Steady State Sequences and Practical Applications

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Last month I wrote about Steady State Imaging and some basic physics about how the sequence functions. Now I would like to go in to more of the practical side of things and look at where it can be put in to practical use. The short TRs used mean that very short imaging times can be achieved with good signal, therefore many of these applications concern body areas where this is an advantage such as breath-hold imaging, cardiac imaging and contrast angiography.

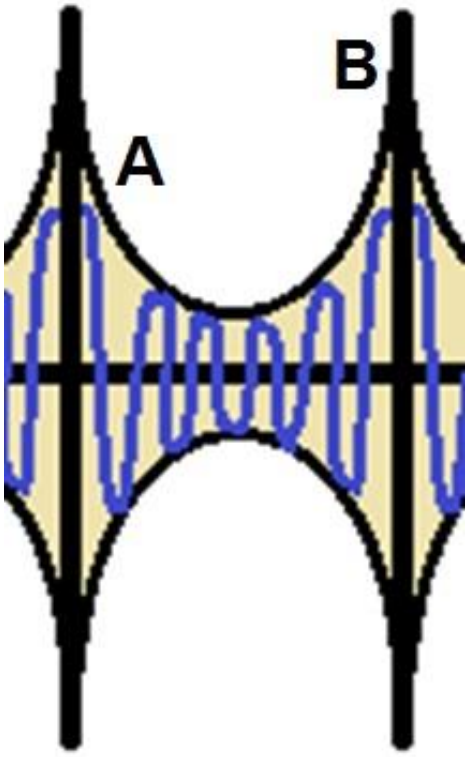


Figure 1 – Section of the Steady State FID

With steady state imaging very short TR times are used, so short in fact that both longitudinal and transverse magnetisation coexist (have not had time to relax) before the next TR comes along. Gradient rephasing rather than spin echo is employed so as to not destroy the steady state. Flip angles are kept low to ensure signal is kept to a maximum (Ernst angle).

Signal from the FID can be sampled just after each excitation RF pulse (position A, commonly known as the FID signal) and / or before each excitation RF pulse (position B, commonly known as the Echo signal) to obtain some useful, and some not so useful image weightings.

The phase coherence of transverse magnetisation will persist between RF pulses and so naturally these sequence will offer some degree of T2(*) weighting. However, Steady State imaging can also be used to generate T1 only weighting by 'Spoiling' this transverse coherence. The first five sequences described below are all 'Coherent', the following two are 'Spoiled' or 'Incoherent'.

Option 1 – Sampling the FID signal only (position A)

Like in spin echo imaging, if the TE is kept short, spin differences can be minimised and so T2 contrast reduced. If this is combined with a small flip angle, then T1 recovery of all tissues will complete before each subsequent RF input, making images proton density weighted.

Increasing the flip angle however, both T2* and T1 effects come into play and both weightings can simultaneously exist making images somewhat unusual in appearance.

Uses:

T2* weighting demonstrates susceptibility effects makes this sequence possible for brain haemorrhage imaging.

Good contrast is also possible for meniscal imaging as bright signal from cartilage is seen well against low signal bone.

Example Images:

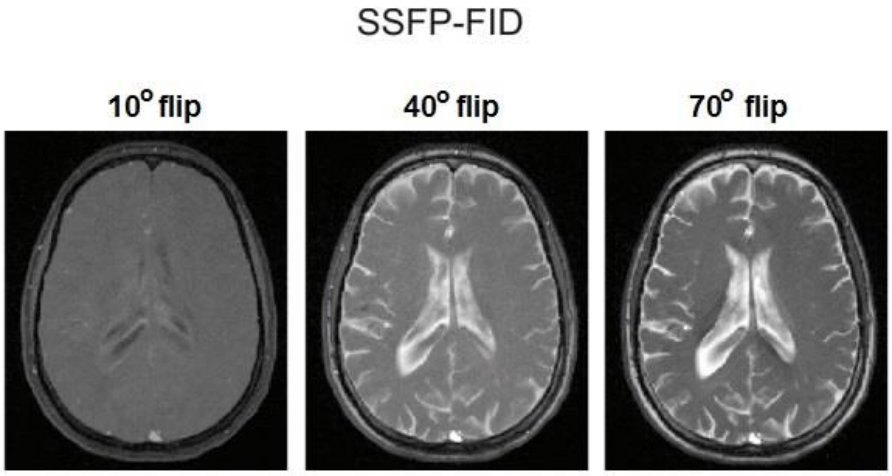


Fig 2 - Note how increasing the flip angle increases T2* weighting

Generic Name: SSFP-FID

Siemens: FISP

GE: GRASS

Phillips: FFE

Canon: SSFP / Field Echo

Option 2 – Sampling the Echo signal only (position B)

This time the FID signal is not required and so spoiled (or crushed) ensuring the gradient moments are dephased. This allows the echo signal alone to be sampled. As a result it is heavily T2 weighted, with negligible T2*. Fluid is bright, but soft tissue contrast is poor. The TE time is relatively long and so it can be liable to suffer from flow artifacts (Fig 3). In the early years of MRI it had a use in myelography but these days is not a commonly used sequence as a similar image weighting with more SNR and less artifacts can be achieved with the balanced FFE sequence.

Uses:

Not a lot!

Example Images:

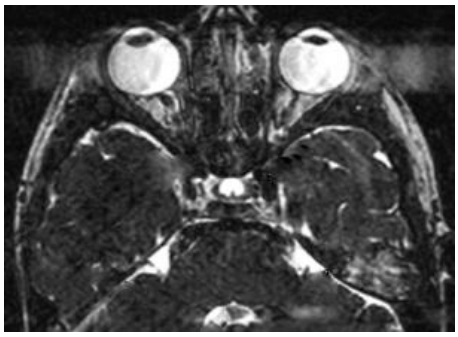


Fig 3 - Flow and motion artefacts

Generic Name: SSFP-echo

Siemens: PSIF

GE: SSFP

Phillips: T2-FFE

Canon: N/A

Option 3 – Sample both the FID and Echo signals (positions A & B)

Unlike the sequence above, this time the FID is not crushed, but is in fact fully re-phased before the next excitation pulse. This is done in all three axes and as such is less prone to motion artifacts. The net of these gradients is therefore zero (or balanced) but to achieve this high magnet homogeneity and good shimming is necessary. Where this is poorly achieved, e.g. near the edge of the field or areas of strong susceptibility, off resonances can cause signal voids or banding artifacts (Fig 4).

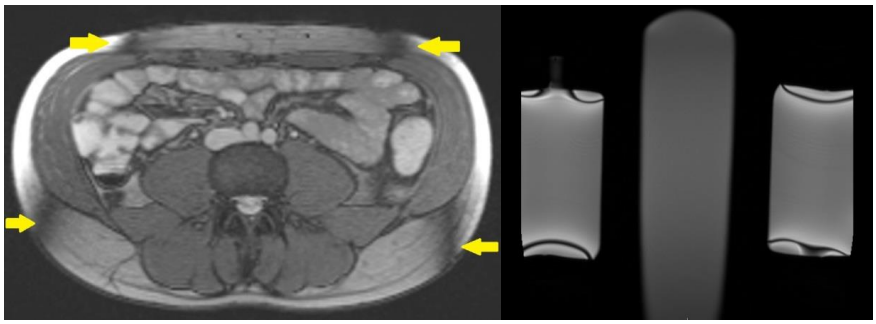


Fig 4 – Balanced FFE with banding artifacts – patient and phantom

Uses:

The contrast weighting achieved is a ratio of the T1 and T2 times of the tissue. This makes it a very versatile sequence that can be used for breath-hold body imaging, dynamic studies and for post contrast imaging. Due to the high signal to noise available during a single breath-hold, this sequence is also very useful for localising scans during body MRI.

Cardiac MRI – both for dynamic cine imaging (Fig 5) and delayed contrast enhancement (Fig 6).

Small bowel breath-hold imaging – good contrast seen in prepared bowel, full of fluid (Fig 7).

Fetal MRI – being a GE sequence, SAR is reasonably low

Example Images:

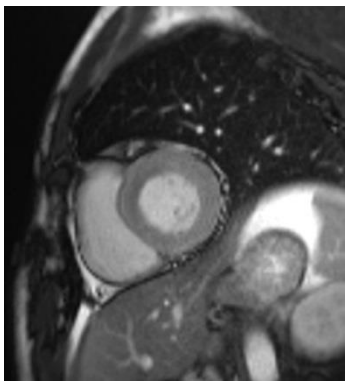


Fig 5 – Frame of a short axis BSSFP cine

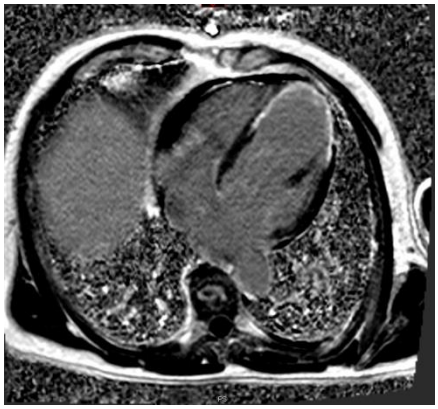


Fig 6 – Cardiac gated delayed contrast enhancement BSSFP four chamber showing apical non-viable myocardium

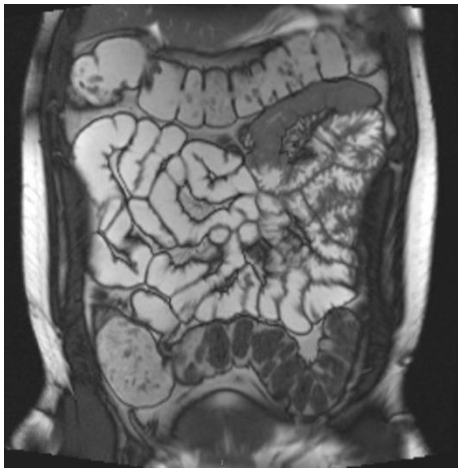


Fig 7 – Breath-hold BSSFP of a fluid-prepared small bowel

Generic Name: BSSFP

Siemens: TruFISP

GE: FIESTA / COSMIC

Phillips: Balanced FFE (BFFE)

Canon: True SSFP

Option 4 – Sample both the FID and Echo signal separately, then combine them

This option is similar to the BSSFP sequence, but employs a very long readout gradient to separate the FID and echo signal described above. The two individual echos are then combined to produce a single image, giving it very good signal to noise ratio. It is of course crucial that no patient movement occurs between the two data sets and as such the sequence is very sensitive to movement unsharpness. For this reason it is really only useful for imaging body parts that are easily immobilised, in particular orthopaedic applications.

Uses:

The image contrast benefits from both the FID signal which offers a very bright fluid signal, and also T2* from the echo component, resulting in dark bone. Adding water excitation to this sequence increases the contrast seen between articular fluid, cartilage and bone.

Orthopaedic MRI – particularly wrist (Fig 8), elbow, knee

Example Images:

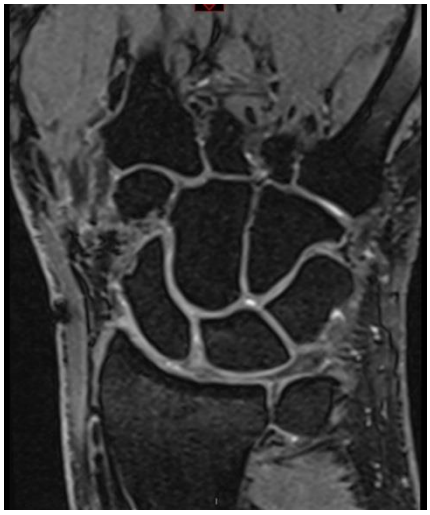


Fig 8 - FADE wrist, in this case a water excitation DESS

Generic Name: FADE (Fast Double Echo)

Siemens: DESS

GE: MENSA

Phillips: N/A

Canon: N/A

Option 5 – Removing the banding artefact

Multi-acquisition SSFP is a trick that can be used to remove the banding artefact seen with BSSFP, however at the cost of doubling the scan time. Two sequential acquisitions are performed with differing RF pulses which shifts the location of any banding by a known amount. A maximum intensity projection (MIP) addition of the data sets is then automatically performed to remove the unwanted banding artefacts.

Uses:

Banding artefacts are particularly problematic in areas where susceptibility distortions are strong such as at the skull base. For this reason, this sequence is commonly used for imaging the internal auditory canal and other skull base cranial nerves (Fig 9).

Example Images:

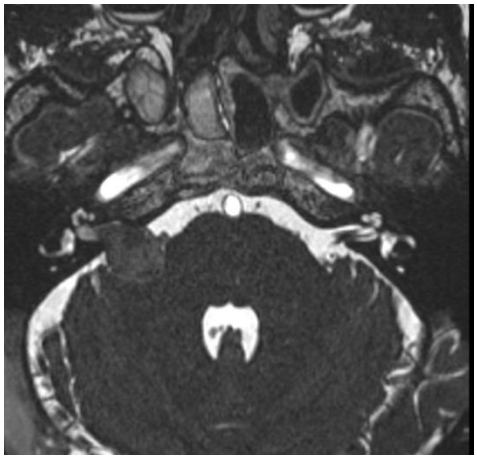


Fig 9 - IAMs image showing a large, right-sided acoustic neuroma

Generic Name: Multi-Acquisition SSFP

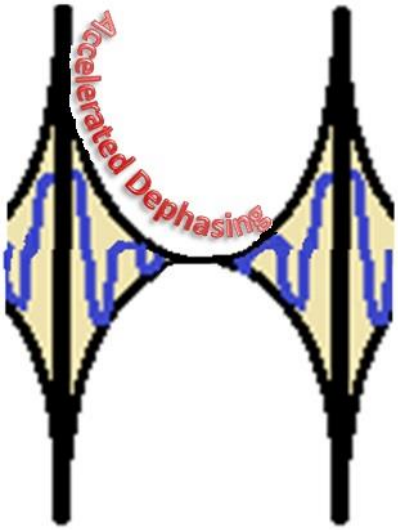
Siemens: CISS

GE: FIESTA-C / COSMIC

Phillips: BTFFE

Canon: N/A

Option 6 - Spoiling the Transverse Coherence = T1 weighting only



Spoiling is a technique that is employed to remove T2 and T2* weighting and thereby allow steady state imaging to generate T1 only weighted images. Instead of waiting for transverse magnetisation of decay, RF and gradients are used to accelerate the dephasing and therefore destroy (or spoil) transverse magnetisation, leaving longitudinal magnetisation as the only imaging signal, and hence produces T1 weighting. These sequences are therefore described as being incoherent, spoiled or sometimes crushed.

Fig 10 – Spoiling the FID

Uses:

Spoiling means we can still benefit from the rapid scan times offered by steady state imaging, but use it for applications where contrast enhancement is important. This includes dynamic contrast angiography (Fig 11), but also time of flight angiography (Fig 10)and in/out of phase body imaging (Fig 13).

Example Images:

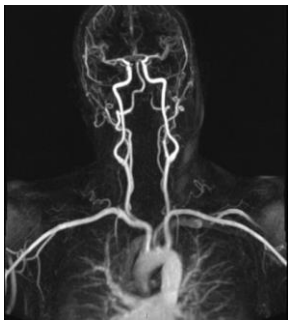


Fig 11 - Dynamic Contrast Enhanced Carotid Angiogram

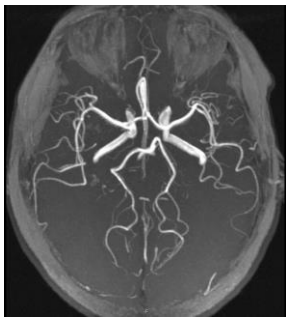


Fig 12 – Time of Flight CoW

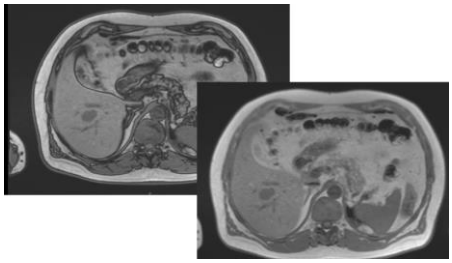


Fig 13 – T1 In and Out of Phase Liver showing a simple cyst

Generic Name: Spoiled SSFP

Siemens: FLASH

GE: SPGR

Phillips: T1-FFE

Toshiba (Canon): T1-FFE

Option 7 – 3D Spoiled Steady State

3D versions are also available, but these are merely three dimensional versions of the sequences described above that have for some reason developed their own acronyms. Usually undertaken with fat saturation, these are employed to acquire high resolution rapid series' through body areas where contrast media passes through quickly.

Uses:

Dynamic liver series (Fig 14), multiparametric dynamic contrast of the prostate (Fig 15).

Images:

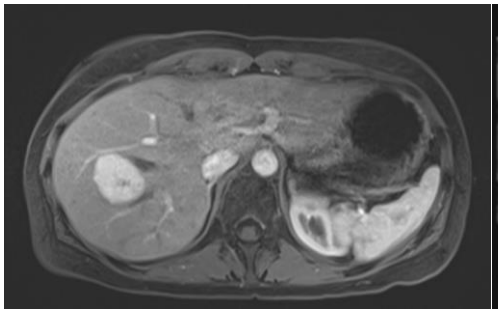


Fig 14 – Liver with Focal Nodular Hyperplasia (FNH)

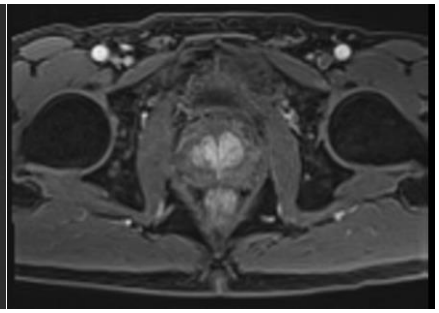


Fig 15 – Dynamic Contrast Enhanced Ca Prostate

Generic Name: 3D Spoiled SSFP

Siemens: VIBE

GE: LAVA / FAME

Phillips: THRIVE

Toshiba (Canon): 3D Quick