

Magnet Homogeneity and Shimming

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Magnet criteria

The magnet is the most prominent – and most expensive – part of an MRI system. It creates the main magnetic field, B_0 , which serves as the basis for all magnetic resonance imaging.

There are several features and specifications of the magnet design that have an influence on different criteria:

Image quality

- Magnetic field strength B_0
- Magnet homogeneity and maximum field of view
- Shimming capabilities

Patient comfort

- Magnet warm bore and bore diameter (including gradient coil, body coil and covers)
- Magnet length and total system length (including covers)
- Magnet height/width and outer dimensions (including covers)

Economic aspects

- Helium boil-off (Zero Helium boil-off for state-of-the-art systems)
- Stray field, reduced with active shielding, to reduce space requirements
- Magnet and system weight, for siting

In this article, the aspects of magnet homogeneity, shimming capabilities, and their respective relevance for MRI will be addressed.

Particular care will be taken to reduce confusion in the interpretation of the effects and benefits of the homogeneity of an empty magnet (installation shim) versus the effects and benefits of patient-specific (active) shimming. We will have a deeper look into the clinical benefits of linear and high-order shimming capabilities as well as new patient-specific shim technologies.

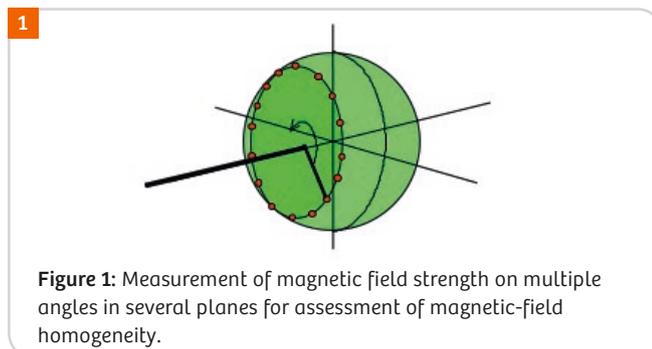


Figure 1: Measurement of magnetic field strength on multiple angles in several planes for assessment of magnetic-field homogeneity.

Relevance and definition of magnetic-field homogeneity

For magnetic resonance to work, a high homogeneity of the magnetic field is imperative. Within the imaging volume, the magnetic field has to be very accurate, with minimal deviations of the magnetic field allowed.

Magnetic-field homogeneity is commonly measured in ppm (parts per million) difference from the B_0 field. For example, if a 1.5-Tesla system has a deviation of, say, 2 ppm (peak to peak) at a particular location, the field strength at this location deviates by $(1.5 \text{ T} \times 2 \times 10^{-6} = 3 \mu\text{T})$.

There are different specification methods for homogeneity, the most important ones being:

- **Peak-to-peak homogeneity**
This is a measure of the maximum deviation within an imaging volume, i.e. the deviation between just the two 'worst-case' points on the surface of that particular volume.
- **Volume-root-mean-square (VRMS) homogeneity**
VRMS provides an 'integral' specification within the whole imaging volume. It is the industry-wide standard of homogeneity specification for the 'empty magnet' as specified in the data sheets. This will be further discussed in the next chapter, Installation shim.

Installation shim

Despite high efforts in the manufacturing process, a new magnet leaving the factory will typically have a magnetic-field inhomogeneity in the range of ~ 500 ppm (peak-peak) over the maximum volume. The conditions on site (e.g., steel reinforcements in the building structure) will also negatively influence the magnetic field homogeneity. The field homogeneity has to be refined during the system installation. This process is called shimming.

First, the magnetic field is measured at the installation site with the help of a tool to accurately measure the magnetic field. The so-called shimming device is positioned exactly at the iso-center of the magnet. The magnetic field is measured at multiple angles in several planes, see Figure 1.

All superconducting MAGNETOM systems use an accurate 24-plane plot with 20 angles each for the measurement of the magnetic-field homogeneity. Due to the cylindrical symmetry of the magnet, the total number of angles is less critical to the measurement. However, the number of planes can make a big difference in the accuracy of the homogeneity

measurement. Most magnets feature 6 superconducting field-generating coils. In such a 6-coil magnet, especially a 12-plane plot will be highly inaccurate since a 12-plane plot measures the magnetic field on 'equivalent zero-crossing' locations, thus artificially 'improving' magnet homogeneity specifications. A 24-plane plot, on the other hand, 'sees' all maxima and minima of the magnetic field and therefore provides more accurate information about the magnet homogeneity.

After the measurement, the measured values are entered into a computer program and the field homogeneity corrections are calculated. In order to perform a magnet shim, there are a number of options available:

- **Passive shim**

Shim irons of defined weight and shape are placed at exact positions, all calculated by the computer program. The shim irons are placed in dedicated shim pockets, typically situated in the gradient coil.

Passive shimming has a very high number of degrees of freedom (multiple shim irons of different weights at multiple positions). It is therefore very accurate and can correct shim terms up to ~ 24th order.

- **Superconducting shim**

This is a method used by one vendor. Additional superconducting shim coils are positioned in the magnet and can, based on the results of the field measurement and the results of the computer program (see above), be used for the improvement of the homogeneity of the (empty) magnet during installation.

The superconducting shim has the advantage of lower inserted iron mass in the magnet/gradient coil, i.e. there is no temperature dependence of the magnetic effect of the iron pieces.

However, the superconducting shim coils offer much fewer degrees of freedom. For instance, with 18 superconducting shim coils, only shim terms up to ~ 4th order can be corrected.

Note that the superconducting shim is only used for the shimming of the 'empty magnet', i.e. the installation shim.

It cannot be changed dynamically and cannot be used for patient-specific shimming. Also, superconducting shims decay over time and need regular re-adjustments. If something goes wrong with the magnet internal switching, that shim term is lost permanently.

- **Active shim**

For fine-tuning the field homogeneity, an active shim can also be performed. The same linear (and, if available) higher-order shim terms can be used as for the patient-specific shimming (see next chapter).

However, this is of less importance for the installation shim. The active shim only affects 1st-order (max. 2nd-order) shim terms, while the passive shim, described above, can affect terms of much higher order. The active shim is mainly used for the correction of patient-induced inhomogeneities (see below).

The measurement of the magnetic-field homogeneity and the homogeneity corrections by the methods described above are performed iteratively. Typically, 2–3 iterations are sufficient to achieve the homogeneity values that are specified in the data sheet.

Figure 2 shows an example of the homogeneity specifications of an 'empty magnet' after installation of the system, achieved with passive shimming and 1st-order active shimming, as described above.

The homogeneity of the 'empty magnet' can also be understood as the theoretical limit of the magnet homogeneity in clinical operation. In particular, it defines an upper limit for the maximum field of view (FOV) that can be used in clinical operation.

Different sequences show different levels of sensitivity to magnetic-field inhomogeneities. 'Insensitive' sequences (e.g. Turbo Spin Echo) will still achieve acceptable imaging results with inhomogeneities in the range of ~ 50 ppm (peak-peak). Spectral fat saturation, on the other hand, will only work with inhomogeneities up to ~ 2 ppm (peak-peak), since the chemical shift between fat and water is 3.5 ppm. Note that the data sheet specifications in Figure 2 are VRMS values, peak-to-peak values over the same volumes will be much higher.

Shape of the homogeneous magnetic field

The 'natural' shape of the homogeneous field of a solenoid magnet, as used in all 'bore-type' magnets, is spherical or ellipsoid. The ellipsoid is typically shorter in z-direction than in x/y-directions since the z-direction is the more critical one in bore-type magnets. A large homogeneity in z-direction is

DSV	Guaranteed	Typical
50 cm	< 1.5 ppm	0.8 ppm
45 cm	< 1 ppm	0.4 ppm
40 cm	< 0.75 ppm	0.2 ppm
30 cm	< 0.5 ppm	0.1 ppm
20 cm	< 0.25 ppm	0.04 ppm
10 cm	< 0.05 ppm	0.01 ppm
DSV – Diameter spherical volume (x, y, and z direction)	Standard deviation VRMS (volume root-mean-square) measured with highly accurate 24-plane plot method (20 points per plane) standard active shim with 3 linear channels	

Figure 2: Example for the specification of the 'installation shim' with VRMS homogeneity specifications over spherical volumes with 10–50 cm diameter. Screenshot from the data sheet for the MAGNETOM Avanto 1.5T system.

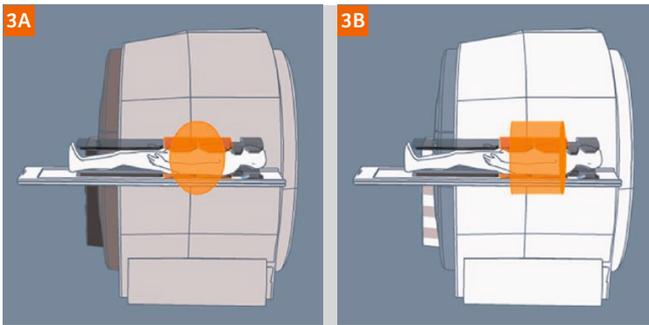


Figure 3: Visualization of the imaging volumes of a conventional magnet with spherical/ellipsoid volume (3A) vs. TrueForm Magnet Design with a cylindrical volume (3B).

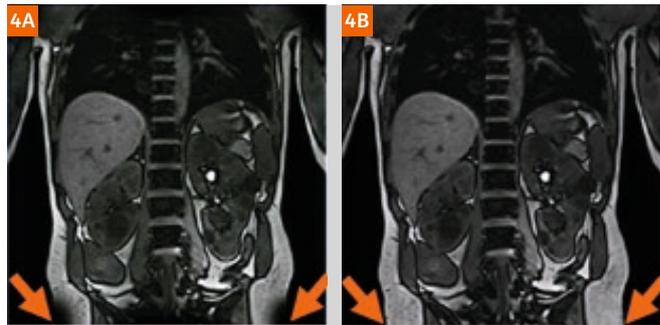


Figure 4: Visualization of the better depiction of the edges in large-FOV coronal images with TrueForm Magnet Design (4B) vs. conventional (4A).

facilitated by a larger magnet length. However, a longer magnet would compromise patient comfort. This needs to be considered in the design phase.

Some MAGNETOM systems (MAGNETOM Aera, Amira, Sempra, Skyra, Spectra, Verio) feature TrueForm Magnet Design. They are optimized for a cylindrical shape of the homogeneous volume of the magnetic field, rather than the typical spherical or ellipsoid volume. The benefit of TrueForm Magnet Design is a better depiction of the edges of the (3-dimensional) FOV. This is in particular beneficial for large-FOV coronal imaging, for multi-step examinations with extended FOV, and for TimCT. A visualization of TrueForm Magnet Design is shown in Figures 3 and 4.

Patient-specific shim

The homogeneity of the 'empty' magnet, as specified in the data sheet, will be strongly affected once a patient is positioned in the bore. This effect can result in several ppm of field inhomogeneity. This effect can easily be seen when forgetting to perform a patient-specific shim procedure that uses spectral fat saturation. The reason for this failure: fat saturation, being sensitive to peak-to-peak variations in the order of 2 ppm, will fail as a result of the greater inhomogeneity.

In many applications, the effect of the patient-specific shimming will be much more important than the homogeneity of the empty magnet. In particular, the homogeneity specifications of the magnet for small volumes with specifications much smaller than 1 ppm (compare Figure 2) will be irrelevant when compared to the inhomogeneity introduced by the patient. The capabilities that the MRI system offers for patient-specific shimming are critical in these applications.

Applications that are especially sensitive to magnetic-field inhomogeneities – and benefit most from patient-specific shimming – include:

- Spectral fat saturation and water excitation because they depend on the chemical shift between fat and

water of 3.5 ppm. A magnetic-field homogeneity better than ~ 2 ppm (peak-to-peak) is important.

- In general, all sequences that are sensitive to susceptibility effects, e.g. gradient echo with long echo times, TurboGSE, sequences using phase information like phase contrast angiography, SWI, etc.
- In particular, Echo Planar Imaging (EPI) methods, as used for diffusion, perfusion and fMRI, since the EPI echo train can be up to 100 ms long and is affected by the (rather short) T_2^* relaxation times. Higher magnet homogeneity will increase T_2^* values.
- TrueFISP sequence because TrueFISP basically consists of an S+ and an S- echo that need to be simultaneous. Magnetic-field inhomogeneities will destroy the synchronicity of S+ and S-, resulting in banding artifacts in the image.
- MR Spectroscopy (especially CSI with large volume of interest) because the chemical shifts of different metabolites in the sub-ppm range need to be resolved. Magnetic-field homogeneity needs to be better than the chemical shift between the metabolites.
- 3 Tesla: magnetic-field homogeneity is especially important for 3T MRI since the higher field strength increases susceptibility artifacts. Therefore, practically all state-of-the-art 3T scanners on the market (with a few exceptions) have a high-order active shim as standard.

As said, in many applications, the patient-specific shim capabilities will be more important than the homogeneity of the empty magnet. The performance of the patient-specific shim depends on two factors:

- Hardware: Dedicated shim coils for patient-specific shimming, for the shimming of linear terms and (if available) higher-order terms.
- Software: Shim algorithms for the measurement and correction of magnetic-field inhomogeneities, making use of the available hardware.

These are covered in the next chapters.

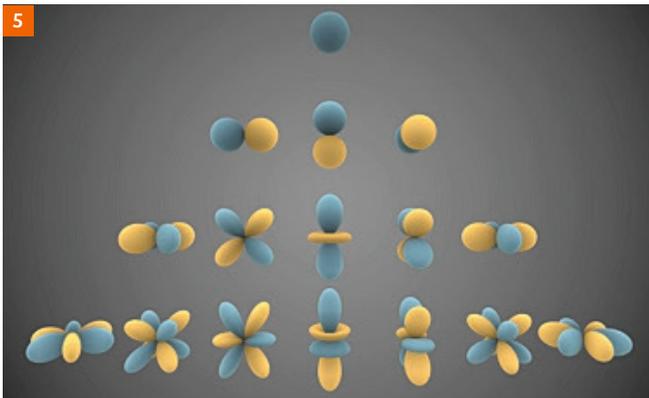


Figure 5: Visual representations of the real spherical harmonics up to 3rd-order. Blue portions represent regions where the function is positive, and yellow portions represent where it is negative. (Source: Wikipedia, http://en.wikipedia.org/wiki/Spherical_harmonics)

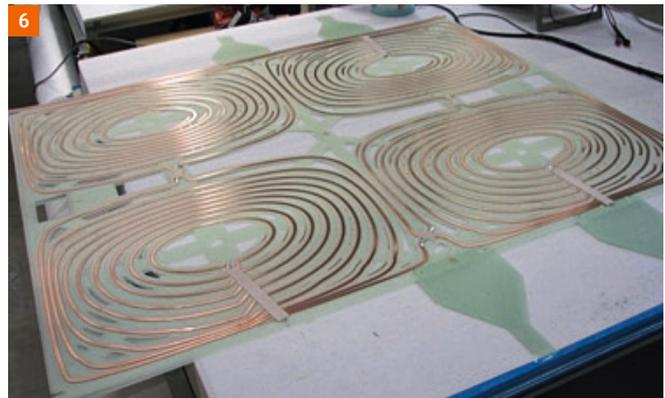


Figure 6: Design of a 2nd-order shim coil. This is wound around (and integrated into) the gradient coil. Shown is the example of the x^2-y^2 coil (same design as xy coil).

Hardware

Linear and higher-order shim terms

The magnetic field is commonly described in the so-called 'spherical harmonics'. The concept of the spherical harmonics is explained e.g. on Wikipedia (http://en.wikipedia.org/wiki/Spherical_harmonics).

The series of harmonics is:

1 0th-order term + 3 1st-order terms + 5 2nd-order terms + 7 3rd-order terms + ...

So, what do these terms mean? A graphical visualization can be found in Figure 5.

- The 0th-order term is nothing else than the static magnetic field B_0 .
- The 1st-order terms are linear deviations from the homogeneous B_0 field. There are 3 linear terms, describing the linear deviations in x, y, and z directions. This is exactly the same shape as is also produced by the 3 axes of the gradient system. The gradient system is there anyway, no additional hardware is required: In all MR systems on the market, the standard gradient system is used for shimming of the linear (= 1st-order) terms.
- The 2nd-order terms are quadratic deviations from the B_0 field. There are 5 2nd-order terms, namely z^2 , xz , yz , xy , x^2-y^2 . Special 2nd-order shim coils are required to correct for 2nd-order field inhomogeneities. Also, 5 additional power supplies and a software implementation are required. A 2nd-order shim set (often called high-order shim or advanced shim) is available for some 1.5T systems in the market. It is standard with most 3T systems.

Integrated coil shim

A new method to improve the local magnet homogeneity even more, beyond the possibilities using 1st- and 2nd-order shimming, was recently introduced with the MAGNETOM Vida¹. CoilShim, a central feature of BioMatrix technology, offers up to four additional independent shim channels that can be used to power and control local shim coils.

The head/neck region is especially critical regarding magnetic-field inhomogeneities. The shape of the human body – the curvature of the posterior neck, the chin region, the lateral extension of the shoulders, and the susceptibility changes due to the trachea and the esophagus – induces severe inhomogeneities for neck and plexus imaging. Even a (global) 2nd-order shim is not sufficient to correct these inhomogeneities in many cases.

To improve the homogeneity in this critical region, the MAGNETOM Vida features a new Head/Neck 20 coil and a new Head/Neck 64 coil. Both coils have two additional dedicated shim coils built into the coil. The shim coils are very close to the critical anatomy, and their design is optimized to address the specific inhomogeneities in this region. The calculation and fine-tuning of the local CoilShim currents are fully integrated into the shim algorithm.

Software

Shim algorithms

For patient-specific shimming, first the field inhomogeneities need to be measured. The result can be visualized in a so-called B_0 map. It is not possible to measure the field homogeneity with special hardware devices while the patient is in the magnet, for various reasons: First, a costly device would be required; second, the setup of such a device would be time-consuming, compromising workflow and throughput; third (and foremost), the patient is just in the way. Therefore, MR-based phase-sensitive scans are used to gain knowledge about magnetic-field inhomogeneities.

There are different approaches to what is actually being measured. The standard procedure is a 'global' measurement of the whole imaging volume of the scanner. If this is done with a 3D scan, one measures spatially resolved information about the magnetic field. For later imaging scans (at the same table position), only the relevant sub-volumes can be taken into account. These sub-volumes can be identical to the imaging volume, i.e. the volume covered by the 2D slice stack or 3D imaging slab. Alternatively, it can be useful to define the shim volume manually, e.g., only selecting a smaller sub-volume which is most critical.

After the shim measurement has been performed, an algorithm will calculate the optimal shim currents for improving the magnetic-field homogeneity, based on the shim volume selected. The algorithm will make use of the available shim hardware by using gradient offset currents for the linear correction terms and – if available – additional higher-order shim currents for the 2nd-order terms.

All of this – the homogeneity measurement and the calculation of the shim currents – is done fully automated in routine clinical applications. The user will only notice a short delay before the actual imaging scan, typically a few seconds. For special applications (like spectroscopy) and for research use, it is also possible to perform an additional manual shim by changing the shim currents directly in the user interface.

Slice-specific shimming

A global shim, as discussed in the last chapter, can only address an 'average' of the homogeneity improvement over a large imaging volume. Even a patient-specific 2nd-order shim may be insufficient to optimize the magnet homogeneity in all parts of this large volume.

As another new BioMatrix feature of the MAGNETOM Vida, SliceAdjust offers a precise slice-by-slice tuning of resonance frequency, transmitter voltage, first order B_0 shim and B_1 shim. For whole-body diffusion, the SliceAdjust technology helps to avoid station boundaries and apparent 'broken spine' artifacts as well as to preserve the SNR for whole-body diffusion imaging.

Clinical comparison

2nd-order shimming vs. linear shimming

The following images show a comparison between shimming with the 1st-order shim terms only (2nd-order shim was disabled) and shimming using 1st-order and 2nd-order shim terms.

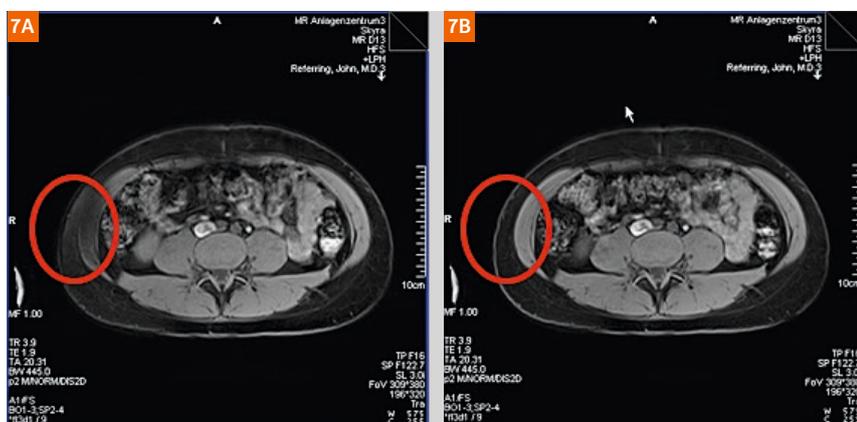


Figure 7: Abdominal imaging with spectral fat saturation, MAGNETOM Skyra 3T.

(7A) With 1st-order shim only (2nd-order shim disabled).

(7B) With 1st-order and 2nd-order shim.

Note the superior fat saturation in the off-center region when using 2nd-order shimming (red circle).

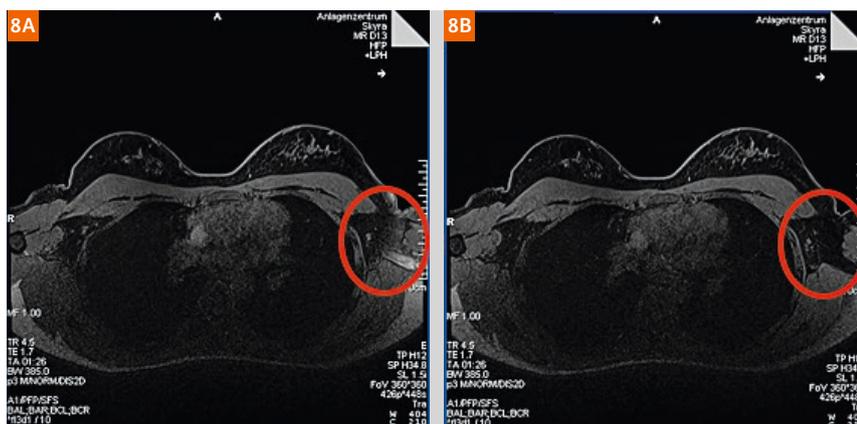


Figure 8: Breast imaging with spectral fat saturation, MAGNETOM Skyra 3T.

(8A) With 1st-order shim only (2nd-order shim disabled).

(8B) With 1st-order and 2nd-order shim.

Note the superior fat saturation in the off-center region when using 2nd-order shimming (red circle).

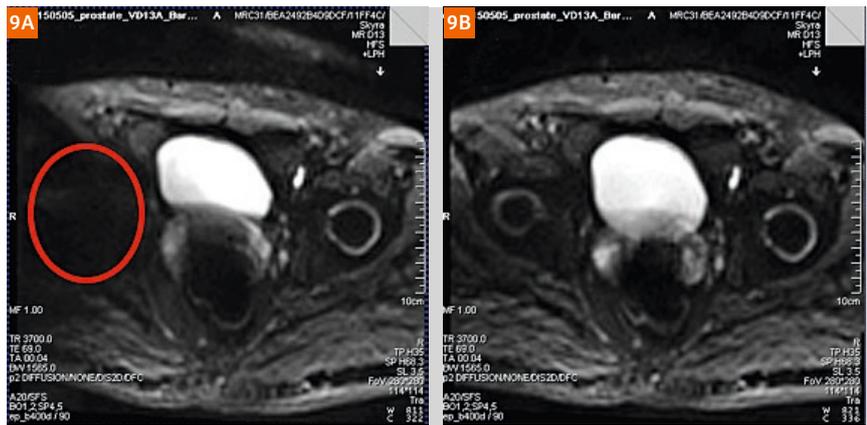


Figure 9: Pelvic imaging with with diffusion-weighted single-shot EPI and spectral fat saturation, MAGNETOM Skyra 3T. (9A) With 1st-order shim only (2nd-order shim disabled). (9B) With 1st-order and 2nd-order shim. Note the strong spatial distortions (red circle) in the presence of strong susceptibility changes without 2nd-order shimming.

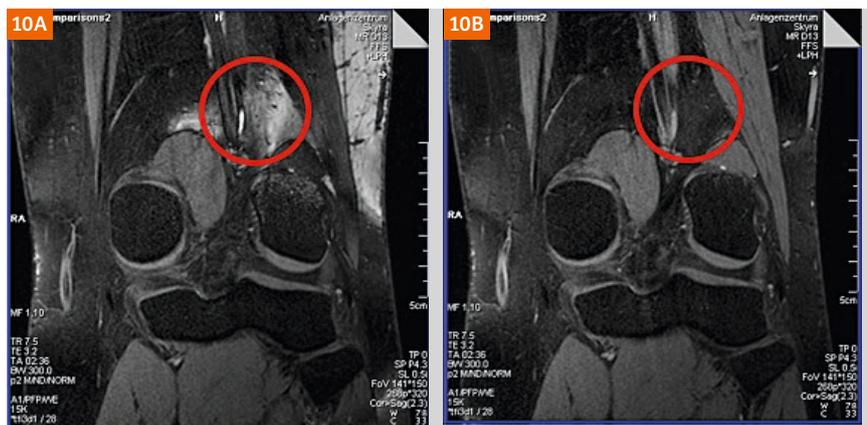


Figure 10: Knee imaging with spectral fat saturation in off-center position, MAGNETOM Skyra 3T. (10A) With 1st-order shim only (2nd-order shim disabled). (10B) With 1st-order and 2nd-order shim. Note the superior fat saturation when using 2nd-order shimming (red circle).

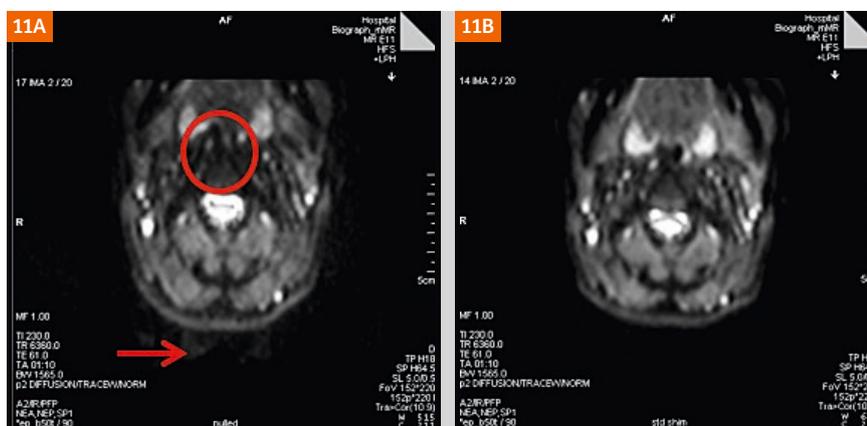


Figure 11: Neck imaging with diffusion-weighted single-shot EPI and spectral fat saturation, Biograph mMR 3T. (11A) With 1st-order shim only (2nd-order shim disabled). (11B) With 1st-order and 2nd-order shim. The neck area is especially critical, due to B₀ inhomogeneities at the head-shoulder transition and due to strong susceptibility changes in the neck. Note the higher level of spatial distortions (red circle) and the stronger appearance of ghosting artifacts (red arrow) without 2nd-order shimming.

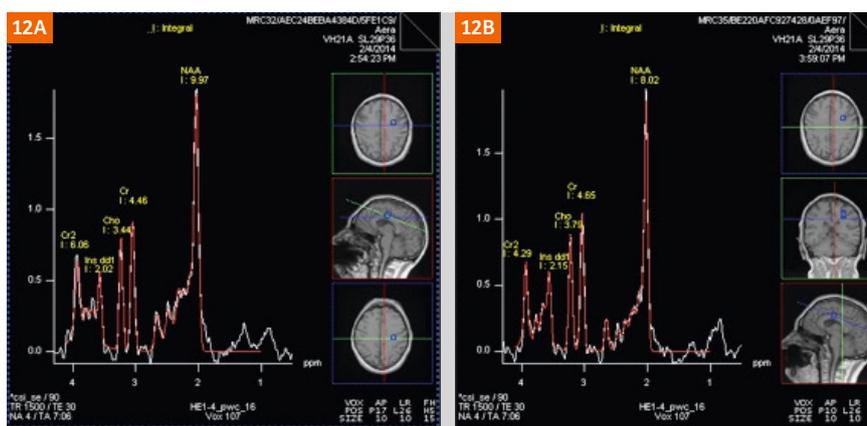


Figure 12: CSI spectroscopy in the brain, MAGNETOM Aera 1.5T. (12A) With 1st-order shim only (2nd-order shim disabled). (12B) With 1st-order and 2nd-order shim. The region in the center of the brain does not suffer from susceptibility effects. The quality of both spectra is similar, i.e. 1st-order shimming is in this 'easy' case sufficient.

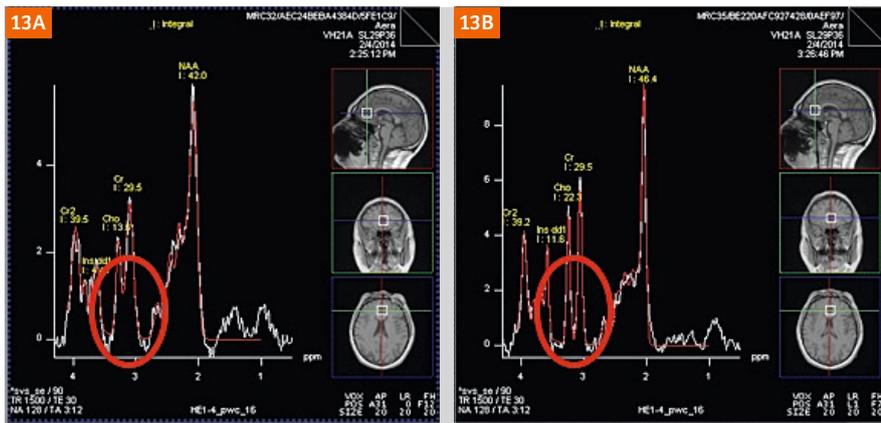


Figure 13: Single-voxel spectroscopy in the brain, MAGNETOM Aera 1.5T. **(13A)** With 1st-order shim only (2nd-order shim disabled). **(13B)** With 1st-order and 2nd-order shim. The frontal lobe, close to the nasal cavities, is a critical region, due to strong susceptibility effects. The spectrum without 2nd-order shim can not be evaluated (red circle). Also note the different scaling of the spectra.

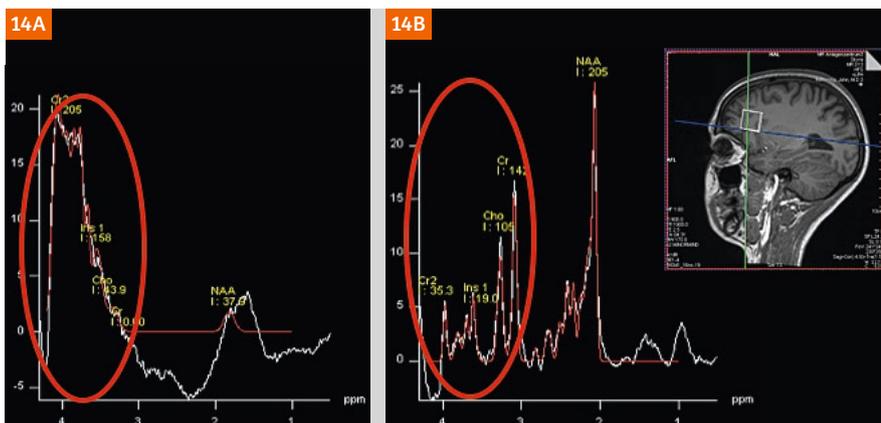


Figure 14: Single-voxel spectroscopy in the brain, MAGNETOM Skyra 3T. **(14A)** With 1st-order shim only (2nd-order shim disabled). **(14B)** With 1st-order and 2nd-order shim. At 3T, the susceptibility effects in the frontal lobe are even more severe. The spectrum without 2nd-order shim can not be evaluated (red oval).

Integrated coil shim vs. conventional global shim

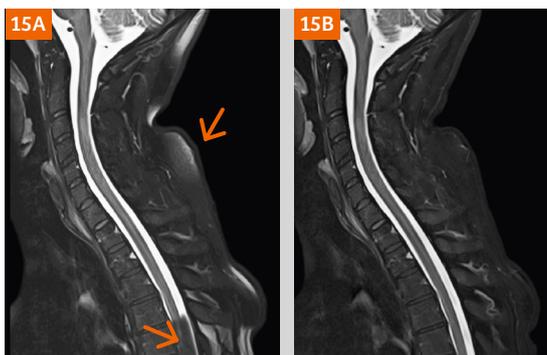


Figure 15: C-spine imaging with fat suppression, MAGNETOM Vida 3T. **(15A)** With conventional global shim. **(15B)** With CoilShim. CoilShim improves the local magnet homogeneity in the critical neck region, resulting in an artifact-free depiction of the spinal cord and perfect fat suppression in the posterior neck region (see orange arrows).

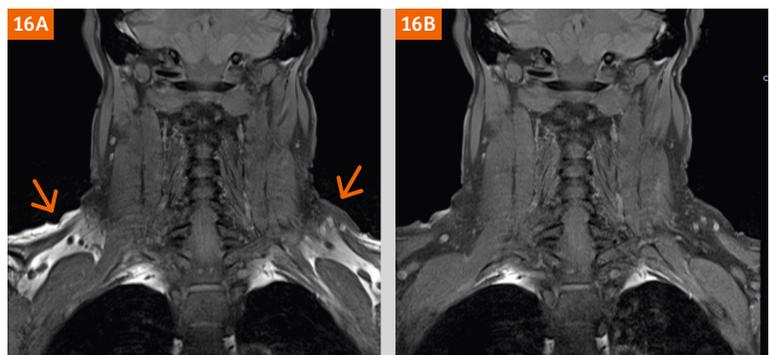


Figure 16: Neck imaging with fat suppression, MAGNETOM Vida 3T. **(16A)** With conventional global shim. **(16B)** With CoilShim. CoilShim improves the local magnet homogeneity in the critical neck region, resulting in perfect fat suppression in the neck/shoulder region (see orange arrows).

Slice-specific shimming vs. conventional global shim



Figures 17 and 18: Whole-spine imaging with diffusion weighting, reconstruction from axially acquired slices. MAGNETOM Vida 3T. The 'average' global shim over a large FOV significantly changes between different steps, resulting in 'broken spine' artifacts (orange arrows). The 'continuous' slice-by-slice shim with SliceAdjust guarantees a smooth transition of the shim states and prevents 'broken spine' artifacts.

(17A, 18A) With conventional global shim, acquired in three steps with three shim regions.

(17B, 18B) With SliceAdjust¹, different optimized shim setting for each slice.

Conclusion

The magnet of an MRI scanner is an important component. It has implication on image quality, patient comfort, and economic aspects. The design of the magnet has to be balanced, addressing all these aspects (which are partly contradictory, e.g. magnet homogeneity vs. magnet length).

In this paper, we focused on the aspects of magnet homogeneity and shimming capabilities.

Different criteria of magnet homogeneity should not be confused. The homogeneity of the empty magnet (installation shim) is mainly important for the maximum field of view. Most clinical applications rather depend on the capabilities of the system to perform patient-specific shimming. The homogeneity specification of the magnet for small volumes is rather irrelevant compared to the inhomogeneities induced by the patient.

1st-order shimming alone (by means of the gradient system) is sufficient for many applications. However, for more critical applications and in critical regions, 2nd-order shimming capabilities can play a crucial role for optimal image quality, consistently. The relevance of 2nd-order shimming capabilities depends on the clinical usage of the system.

The new BioMatrix technologies¹, CoilShim and SliceAdjust, allow to improve the local field homogeneity even more, beyond the capabilities of global 1st- and 2nd-order shimming.

¹ 510(k) pending. The product is not commercially available. Future availability cannot be guaranteed.

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