Shimming: Fields, Coils & Control

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Introduction

Spatial homogeneity of the main magnetic field B_0 is essential for the majority of MR applications. In MR imaging (MRI), the presence of magnetic field inhomogeneity can lead to image distortion and signal loss, whereas spatial field variations in MR spectroscopy (MRS) cause loss of sensitivity and spectral resolution. Although manufacturing imperfections such as minute variations in magnet coil windings exist, the majority of magnetic field imperfections are sample induced. Materials differ in their permeability to magnetic fields, an effect governed by the material's magnetic susceptibility [1]. Materials of different magnetic susceptibility therefore express different interior magnetic fields when placed in a magnetic field along with a transition zone at their boundary. Magnetic field imperfections observed in the human brain are susceptibility-induced and mostly simple in nature, but some complex and high-amplitude terms are observed. The largest differences in magnetic susceptibility occur between brain tissue and air in the nasal and auditory passages and lead to strong magnetic field distortions in the frontal cortex and temporal lobes, respectively. Post-processing methods have been developed to minimize artifacts that are due to magnetic field inhomogeneity [2-6]. However, such alleviation of symptoms is not able to recover severe distortions and complete signal dropout in MRI or line broadening in MRS. MRI and MRS artifacts as a result of magnetic field inhomogeneity can only be prevented when the underlying physical origin of the problem is removed and the apparent magnetic field imperfection is compensated experimentally.

Basics of Shimming

Magnetic fields obey the superposition principle and, therefore the effective magnetic field present during the MR experiment can be manipulated through addition of correction fields in a process called "shimming". An ideal shim field exactly resembles the field variation to be compensated for in shape and amplitude, however, at reversed polarity. The application of such shim field then fully removes the field imperfection and results in a perfectly homogeneous magnetic field distribution, i.e. constant field amplitude throughout the considered region-of-interest. In reality, the outcome of shimming is limited by the ability of the field-generating method to model and reproduce the distortion at hand. Differences of the applied shim field from the field imperfection to be corrected manifest themselves as remaining field inhomogeneity after shimming. The importance of obtaining adequate magnetic field homogeneity, e.g. across the entire human brain including its critical areas, has sparked the development of various shimming techniques that are grouped in "passive" and "active" methods based on the way the magnetic correction fields are generated.

Passive Shimming

Field-induced magnetic polarization due to varying magnetic susceptibility is responsible for the creation of magnetic field distortions, but the very same effect can also be applied for their correction. Magnetically susceptible materials alter the magnetic field distribution they are exposed to on their inside and in their surroundings and therefore provide a handle on the magnetic field distribution in neighboring objects. "Passive shimming" employs this effect through placement of magnetically susceptible materials to strategic positions in the scanner bore to manipulate and homogenize the magnetic field over a subject under investigation or parts thereof. Materials and applications for passive shimming range from diamagnetic intraoral shims for the minimization of field artifacts in the human prefrontal cortex [7-9] to whole brain shimming in the mouse with external dia- and paramagnetic passive shims [10]. Passive shimming with ferromagnetic substances provides an inexpensive means of efficiently producing very strong magnetic fields. Ferromagnetic materials are regularly used to improve the quality of the scanner field itself, but have also been applied in a subject-specific fashion [11, 12]. Passive shimming stands out due to the ease of the field generation by simple placement of the assemblies to be polarized inside the scanner field. The creation and adjustment of passive shim assemblies, however, is tedious and error-prone and requires preparation ahead of time for the particular application at hand. As such, passive shimming largely lacks the flexibility to accommodate experiment-specific conditions and varying shim requirements due to differences in subject anatomy, subject placement or altered susceptibility distributions (e.g. due to nasal congestion of a subject having a cold).

Active Shimming with Spherical Harmonic Shapes

For more than 50 years, the standard approach to minimize magnetic field variations is to superimpose magnetic fields with a spatial variation governed by spherical harmonic (SH) functions [13, 14]. Magnetic field distributions, e.g. encountered in the human brain when placed inside the scanner B_0 field, are decomposed into a set of SH basis shapes and the best available fit is applied with reversed polarity as shim field for their homogenization. Individual SH shapes are produced by dedicated, current-driven wire patterns – one for each term – and a set of SH coils is combined to form a shim system and to generate shim fields over the subject of interest. The more basis functions are available for the modeling of the field distortion, i.e. the higher the available SH order, the more flexible the magnetic field shaping and the better the expected shim outcome. In practice, SH shim systems are limited to low-order terms mostly due to space and cost restrictions, and most human MR systems are equipped with shim coils capable of generating SH fields up to second or third order. SH shimming is a robust method that can be fully automated to provide objective, user-independent magnetic field homogeneity [15-18]. The sparse sampling of 3D field distributions along selected column projections with FASTMAP (and its derivatives) has become the method of choice in many laboratories due to significantly reduced acquisition times compared to B_0 mapping methods that are based on full 3D MRI. Active shimming enables the accurate and flexible generation of correction fields simply by driving the shim coils with appropriate currents. The orthogonality of the SH functions furthermore allows the independent adjustment of its basis fields under the assumption that the fields generated by the SH wire patterns perfectly resemble the SH shapes. Complex and highly localized magnetic field distribution as observed in the human prefrontal cortex cannot be adequately compensated by low-order SH fields and magnetic field homogenization of the entire human brain has been a long-standing problem.

Dynamic Shimming with Spherical Harmonic Shapes

Complex magnetic fields can be described by simpler field shapes when considered regionally over smaller volumes. This characteristic is comparable to the approximation of a 1-dimensional, complex mathematical function through straight lines (e.g. to compute its derivative via a difference quotient) and becomes progressively more accurate as the considered functional range becomes more localized. So-called “dynamic shimming” capitalizes on this principle by breaking down a large volume to be shimmed (e.g. the human brain) into virtual subunits. The adjustment of subunit-specific shim settings then allows the improved optimization of magnetic field homogeneity over the original, larger volume based on the individual improvements that can be realized in the constituent subvolumes. The individual slices of multi-slice MRI are natural candidates for dynamic shimming due to the modular organization of multi-slice MR sequences in which all spin manipulations, i.e. spatial encoding and signal readout, are completely slice-specific. In practice, the best slice-specific shim field is applied before the corresponding slice is imaged. Subsequent application of the best available shim field for the next slice to be imaged then provides optimal field homogeneity therein and so on. After the introduction of dynamic shimming for multi-slice MRI with linear gradients [19, 20], the benefits with the inclusion of second order SH terms [21, 22] and third order SH terms [23] have been demonstrated. Besides the application of dynamic shimming to MRI, multi-voxel MRS with dynamically updated, voxel-specific shim settings has been shown to allow multi-fold efficiency gains [24, 25]. Dynamic shimming requires dedicated amplifier electronics for the switched application of the various shim fields and their updating for the individual subvolumes during the experiment execution [22, 23]. The rapid field switching with coils fitted to the scanner bore induces eddy-currents in the magnet's cold conducting structures which in return generate a multitude of artificial field terms throughout the bore including the designated subject position. The quantitative characterization of all of these field terms along with their temporal behavior is necessary for the identification of significant components. Their subsequent experimental minimization by pre-emphasis and B_0 compensation is essential for successful higher SH order dynamic shimming [22, 23]. Dynamic shimming is inherently more powerful than static (global) shimming for any given shim system. The increased effort and complexity of its experimental realization with the inclusion of additional SH orders, however, eventually outweighs the progressively smaller additional benefits [23]. Correction fields for dynamic shimming are updated once per repetition time corresponding to the time spent by the MR sequence on its individual subvolumes, i.e. the term dynamic shimming describes the fast adjustment of otherwise constant shim fields. As such, dynamic shimming cannot account for continuously changing magnetic field distortions as they are observed e.g. in the human brain due to oscillatory changes in the body's susceptibility distribution during the breathing cycle. The continuous adaption of shim fields, so-called "real-time shimming", has been shown to compensate such temporally varying field alterations [26].

Static and Dynamic Multi-Coil Shimming

The experimentally available low-order SH terms allow to resemble and, therefore compensate large-scale and shallow magnetic field components, however, the complex field terms generated by the sinuses in the prefrontal cortex and by the auditory cavities in the temporal lobes cannot be corrected adequately. While significant improvements in magnetic field homogeneity have been demonstrated with dynamic shimming for most parts of the human brain, even state-of-the-art dynamic shimming including all zero through third order SH terms is not capable of completely homogenizing the entire human brain [23]. SH functions are only one of many possible basis sets for the description and synthesis of magnetic fields. However, despite some specialized, non-SH shim approaches for the human prefrontal cortex on the basis of localized, intra-oral coils [27] or a specifically tailored set of external coils [28], the orthogonality of the basis shapes has been accepted by the MR community as an essential prerequisite for successful magnetic field modeling and shimming based on early articles [14]. It has been demonstrated recently that a set of generic, circular coils can be converted to a powerful magnetic field modeling system when each of the electrical coils is driven individually [29]. In other words, the orthogonality of the basis functions is not a requirement for successful magnetic field modeling when least-squares methods are used for the field decomposition. The multi-coil (MC) concept allows the synthesis of simple and complex magnetic fields in a flexible and accurate fashion by superposition of non-orthogonal, generic basis fields. After the application of MC magnetic field modeling for the generation of low order SH fields, static and especially dynamic MC (DMC) shimming has been shown to outperform shimming the available SH shimming in the mouse brain [30], the rat brain [31] and the human brain [32]. Along with the achievable efficiency gains of MC shimming compared to SH-based approaches, the MC concept has the potential to replace conventional shim systems that are based on sets of SH coils [33].

Practical Aspects of Shimming

The definition of magnetic field homogeneity is straightforward, but the quantification of magnetic field inhomogeneity and the evaluation of its impact on MR applications are not. Typical features of magnetic field distributions before and after shimming are discussed and related to the underlying optimization algorithms, shimming methods and targeted MR applications. Successful magnetic field homogenization relies upon the application of suitable methods along with their proper use. Even the best shimming technique will fail if insufficient attention is paid to the details of its experimental realization. To this end, a series of general and method-specific aspects will be discussed that help ensure the consistency of theoretical predictions and experimental outcome, and prevent the need for multiple shim adjustments or iterations. Magnetic field distortions have to be measured before they can be addressed by shimming and imperfections of the inhomogeneity assessment inevitably diminish the possible shim outcome. Potential error sources of B_0 mapping are detailed and strategies for their minimization are discussed. In the same vein, imperfect knowledge of the shim system's basis shapes translates to reduced shimming quality and, therefore the thorough calibration of shapes and amplitudes of the available basis fields is of paramount importance. The effect of amplitude limitations on the projected shim outcome is discussed for SH coil systems and for (D)MC shimming. It is shown that cross-compensation between channels is possible with (D)MC shimming to some degree whereas the orthogonality of the SH functions precludes a similar approach with SH-based methods. Finally, the quantification of shape imperfections of SH coil systems is discussed along with ways for their consideration in the calculation of shim settings.

Which Shimming Method is Best for Me?

There is no trivial and effortless shimming technique that provides perfect homogeneity under all circumstances, i.e. in every region-of-interest of every species. MR laboratories therefore have to decide on the shimming capability of their MR system and scientists have to select the particular method they are going to use. However, choosing the 'best' shimming method for the MR application at hand is not a trivial task, as multiple factors ranging from the species- and region-dependency of apparent magnetic field distortions to the level of field homogeneity required along with the projected outcome of the various techniques are to be considered. Further indirect, but not less significant factors influencing the choice of a shimming method include the availability of techniques, the complexity and expenses related to their implementation as well as the effort and level of expertise required for their use. For instance, adequate magnetic field homogeneity throughout the entire human brain is required for true whole brain applications such as susceptibility weighted imaging (SWI) that is based on two phase and one frequency encoding, and a potent method for global, static shimming has to be chosen. Small volumes for single voxel MRS can typically be shimmed well with second order SH functions [34]. Magnetic field homogenization within dorsal axial slices, thereby excluding the distortion in prefrontal cortex, for MRS imaging (MRSI) requires shim fields with significantly less shape complexity and has been addressed by inclusion of additional SH terms [35]. Also, some MR applications are less susceptible to magnetic field imperfections than others. As such, lower quality magnetic field homogeneity is acceptable e.g. for spin-echo MRI, whereas MRS and MRSI applications always require the best possible shim. The necessary degree of magnetic field homogeneity will be discussed for typical MR applications and analyzed with respect to the required effort, methodological complexity and financial burden for the implementation of various shimming methods.

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