Shimming and MRS

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Adjustment of the static magnetic field homogeneity, commonly known as the B_0 shimming or simply shimming, is essential for magnetic resonance spectroscopy because it determines the spectral resolution which is critical for reliable metabolite quantification. Inhomogeneities in the B_0 field, resulting primarily from susceptibility differences between air and tissue, are scaled with the B_0 field and become highly non-linear at ultra-high magnetic fields. Although efficient minimization of the B_0 inhomogeneity in the whole human brain is extremely difficult especially at high fields, successful results were recently achieved at 7T by using shim coils up to the 3rd order [1]. The B_0 field is usually most distorted in prefrontal regions due to its close proximity to the sinuses. Different techniques have been proposed in combination with active shimming to minimize strong local inhomogeneities including localized shim coils [2,3], diamagnetic and paramagnetic passive shims [4-6] and dynamic shimming [7].

In general, successful shimming requires efficient shimming methods for mapping the B_0 field variations over the region of interest as well as a shim system (coils and drivers) which is strong enough to compensate these field gradients. Methods developed for B_0 field mapping can be grouped into two categories; methods based on 3D B_0 mapping [8-10] and B_0 mapping along projections [11-15]. In both types of shimming techniques, information about the B_0 field variation is calculated from phase differences acquired during the evolution of the magnetization in a non-homogeneous field. The precision of the B_0 field mapping depends on the duration of the evolution time and the spatial resolution of the mapping. Longer evolution times increase sensitivity to small B_0 changes and allow a fine adjustment of shims. However, longer evolution times result in a substantial signal loss and severe phase unwrapping problems when the B_0 field homogeneity is poor, typically in the beginning of the shimming process. Therefore, methods utilizing multiple evolution times are preferable [13,8,9].

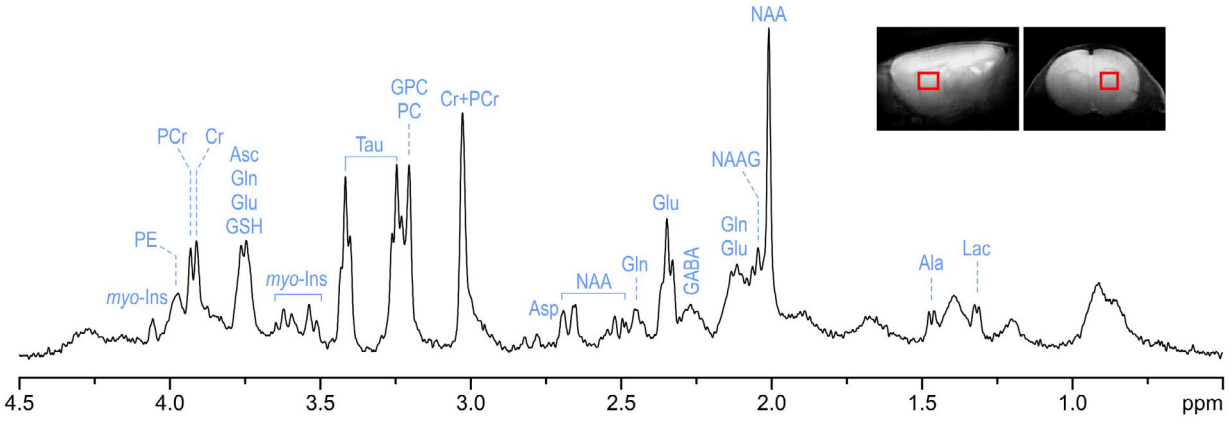
The strength of linear shims (X, Y, Z) is not a problem, because powerful gradient coils and gradient amplifiers are preferentially used for 1st order shim corrections in MR scanners. Therefore, limitations in the shim strength are more an issue with higher-order shim coils, usually the strength of the 2nd order shim system. The maximum strength of a shim coil depends on its inductance and the maximum current of the corresponding shim driver. The higher shim coil inductance requires less current to generate a specific field, however, this may result in stronger coupling to the gradient coil. Which means that the gradient switching can negatively influence the stability of the shim current. Shim coils with lower inductance may exhibit decreased coupling with the gradient coil but require more current to generate a given field, which can result in difficulties with sufficient heat extraction from the shim coil.

MR spectroscopic imaging (MRSI) requires a highly homogeneous B_0 field within a large region of the brain, typically across a whole slice through the brain or possibly within the entire brain volume. Due to substantial B_0 field distortions at high magnetic fields, adjustment of an acceptable B_0 homogeneity in large volumes requires shim corrections up to the 3rd order and probably some 4th-order terms, such as Z4, might be necessary [8]. Despite all this effort, complete elimination of small local deviations from the B_0 field uniformity is very difficult. On the other hand, single voxel MRS requires adjustment of the B_0 field homogeneity in a relatively small volume, which is technically much easier. In addition, the B_0 field distortions can be very well approximated using only 1st and 2nd order shim terms, which is the most common shim coil configuration on MR scanners. High levels of the B_0 uniformity can be achieved in small

volumes selected for a single voxel MRS by a fine adjustment of all 1st and 2nd order shims. Resulting spectral linewidths are determined only by the intrinsic parameters of the tissue (relaxation parameters of detected molecules and microscopic variations in tissue susceptibility). Precise B_0 field mapping in small volumes requires high spatial sampling, which is much easier and faster to achieve using methods based on mapping along projections, such as FASTMAP [12,13] than by using techniques based on 3D B_0 field mapping [8,9].

The recommended strengths of the 2nd-order shim system for the human brain MRS at 7T are 20 – 40 Hz/cm^2 (0.48 – 0.96 μT/cm^2) for XZ, YZ, Z2 shims and 10 Hz/cm^2 (0.24 μT/cm^2) for XY and X2Y2 shims [16,17]. The smaller the measured object and the radius of the air/tissue interface, the stronger are the B_0 field local gradients. This means that the compensation of B_0 field distortions in the brain of rodents requires significantly stronger 2nd-order shims, approximately by two orders of magnitude relative to human applications. In addition, shim requirements are substantially higher in mice relative to rats. For example, recommended lowest values for the mouse brain MRS at 9.4T are the following: 2000 Hz/cm^2 (48 μT/cm^2) for XZ, YZ, Z2 and 1000 Hz/cm^2 (24 μT/cm^2) for XY and X2Y2 shims [18].

FASTMAP shimming [12,13] is very robust and fully automated, which guarantees that the resulting spectral resolution is highly reproducible. For example, the water signal linewidth 10.5 ± 0.3 Hz was achieved in mouse striatum at 9.4T (n = 50). FASTMAP is a projection method, which means that the assessment of local variations in B_0 is based on assumption that the magnetization dephasing occurs only in one direction. In other words, the thickness on the excited bar must be significantly smaller than the length of the evaluated phase profile. The best shimming quality with FASTMAP is usually achieved after three or four iterations. Time requirements for FASTMAP shimming are minimal, because four iterations with interleaved update of the resonance frequency require less than two minutes. It is important to mention that in addition to shimming, the final spectral linewidth after averaging is influenced by other factors, such as the B_0 field drift as well as frequency and phase variations resulting from physiological motion. Therefore, single scan averaging is optimal if there is enough SNR after one scan to perform frequency and phase correction. If the SNR of single scan data is not high enough then averaging in blocks is recommended. The ability to resolve the resonances of creatine (3.91 ppm) and phosphocreatine (3.93 ppm) at 9.4T is an excellent indicator that near optimal shimming was achieved, as shown in the figure.



In vivo ^{1}H MR spectrum measured from the rat striatum at 9.4T. STEAM, TE = 2 ms, TR = 5 s, VOI = 10 μl, FASTMAP shimming, rat age = 3 weeks.

To take advantage of increased chemical dispersion at high magnetic fields, optimal shimming is absolutely essential. High quality shimming enables reliable quantification of a broad range of brain metabolites, the so called neurochemical profile. Neurochemical profiles were measured non-invasively in rats [19,20], mice [18], monkeys [21], during brain develop-

ment [22], in iron deficiency studies [23], after transient cerebral ischemia [24,25], in transgenic mouse models [26], etc. Neurochemical profiles of the human brain have also been measured at 3T, 4T and 7T [27,17].

In conclusion, the B_0 shimming is crucial for high performance in vivo ^{1}H MRS. Efficient shimming methods are available for a routine use. For a successful shimming it is important to guarantee that the strength of the higher order shim system is strong enough to compensate induced B_0 field distortions.

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