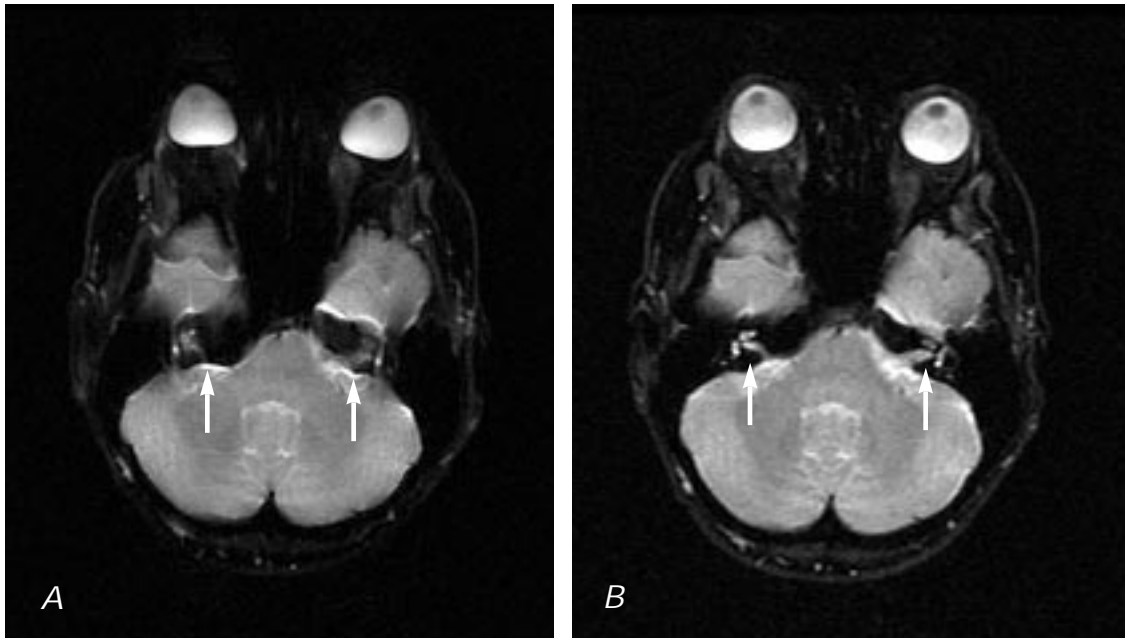


Figure 44: EPI imaging in the region of the IACs is possible with correct parameter selection. Figure A: 8 shots, 256x256, ESP=384 microseconds, scan time: 1:23. Figure B: 32 shots, 192x256, ESP=128 microseconds, scan time: 2:43. All other parameters remain the same (TR:2500, TE:80, 4mm thickness, FOV:22cm). Note the sharp visualization of the IAC region in Figure B.

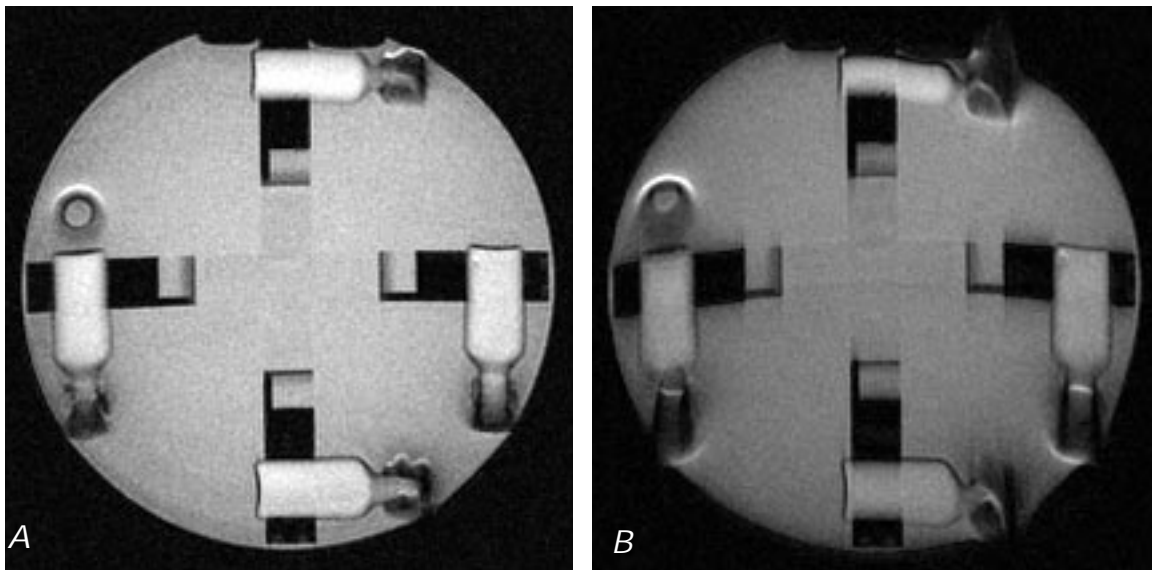


Figure 45 a and b (Air Bubbles): The effect of air on geometric distortion in a phantom containing air bubbles. Figure A is a 32 shot EPI scan while figure B is 8 shots. All other parameters are the same. Note the increase in distortions in B due to the effects of the air interfaces. Figure B with its fewer number of shots has a greater ESP and therefore is more prone to distortions.

POINTS TO REMEMBER

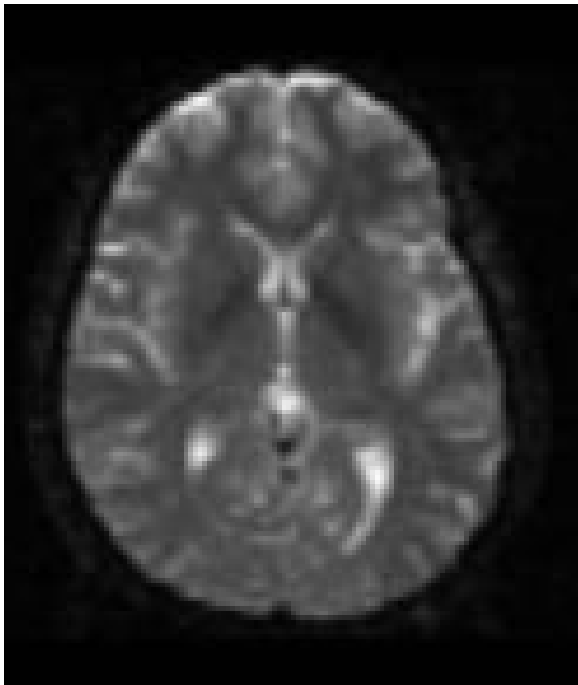
- Severe ghosting MAY be a symptom of a system problem but its presence is not exclusive to a system problem.
- Eye motion can be troublesome in the axial plane since the phase direction runs anterior-to-posterior. Reduce eye motion through patient intervention.
- Use SAT and Flow Compensation to reduce artifacts caused by flow motion in the abdomen.
- Geometric distortions are a fact of life in EPI but can be reduced (by increasing shots, receive bandwidth, etc.) to decrease the ESP.

PROTOCOLS AND IMAGES

Listed on the pages that follow are several suggested protocols for the head, abdomen, and cardiac regions. These are not the only possible combination of parameters. Also, they can be used and varied for other anatomic regions. These protocols assume 1.5T field strength. For other field strengths,

variations should be made to accommodate signal-to-noise ratio issues. When varying the parameters remember to consider number of shots, receive bandwidth, anatomic region (tissue-air interfaces), and slew rate in order to keep the ESP short yet still provide adequate SNR and resolution.

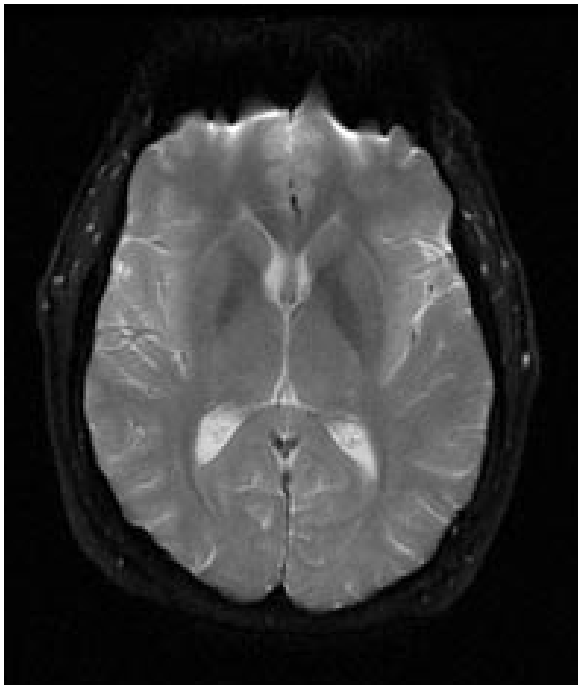
ECHO SPEED EPI PROTOCOLS: HEAD



RAPID BRAIN SCAN

PSD	SE
OPTIONS	EPI , FC
TR	2200
TE	80
TI	-
SHOTS	1
FOV	40 x 20
SLICE THK	5 x 2.5
MATRIX	128 x 128
NEX	1
APPROX. SCAN TIME	:02
RAMP SAMPLING	1
BURST TIME	5
RBW	SYSTEM SET
NOTES	

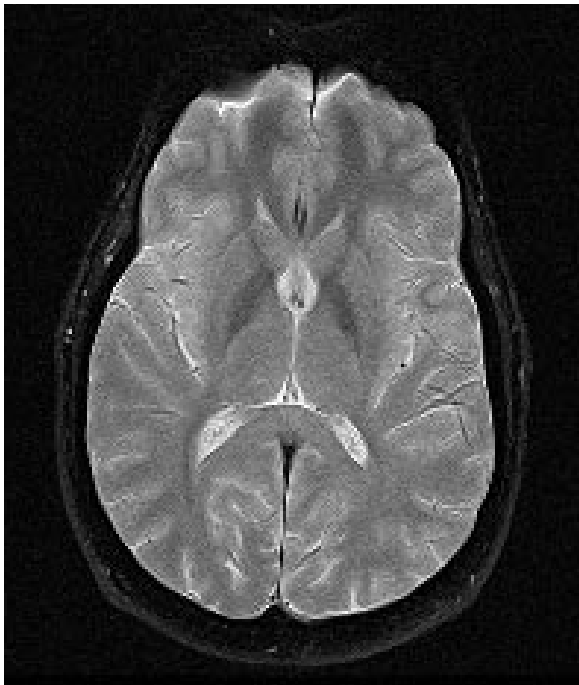
ECHO SPEED EPI PROTOCOLS: HEAD



T2-WEIGHTED MULTI-SHOT

PSD	SE
OPTIONS	EPI , FC
TR	2500
TE	80
TI	-
SHOTS	8
FOV	24 x 24
SLICE THK	5 x 2.5
MATRIX	256 x 256
NEX	4
APPROX. SCAN TIME	1:23
RAMP SAMPLING	0
BURST TIME	0
RBW	62.5
NOTES	

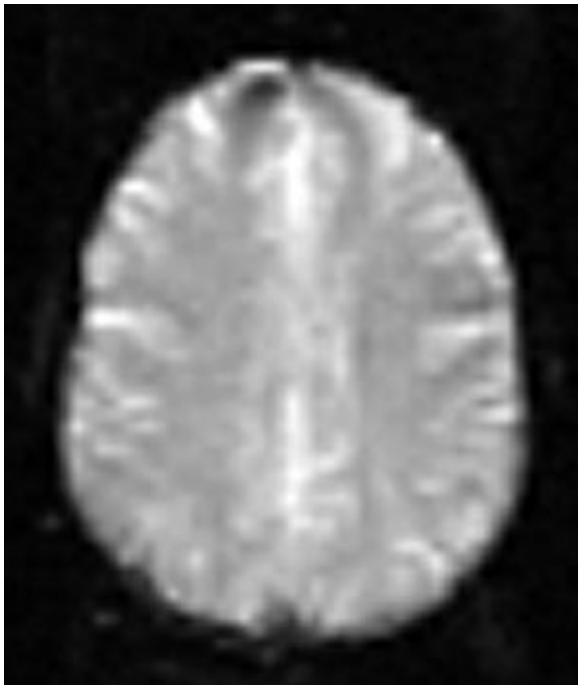
ECHO SPEED EPI PROTOCOLS: HEAD



HIGH RESOLUTION
T2-WEIGHTED MULTI-SHOT

PSD	SE
OPTIONS	EPI , FC
TR	3500
TE	80
TI	-
SHOTS	8
FOV	24 x 24
SLICE THK	5 x 2.5
MATRIX	256 x 512
NEX	4
APPROX. SCAN TIME	1:56
RAMP SAMPLING	0
BURST TIME	0
RBW	62.5
NOTES	512 IN PHASE DIRECTION

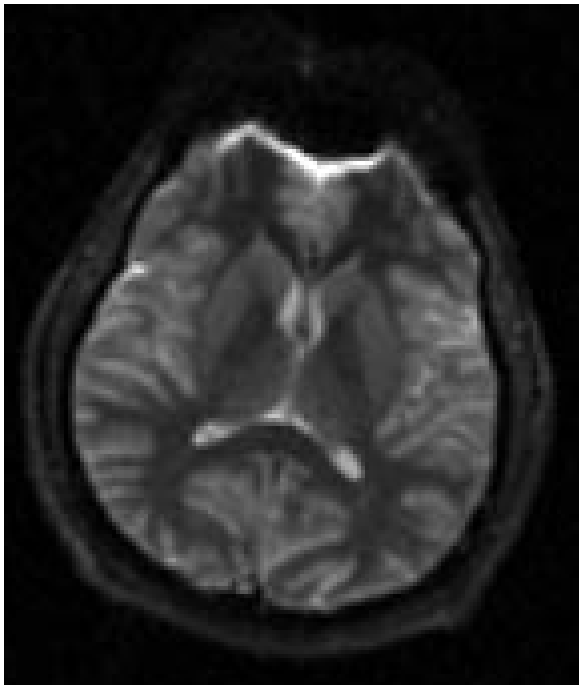
ECHO SPEED EPI PROTOCOLS: HEAD



MULTI-PHASE
SUSCEPTIBILITY WEIGHTED

PSD	GRE
OPTIONS	EPI , FC MP
TR	3000
TE	60
TI	-
SHOTS	1
FOV	40 x 20
SLICE THK	10 x 2
MATRIX	128 x 128
NEX	1
APPROX. SCAN TIME	6:27
RAMP SAMPLING	1
BURST TIME	0
RBW	SYSTEM SET
NOTES	LOCATIONS = 4 PHASES PER LOCATION = 128 MIN. DELAY AFTER ACQUISITION, INTERLEAVED

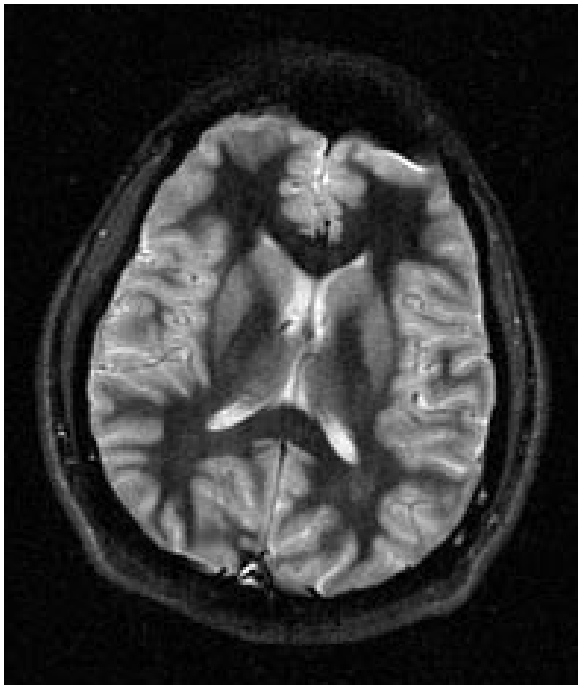
ECHO SPEED EPI PROTOCOLS: HEAD



IR-PREP FOR GRAY/WHITE
MATTER CONTRAST SINGLE-SHOT

PSD	SE
OPTIONS	EPI , FC IR-PREP
TR	4500
TE	40
TI	200
SHOTS	1
FOV	36 x 18
SLICE THK	5 x 2.5
MATRIX	128 x 128
NEX	1
APPROX. SCAN TIME	:05
RAMP SAMPLING	1
BURST TIME	6
RBW	SYSTEM SET
NOTES	

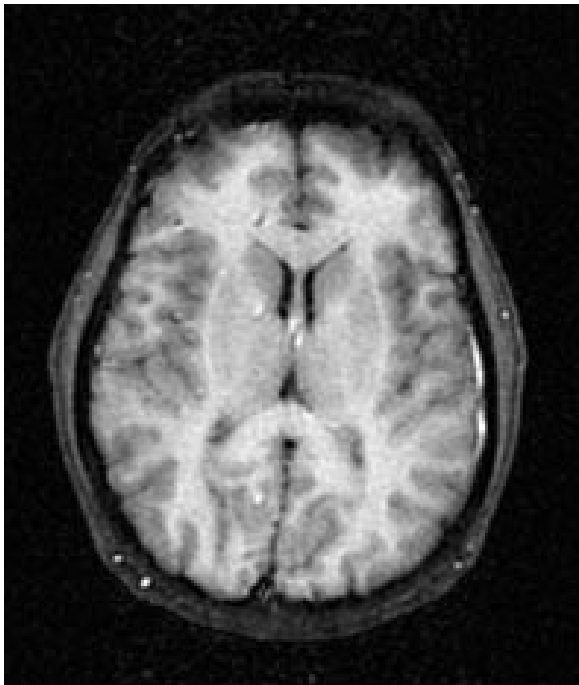
ECHO SPEED EPI PROTOCOLS: HEAD



IR-PREP FOR GRAY/WHITE
MATTER CONTRAST MULTI-SHOT

PSD	SE
OPTIONS	EPI , FC IR-PREP
TR	3500
TE	40
TI	250
SHOTS	8
FOV	24 x 24
SLICE THK	5 x 2.5
MATRIX	256 x 256
NEX	2
APPROX. SCAN TIME	1:59
RAMP SAMPLING	-
BURST TIME	-
RBW	62.5
NOTES	

ECHO SPEED EPI PROTOCOLS: HEAD



IR-PREP
T1-WEIGHTED MULTI-SHOT

PSD	SE
OPTIONS	EPI , SAT:1 IR-PREP
TR	2000
TE	MIN
TI	800
SHOTS	8
FOV	24 x 24
SLICE THK	5 x 2.5
MATRIX	192 x 192
NEX	2
APPROX. SCAN TIME	2:42
RAMP SAMPLING	-
BURST TIME	-
RBW	62.5
NOTES	

ECHO SPEED EPI PROTOCOLS: ABDOMEN



MULTI-SHOT BREATH-HELD

PSD	SE
OPTIONS	EPI , FC SAT:SI
TR	2000
TE	60
TI	-
SHOTS	8
FOV	36 x 27
SLICE THK	10 x 2
MATRIX	256 x 128
NEX	1
APPROX. SCAN TIME	:18
RAMP SAMPLING	0
BURST TIME	0
RBW	62.5
NOTES	USE TORSO ARRAY COIL

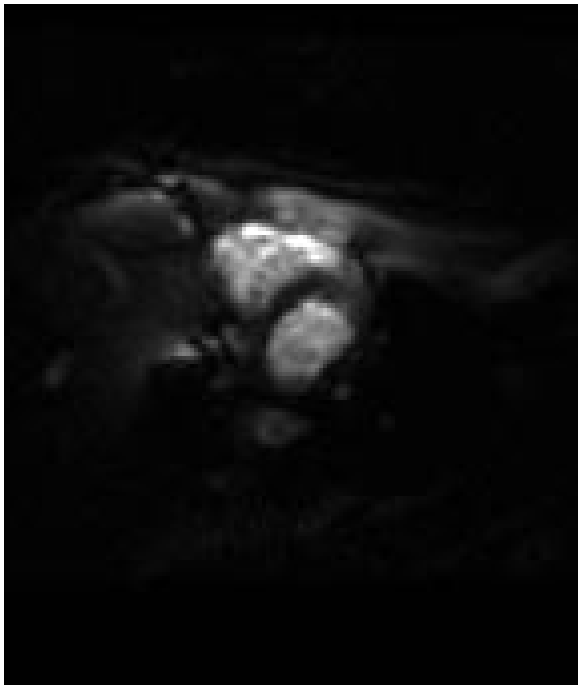
ECHO SPEED EPI PROTOCOLS: ABDOMEN



SINGLE-SHOT NON-BREATH-HELD

PSD	SE
OPTIONS	EPI , FC SAT:SI
TR	2500
TE	60
TI	-
SHOTS	1
FOV	40 x 30
SLICE THK	10 x 2
MATRIX	128 x 128
NEX	1
APPROX. SCAN TIME	:03
RAMP SAMPLING	1
BURST TIME	5
RBW	SYSTEM SET
NOTES	BODY COIL OR BODY FLEX COIL

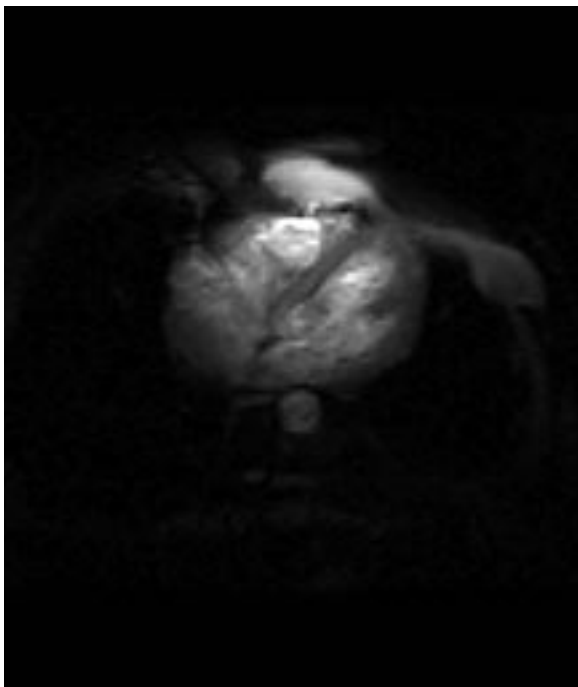
ECHO SPEED EPI PROTOCOLS: HEART



SINGLE-SHOT
NON-BREATH-HOLD NON-GATED
SINGLE-LOCATION MULTI-PHASE

PSD	GRE
OPTIONS	EPI , MP
TR	MIN
TE	MIN
SHOTS	1
FLIP	90
FOV	40 x 30
SLICE THK	7 MM
MATRIX	128 x 128
NEX	1
APPROX. SCAN TIME	:05
RAMP SAMPLING	1
BURST TIME	6
RBW	SYSTEM SET
NOTES	GP FLEX OR BODY FLEX COIL; PHASES=16, SEQUENTIAL

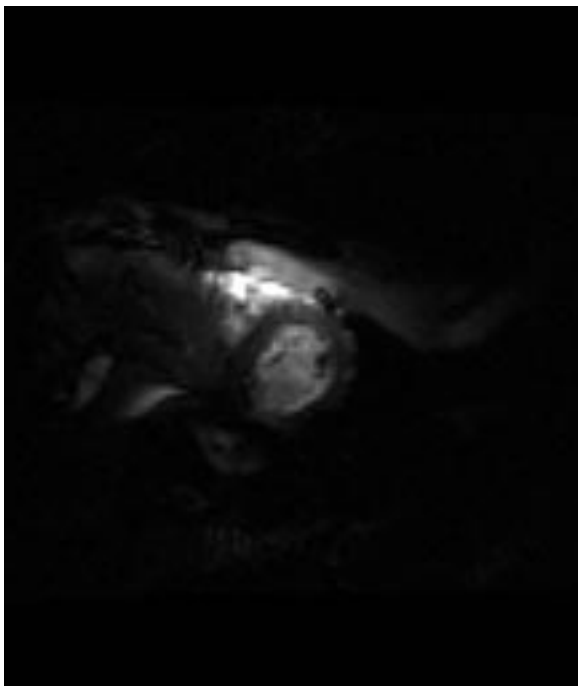
ECHO SPEED EPI PROTOCOLS: HEART



SINGLE-SHOT MULTI-LOCATION
SINGLE-PHASE BREATH-HELD

PSD	GRE
OPTIONS	EPI , FC GATING
TR	GATED
TE	MIN
SHOTS	1
FLIP	90
FOV	40 x 30
SLICE THK	7 x 3
MATRIX	128 x 128
NEX	1-2
APPROX. SCAN TIME	PATIENT DEPENDENT
RAMP SAMPLING	1
BURST TIME	1 SEC > SCAN
RBW	SYSTEM SET
NOTES	GP FLEX OR BODY FLEX COIL; 1 R XR, MIN TRIG DELAY; 15% TW EVEN SPACING; CARDIAC PHASES=1

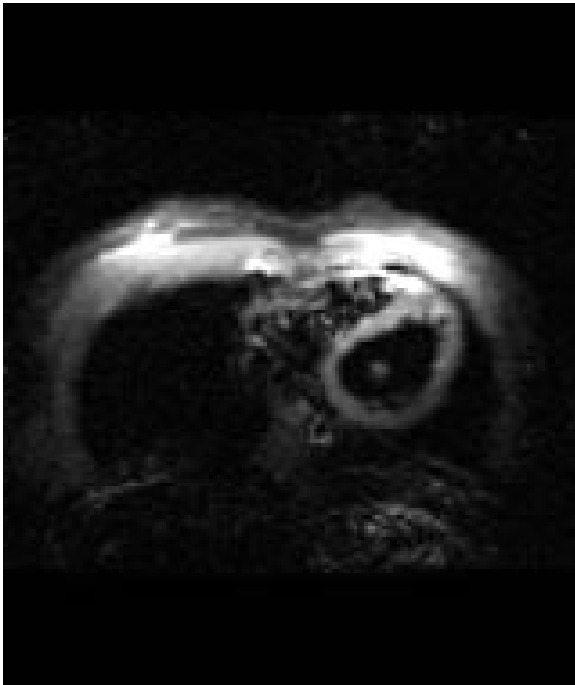
ECHO SPEED EPI PROTOCOLS: HEART



SINGLE-SHOT MULTI-LOCATION
MULTI-PHASE BREATH-HELD

PSD	GRE
OPTIONS	EPI , FC GATING
TR	GATED
TE	MIN
SHOTS	1
FLIP	90
FOV	40 x 30
SLICE THK	7 x 3
MATRIX	128 x 128
NEX	1-2
APPROX. SCAN TIME	PATIENT DEPENDENT
RAMP SAMPLING	1
BURST TIME	1 SEC > SCAN
RBW	SYSTEM SET
NOTES	GP FLEX OR BODY FLEX COIL; 1 R XR, MIN TRIG DELAY; 15% TW EVEN SPACING; CARDIAC PHASES=8

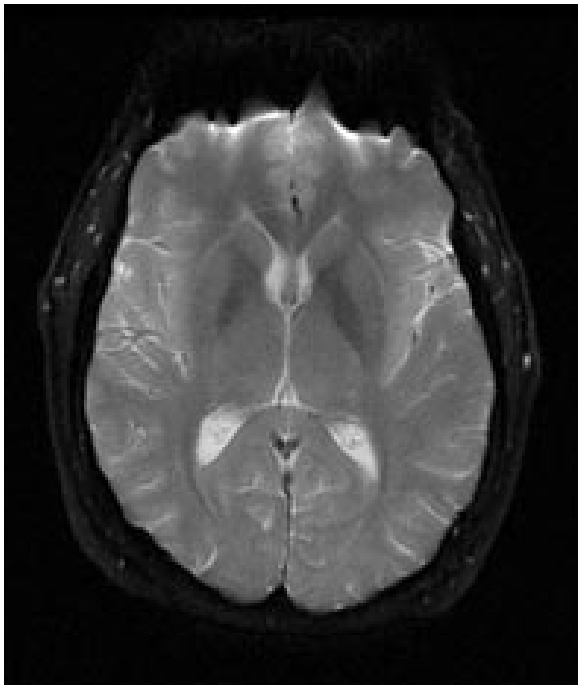
ECHO SPEED EPI PROTOCOLS: HEART



SINGLE-SHOT
MULTI-LOCATION SINGLE-PHASE
MULTI-PHASE BREATH-HELD

PSD	GRE
OPTIONS	EPI , GATING SAT: S/I;MP
TR	GATED
TE	MIN
SHOTS	1
FLIP	-
FOV	40 x 30
SLICE THK	7 x 3
MATRIX	128 x 128
NEX	1-2
APPROX. SCAN TIME	PATIENT DEPENDENT
RAMP SAMPLING	1
BURST TIME	1 SEC > SCAN
RBW	SYSTEM SET
NOTES	GP FLEX OR BODY FLEX COIL; 1 RxR, PHASE=12/LOCATION; INTERLEAVED; MIN DELAY; 1 RxR, MIN TRIG DELAY; 15% TW; EVEN SPACING; CARDIAC PHASES=1

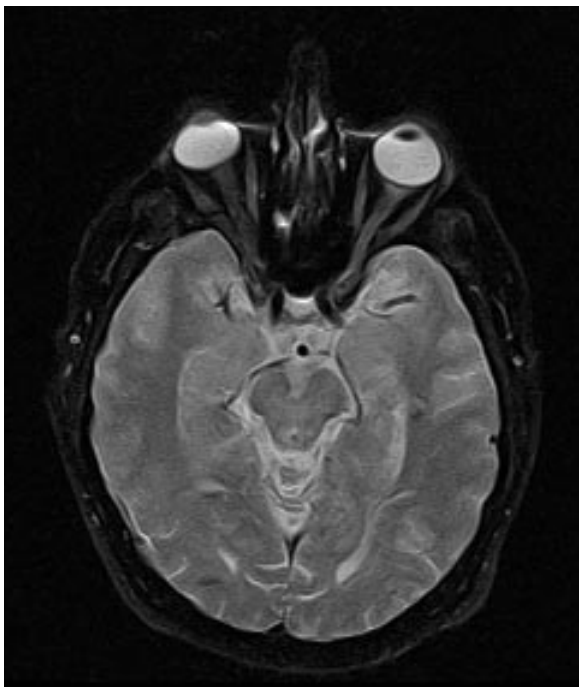
HISPEED EPI PROTOCOLS: HEAD



MULTI-SHOT T2-WEIGHTED

PSD	SE
OPTIONS	EPI , FC
TR	2600
TE	80
TI	-
SHOTS	8
FOV	24 x 24
SLICE THK	5 x 2.5
MATRIX	256 x 256
NEX	3
APPROX. SCAN TIME	1:05
RBW	32
NOTES	

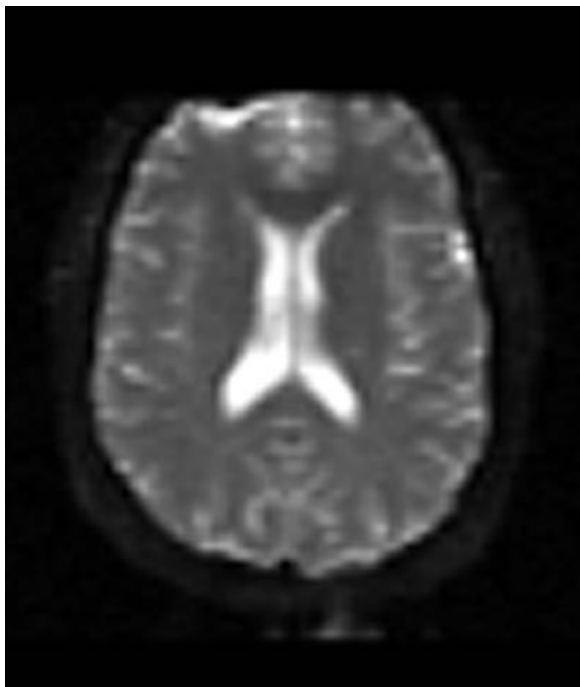
HISPEED EPI PROTOCOLS: HEAD



HIGH RESOLUTION
T2-WEIGHTED MULTI-SHOT

PSD	SE
OPTIONS	EPI , FC
TR	3000
TE	80
TI	-
SHOTS	8
FOV	24 x 24
SLICE THK	5 x 2.5
MATRIX	256 x 512
NEX	4
APPROX. SCAN TIME	1:30
RBW	64
NOTES	512 IN PHASE DIRECTION

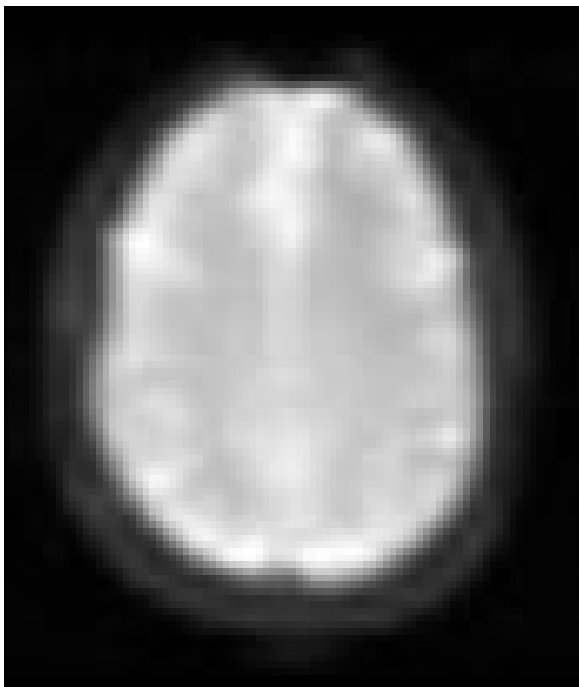
HISPEED EPI PROTOCOLS: HEAD



SINGLE-SHOT T2-WEIGHTED

PSD	SE
OPTIONS	EPI , FC
TR	4000
TE	80
TI	-
SHOTS	1
FOV	36 x 18
SLICE THK	5 x 2.5
MATRIX	128 x 128
NEX	1
APPROX. SCAN TIME	:04
RBW	64
NOTES	

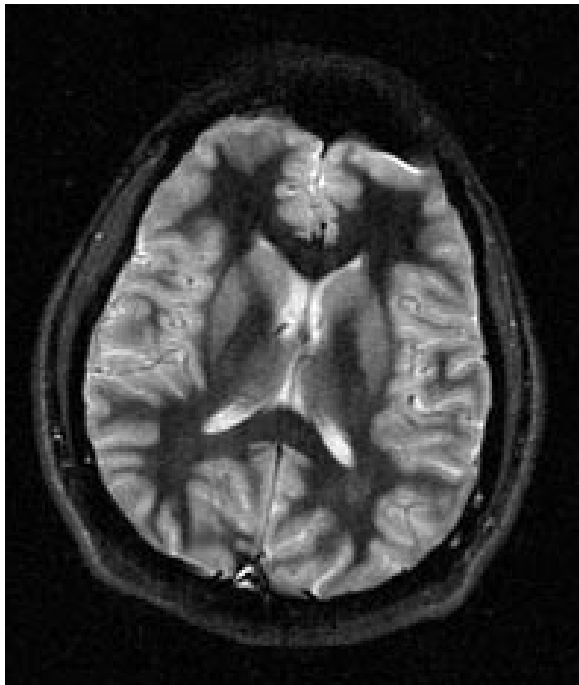
HISPEED EPI PROTOCOLS: HEAD



MULTI-PHASE
SUSCEPTIBILITY WEIGHTED

PSD	GRE
OPTIONS	EPI , FC MP
TR	3000
TE	60
TI	-
SHOTS	1
FOV	40 x 20
SLICE THK	10 x 2
MATRIX	64 x 64
NEX	1
APPROX. SCAN TIME	6:27
RBW	64
NOTES	LOCATIONS = 4, PHASES PER LOCATION = 128 MIN DELAY AFTER ACQUISITION INTERLEAVED

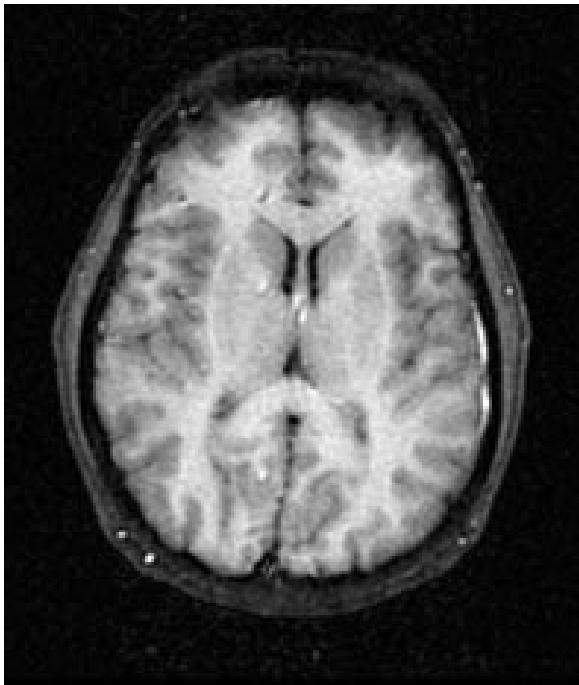
HISPEED EPI PROTOCOLS: HEAD



IR-PREP FOR GRAY/WHITE
MATTER CONTRAST MULTI-SHOT

PSD	SE
OPTIONS	EPI , FC IR-PREP
TR	3500
TE	40
TI	250
SHOTS	8
FOV	24 x 24
SLICE THK	5 x 2.5
MATRIX	256 x 256
NEX	2
APPROX. SCAN TIME	1:59
RBW	64
NOTES	

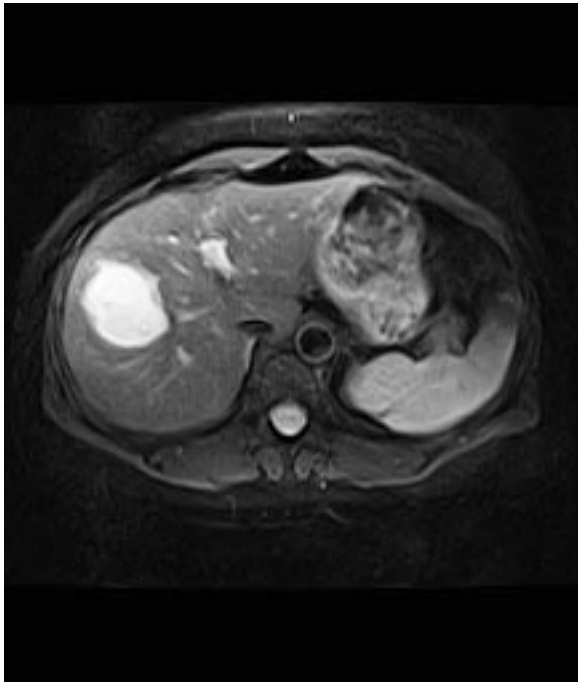
HISPEED EPI PROTOCOLS: HEAD



IR-PREP
T1-WEIGHTED MULTI-SHOT

PSD	SE
OPTIONS	EPI , SAT:1 IR-PREP
TR	2000
TE	MIN
TI	800
SHOTS	8
FOV	24 x 24
SLICE THK	5 x 2.5
MATRIX	192 x 192
NEX	2
APPROX. SCAN TIME	2:42
RBW	64
NOTES	

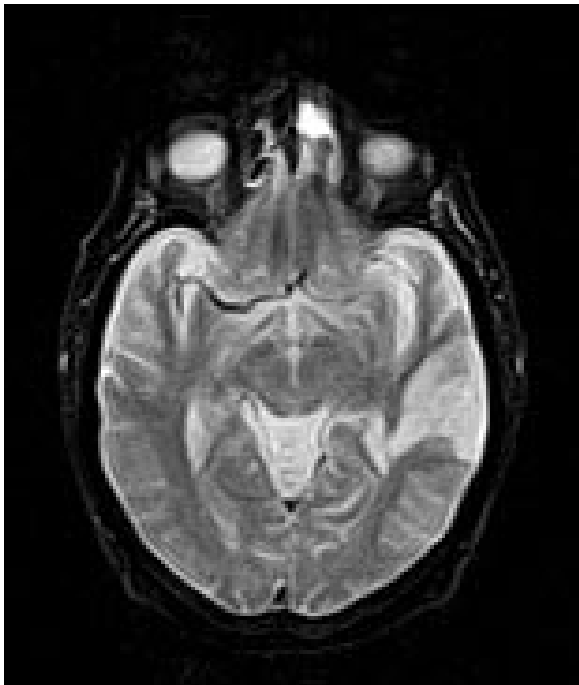
HISPEED EPI PROTOCOL: ABDOMEN



MULTI-SHOT BREATH-HELD

PSD	SE
OPTIONS	EPI , FC SAT:SI
TR	2000
TE	60
FLIP	-
SHOTS	8
FOV	36 x 27
SLICE THK	10 x 2
MATRIX	256 x 128
NEX	1
APPROX. SCAN TIME	:18
RBW	64
NOTES	USE TORSO ARRAY COIL

HORIZON AND ADVANTAGE RP EPI PROTOCOL: HEAD



MULTI-SHOT T2-WEIGHTED

PSD	SE
OPTIONS	EPI , FC
TR	2500
TE	80
FLIP	-
SHOTS	16
FOV	24 x 24
SLICE THK	5 x 2.5
MATRIX	256 x 256
NEX	3
APPROX. SCAN TIME	2:13
RBW	32
NOTES	



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96-4629 11/96 Printed in USA

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