

Bandwidth in MRI?

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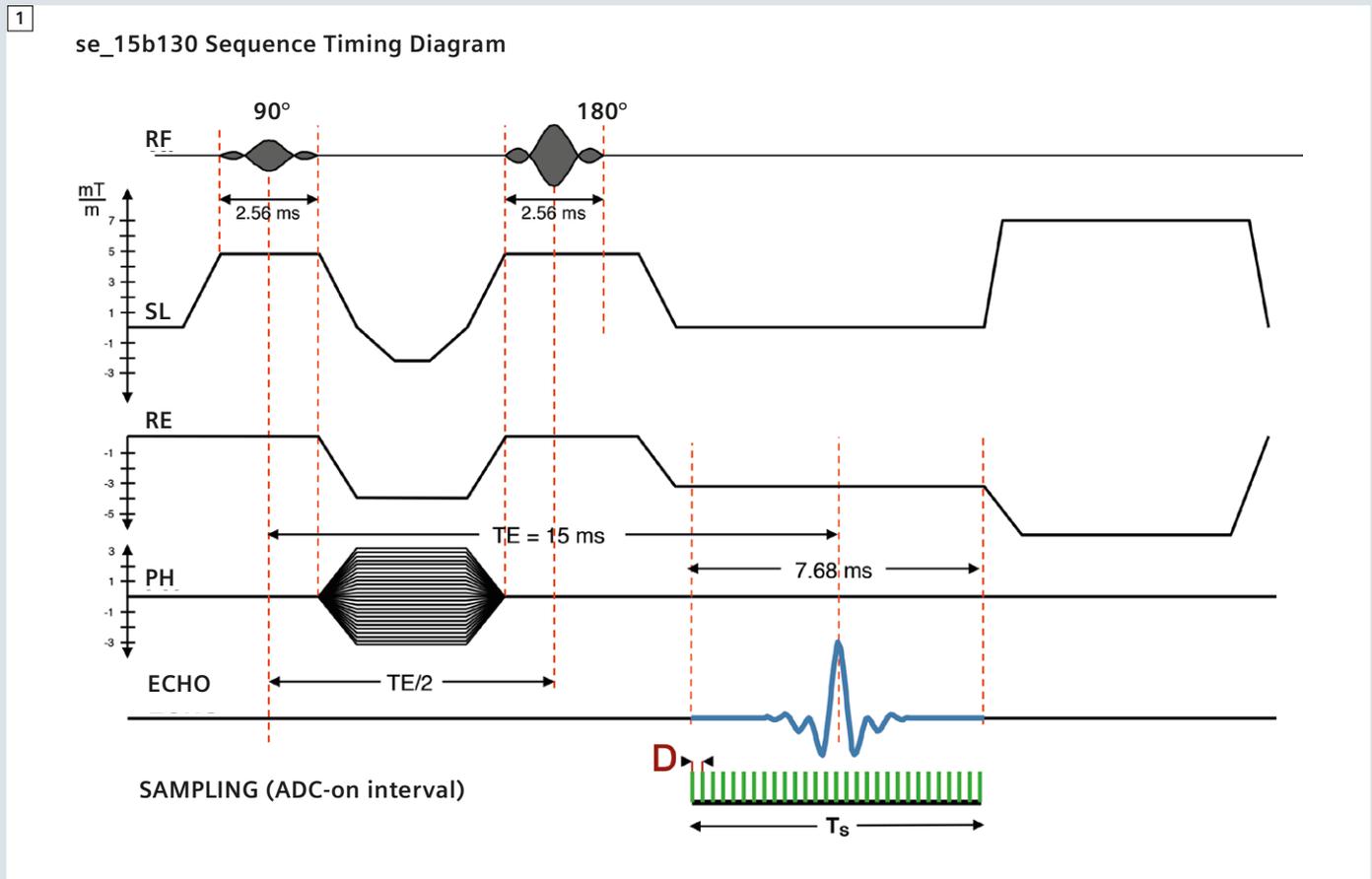
Siemens Healthcare, Hamburg, Germany

Questions about the term ‘bandwidth’ are most frequently asked during MR trainings and discussions regarding MR parameters and image quality. This article is intended to clarify the meaning of bandwidth in MRI, to show dependencies with other MR parameters,

and to give hints for daily routine work and protocol optimization. The bandwidth occurs twice in the course of an MR sequence (Fig.1): during transmission describing properties of the radiofrequency (RF) pulses and during reception of the MR signal.

Transmission phase

During transmission you have to apply RF pulses which contain a certain range of frequencies, i.e., bandwidth, to excite a discrete slice thickness or volume while a local gradient is on as well. The bandwidth typically lies in the range of a



1 Sequence timing for se15_b130.

few kilohertz (kHz). The *syngo* user interface offers three types of pulses for most sequences in the Sequence parameter card, part 2: Low SAR, Normal, and Fast (Fig. 2).

Pros and Cons for RF pulse types with timing examples:

Low SAR (3.84 ms)

- Longer RF pulse with good slice profile
- Reduced SAR values (lower amplitude)
- Less crosstalk between slice; narrower gaps tolerated
- Longer minimum TEs and TRs

Normal (2.56 ms)

- Normal RF pulse with good slice profile
- Optimized SAR behavior

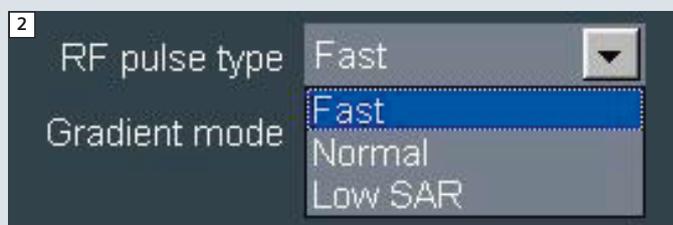
Fast (1.28 ms)

- Shorter RF pulse, with a compromised slice profile
- Higher SAR compared to the other modes (higher amplitude)
- Shorter echo spacing (ES)
- Opportunity for shorter TEs and TRs
- Fewer susceptibility artifacts

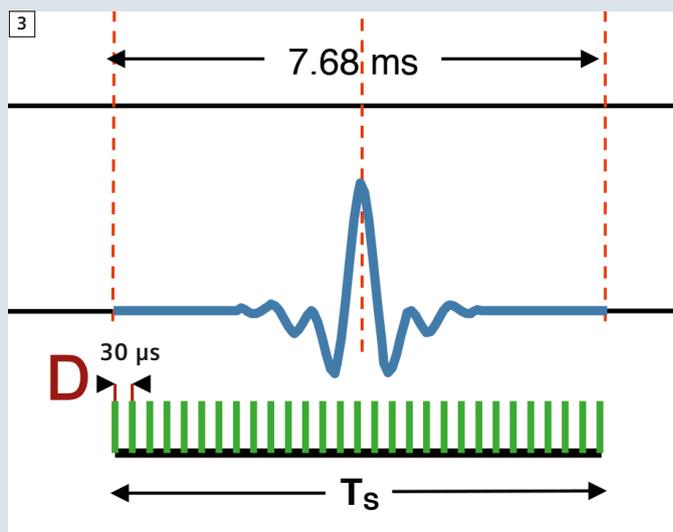
The 'Fast' mode is mainly applied in sequences where measurement speed and short echo spacing (ES) – the time from one echo to the next echo – is essential for good image quality: HASTE, EPI, TrueFISP, and TurboFlash. These modes can be combined with up to three gradient modes: Whisper, Normal and Fast. The gradient modes influence the slew rate of the gradient pulses, or the steepness of the ramps from zero to full gradient strength and back. The trade-off for faster sequence timing with shorter TEs and TRs usually results in more noise and a higher potential for peripheral stimulation.

Reception phase

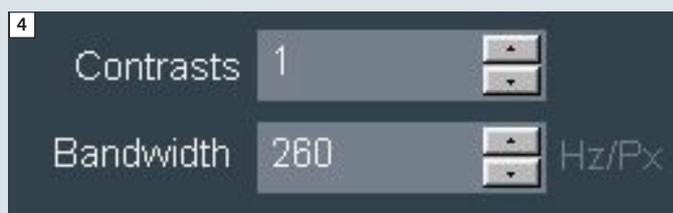
When the echo signal appears, a read-out gradient is switched on and the analog-digital-converter (ADC) samples this signal. The gradient encodes different rows of frequencies into signal; the time-amplitude integral defines the measured field-of-view (FOV). The ADC is virtually asking the echo-signal (e.g., every 30 microsecond (μ s)) how high its



2 RF pulse types.



3 Sampling time T_s and dwell time D .



4 Bandwidth in the *syngo* user interface.

amplitude is and writes these values in a digital fashion into the memory of the image computer. This time is called the dwell time D . For a 256 base matrix this process has to be repeated 256 times. The whole sample period T_s will be in this example (Fig. 3):

$$T_s = 256 \times 30 \mu\text{s} = 7.680 \text{ ms}$$

$$T_s = N \times D \text{ with } N = \text{matrix in read}$$

The frequency content of this sampled signal is the reciprocal of the dwell time:

$$f = 1/D.$$

In the above example it is roughly 33 kHz.

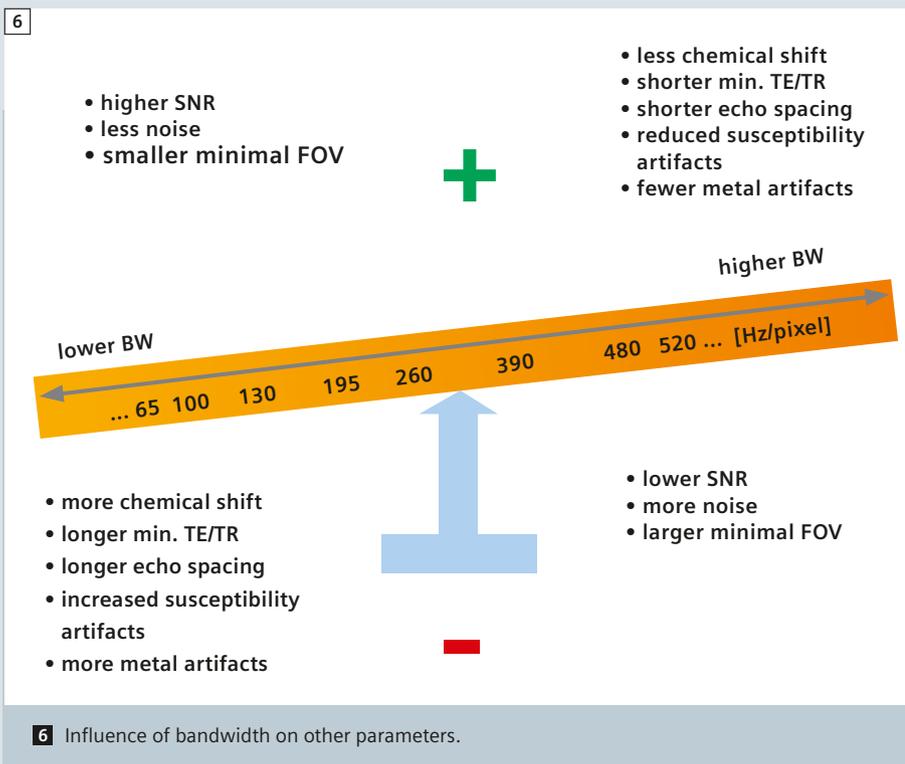
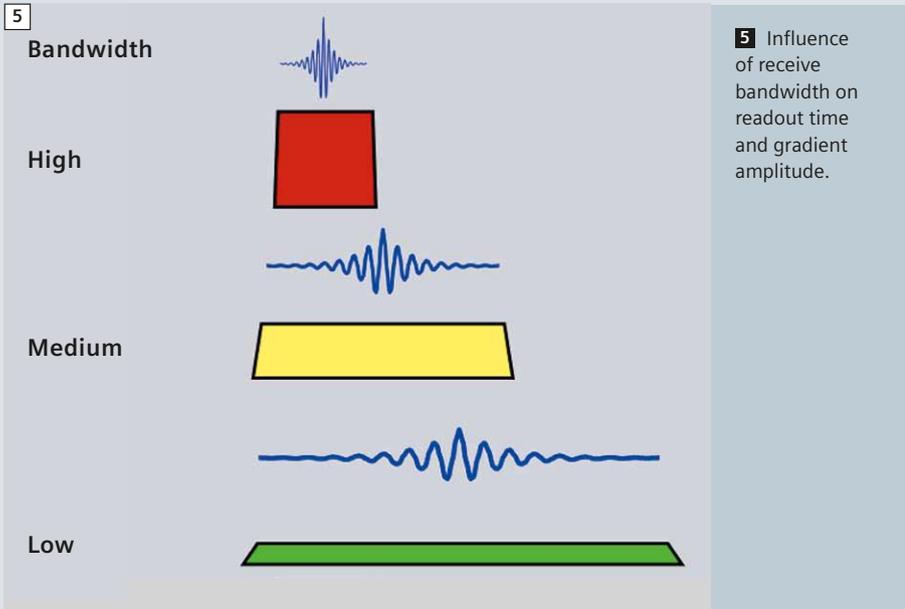
The magic term bandwidth (BW) is the reciprocal of the total sampling time T_s and has the unit of Hz/pixel:

$$\text{Bandwidth: } BW = 1/T_s \text{ [Hz/pixel]}$$

The parameter 'Bandwidth' is found on the Sequence parameter card, part 1 (Fig. 4).

The bandwidth describes in a simplified manner which frequency range from our analyzed echo signal is transferred into one pixel:

1. lower left pixel: 0-130 Hz
2. lower left pixel 130-260 Hz and so forth. If you continue this fill-up task to the last pixel of a 256 matrix you end up with 33 kHz in the lower right pixel.



Increasing the bandwidth reduces the sampling time T_s and shortens the sequence timing, allowing shorter TE and TR values and vice versa (Fig. 5). The disadvantage of a higher bandwidth is the larger amount of noise which is sampled due to larger frequency range.

This translates into a lower signal-to-noise-ratio (SNR). A slightly bumpy analogy is a motorway, where you have a speed limit and the number of cars per hour is limited. If you increase the speed limit, more cars will pass per hour and the noise for the neighbors rises as well.

On the positive side we have the shorter echo spacing (ES) which delivers less blurring in the images. The lipid signal in turbo spin echo protocols is also influenced by the echo spacing and the turbo factor (TF) [1]; the shorter the ES and the higher the TF, the brighter the fat in TSE protocols. The larger readout (RE) gradient amplitude needed for a high BW protocol increases the minimally adjustable FOV (Fig. 6). Furthermore, high bandwidth protocols play an important role in metal artifact reduced scanning. Shorter optimized excitation pulses combined with short readout intervals and short ES enables fewer distortions due to conditional implants. This feature is enhanced with optimized protocols which use WARP and VAT (view angle tilting) [2–4].

Last but not least, the chemical shift between water and fat gets smaller with high BW and larger with lower BW. This feature is of less importance for fatsat protocols. Fat resonates at an approximately 3.3 ppm lower frequency than water. Although commonly excited in the first part of a sequence, fat and water from the same physical place answer with different frequencies. In the above mentioned sorting process of frequency ranges into pixels we have to face a missorting. Fat will always appear shifted to lower frequencies by a certain amount of pixel in the readout direction. The only exception is the EPI sequence where we have a very strong chemical shift artifact in the phase encoding direction (PH) due to the long sampling period producing echoes. This very long sampling period in the order of >40 ms or more translates into a quite low bandwidth (<25 Hz/pixel). Fatsat is therefore mandatory for EPI measurements.

The chemical shift in readout direction is indicated as a mouse-over tooltip on the bandwidth field in the Sequence parameter card, part 1 (Fig. 7).

As one can see, chemical shift is not a big issue at low field strengths (Table 1). It is getting important at 1.5T and above for the range of practical bandwidth of a few hundreds Hz/pixel. But with the rise of the magnetic field the resolution typically goes up as well, keeping the abso-

lute chemical shift in millimeters reasonably low. A protocol at 3T with a bandwidth of 195 Hz/pixel and an inplane resolution of 0.3 mm creates an absolute chemical shift of less than 0.7 mm. Figure 8 demonstrates in an exaggerated way the artificial movement of the intervertebral discs (orange) towards the upper vertebrae or the spinal cord depending on the chosen readout direction and bandwidth option. The low bandwidth examples should be avoided in daily routine, although one may gain SNR and shorter scan time with lower bandwidth protocols.



Table 2 shows the effects of optimizing a TSE protocol with respect to change of bandwidth and resolution for a 1.5T scanner. Identical SNR is the border condition for these four examples. TE was kept in the mid thirty ms range. The

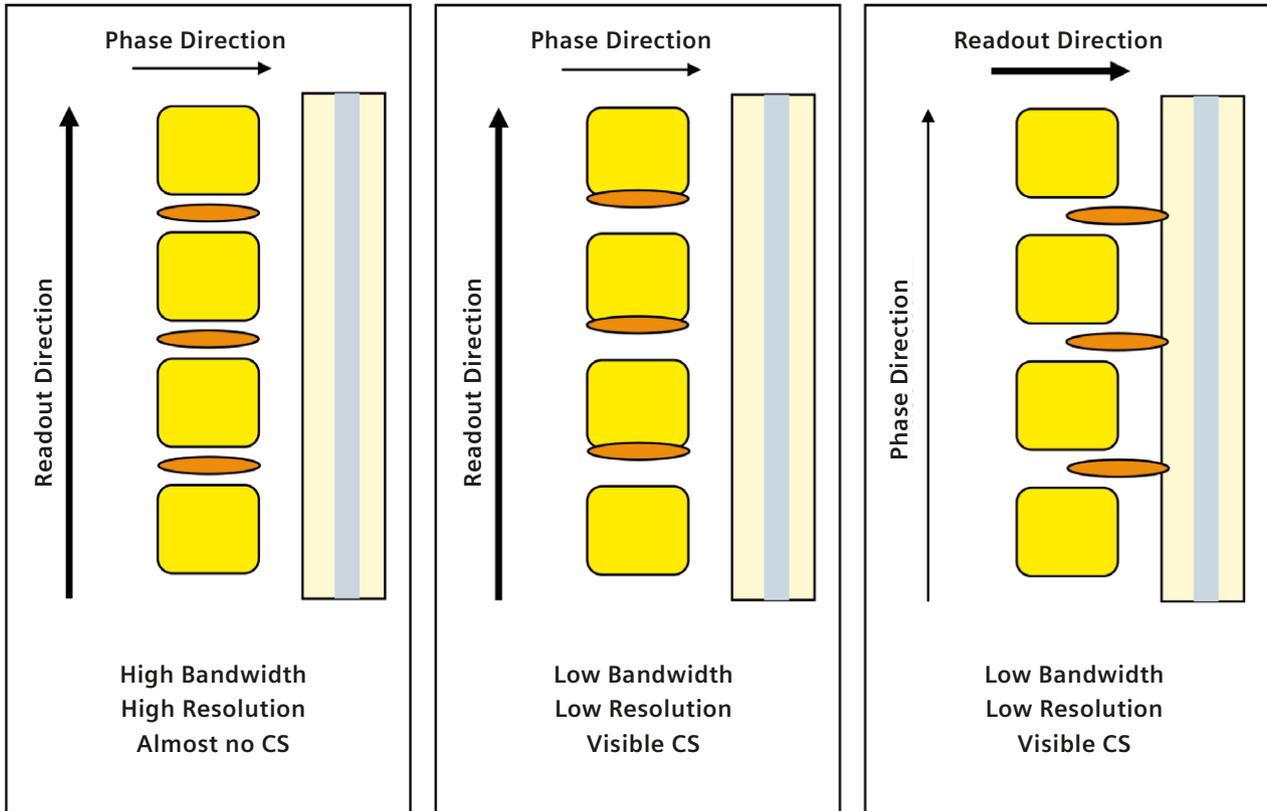
penalty for better resolution is usually longer measurement time. Personal taste and application dictates the parameters chosen. Starting with protocol B, one can speed up the scan by halving the bandwidth to

Table 1: Absolute pixel shift for different field strengths.

Bandwidth*	Readout time	Chemical Shift*					Relative SNR change*
		0.35T	1T	1.5T	3T	7T	
[Hz/pixel]	[ms]	[pixel]	[pixel]	[pixel]	[pixel]	[pixel]	[%]
3000	0.330	0.017	0.05	0.075	0.15	0.3	-79
2000	0.500	0.025	0.07	0.1	0.2	0.5	-74
1000	1.000	0.05	0.1	0.2	0.4	1.0	-64
520	1.920	0.09	0.3	0.4	0.8	1.9	-50
480	2.080	0.1	0.3	0.4	0.9	2.1	-48
390	2.560	0.13	0.35	0.5	1.1	2.5	-42
260	3.840	0.2	0.5	0.8	1.6	3.8	-29
195	5.120	0.25	0.7	1.1	2.2	5.1	-18
130	7.680	0.4	1.1	1.6	3.2	7.6	0
100	1.000	0.5	1.4	2.1	4.2	9.9	14
78	12.280	0.6	1.8	2.7	5.4	12.7	29
65	15.380	0.8	2.1	3.2	6.4	15.2	41
50	20.000	1.0	2.8	4.2	8.4	19.8	61

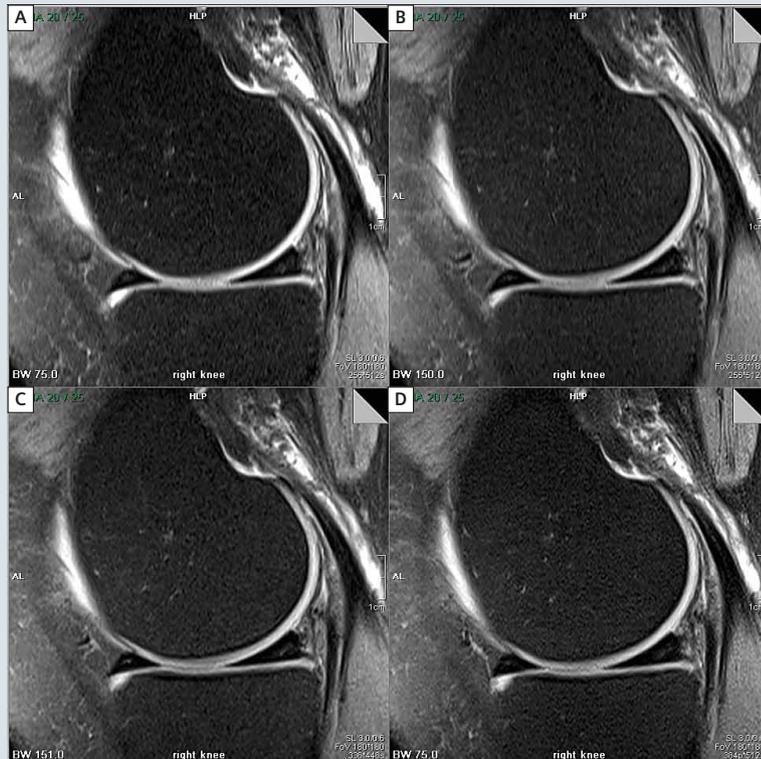
*Rounded values for convenience.

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8 Chemical shift (CS) on an example sagittal spine.

compensate for the SNR loss coming from the reduction of acquisitions. An increase of the inplane resolution in protocol C and D results in an obvious prolongation of the scan time which could be kept tolerable when reducing the bandwidth. In example D partial Fourier, i.e., reducing the measured turbofactor, allows a TR minimization for an acceptable scan time. One could save further time in this example by a decrease of phase oversampling, which was chosen 100% for a phase encoding in head-feet direction to minimize flow artifacts from the arteries; a slight increase of the FOV, e.g., to 200 mm, could compensate for this SNR reducing step though sacrificing some hundreds of a mm inplane resolution. On a 3T system one should at least increase the bandwidth by 50% and save time by adjusting the other parameters. The higher signal of 3T supports this measure.



9 Image examples for table 2.

Table 2: Protocol optimization.

Knee sagittal, 25 slices, FOV 180 mm, 3 mm, matrix 512 x 256, TF 7, weak Fatsat, 100% Phase OS, iPAT 2, 15-channel coil, identical SNR.

#	Parameter	Bandwidth	Matrix	Resolution	Scantime	TR	TE	Echo-spacing	Averages	partial Fourier	rel. SNR
	Unit	[Hz/pixel]	-	mm ²	min:s	ms	ms	ms	-	-	-
A	low BW normal Resolution*	75	256 x 512	$0.7 \times 0.35 = 0.245$	2:46	4020	36	17.8	1	off	1
B	high BW normal Resolution*	150	256 x 512	$0.7 \times 0.35 = 0.245$	3:32	2770	34	11.2	2	off	1
C	high BW higher Resolution	150	336 x 448	$0.54 \times 0.4 = 0.216$	4:43	2870	34	11.7	2	off	1
D	low BW higher Resolution*	75	384 x 512	$0.47 \times 0.35 = 0.165$	6:04	3240	37	18.7	2	on	1

* In Accordance to the German MR Guidelines (BÄ)

Further reading

1. Magnets, Spins and Resonances; Siemens 2003.
2. Magnets, Flow and Artifacts; Siemens 2004.
3. The Physics of Clinical MR Taught Through Images: Runge, Nitz, Schmeets; Thieme 2008.
4. MRI the Basics: Hashemi, Bradley, Lisanti; LWW 2010.
5. Handbook of MRI Sequences: Bernstein, King, Zhou; Elsevier 2004.
6. MRI from Picture to Proton: McRobbie, Moore, Graves, Prince; Cambridge 2007. Especially recommended for the German speaking community:
7. Praxiskurs MRT: Nitz, Runge; Thieme 2011.
8. MRT-Guide für MTRA/RT: Nitz; Thieme 2012.

References

- 1 Piraino D, Hardy PA, Schils JP, Richmond BJ, Tkach JA, Belhobek GH. (1993). Fast Spin-Echo Imaging of the Knee: Factors Influencing Contrast. JMRI 3:835-842.
- 2 Ulbrich EJ, Sutter R, Ranieri FA, Nittka M, Pfirrmann CW (2012). STIR Sequence With Increased Receiver Bandwidth of the Inversion Pulse for Reduction of Metallic Artifacts. AJR 199: 735-742.
- 3 Sutter R, Ulbrich EJ, Jellus V, Nittka M, Pfirrmann CWA (2012). Reduction of Metal Artifacts in Patients with Total Hip Arthroplasty with Slice-encoding Metal Artifact Correction and View-Angle Tilting MR Imaging. Radiology 265: 204-214.
- 4 Koch KM, Hargreaves BA, Butts Pauly K, Chen W, Gold GE, King KF (2010). Magnetic Resonance Imaging Near Metal Implants. JMRI 32: 773-787.

Helpful links



The Impact of Bandwidth on MR Image Quality: Chen Lin, 2012.
<http://www.indiana.edu/~mri/seminars/slides/The%20Impact%20of%20Bandwidth%20on%20MRI%20Image%20Quality%20CL20120324.pdf>



Metal Artifact Reduction in MRI – High Bandwidth Techniques, SEMAC, and VAT: Val Runge, 2013.
http://www.clinicalmri.com/pdf/Garmisch/2_Garmisch_2013_Metal_artifact_reduction.pdf

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