Experimental Evaluation of RF Non-uniformity Correction in the Mapping of the Proton Density

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RF non-uniformity causes significant intensity variations in MR images and raises challenging problems at high field strength. An important part of the problem is solved by optimizing the equipment (multiple transmit or receive systems), but still proton density (**PD**) mapping requires an accurate RF non-uniformity correction, since the accuracy of a PD map is directly driven by this correction. More precisely, the effect of the transmit and receive non-uniformity can be seen in the following equation, describing the NMR signal S(r) at location r:

$$S(r) = C \times M_0(r) \times B_1^-(r) \times f_{seq}(\alpha(r), r),$$

where $M_0(r)$ is the proton density, $B_1^-(r)$ is the sensitivity of the receiving coil, $\alpha(r)$ is the flip angle and C a system constant. The term $f_{seq}(\alpha(r), r)$ represents the contrast of the sequence, which depends on $\alpha(r)$. In addition to this, from the flip angle formula, it is known that the flip angle, $\alpha(r)$, is proportional to the RF field strength $B_1^+(r)$ created by the transmitting coil at the location r. Since it is possible to measure the flip angle map (using, for example, the double angle method or using the spin echo – stimulated echo method [3]), we have a direct access to the strength of $B_1^+(r)$. This, however, does not hold for the receiver sensitivity. Interestingly, a method has been proposed that is able to measure the PD without measuring the sensitivity [8] and it relies on the distant dipolar field [7]. However, this method only gives access to low resolution PD maps and preferably requires very high field strengths. At low field strength, the problem can be solved if we assume that the RF field distribution is not dependent on the sample. Under this approximation, it is possible to measure the B_1^+ and B_1^- distribution in a large container of homogeneous PD and carry on an external RF non-uniformity correction [5]. At 3T, dielectric resonance effects are expected to be significant [1] and an alternative to the external RF calibration is often preferred. To our knowledge, the only existing alternative makes use of the NMR reciprocity principle [6], guaranteeing that *for a transmit-and-receive system*, the ratio B1-(r)/B1+(r) is independent of r. The present study aims to evaluate RF non-uniformity correction at 3T on MAGNETOM Trio MRI system using a transmit-and-receive birdcage coil, based on the NMR reciprocity principle.

Material and Method

A series of four phantom experiments were conducted using two different cylindrical containers of height 200 mm: container A (∅ 190 mm), and B (∅ 140 mm), filled with distilled water or vegetable oil. The positioning of the cylinders with respect to the coil was carefully defined, the axis of the cylinders being parallel to the static field. A 2-D gradient echo sequence (TR = 20s, ensuring full recovery of the magnetisation, 2 mm in plane resolution, 2 mm slice thickness) was repeated, the applied RF voltage, V, being progressively increased. This experiment can be understood as a voxel-wise measurement, S(r, V), of the precession of the magnetisation as the voltage increases. Therefore, in each voxel r, the following model applies:

$$S(r, V) = C \,.\, M_0(r) \,.\, B_1^-(r) \,.\, \sin(B_1^+(r) \,.\, V).$$

By fitting acquired data with this model, the maps B_1^+ and B_1^- can be estimated up to a constant, which is sufficient for the purpose of this study.

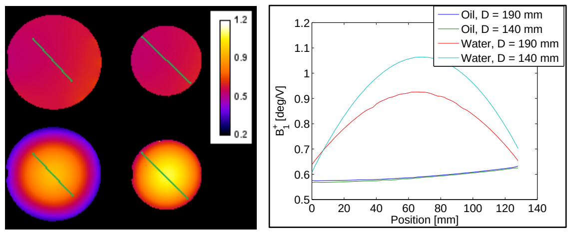

Figure 1: a) Active field maps acquired at 3T in phantoms A (left) and B (right) and in vegetable oil (upper) and water (lower images). b) associated B1+ profiles

Results

In Fig. 1a), the excitation maps measured in vegetable oil (upper row) and water (lower row) in both phantoms A (left column) and B (right column) are shown. The B_1^+ profile (green segment depicted on the disks in Fig. 1a)) is plotted in Fig. 1b) and allows one to visualize more precisely the changes arising from a variation in the sample size (from 140 mm to 190 mm diameter) or in the dielectric permittivity (from $\varepsilon_r = 80$ in water to $\varepsilon_r = 3$ in oil). The profiles depicted in Fig. 1b) show two distinct patterns, associated to oil and water, respectively. In addition to this, in the water phantoms, the measured B_1^+ distribution appears to be strongly dependent on the diameter of the cylinder. From these results, we conclude that dielectric resonance effects are important at 3T in "water" samples, comparable in size to the human head. As a consequence, non-uniformity correction based on external field maps is expected to be inaccurate at 3T. In Fig. 2), the ratio of the passive and active B_1 field is shown in phantom B, in vegetable oil (upper figure) and water (lower figure). In oil and water, the hypothesis of a constant B_1^-/B_1^+ ratio is verified to within 2%. In case of water, a residual variation in the ratio B_1^-/B_1^+ can be distinguished (a darker spot in the middle of the disc in the lower figure in Fig. 2). Such effects were also observed at higher field strength (4Tesla) in a more pronounced manner. Fit error maps (mean square distance between the experimental curve and the model) also indicate that the equation for S(r, V) might not be perfectly valid, under circumstances that need to be determined. This issue actually points to an active area of research and various theories could explain the reported inaccuracy, such as field propagation phenomena [4].

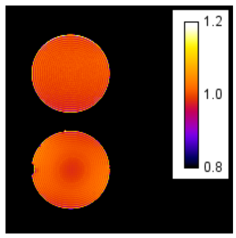

Figure 2: Ratio of the receive and transmit non-uniformity maps B_1^-/B_1^+ measured in phantom B in oil (upper) and water (lower figure).

Conclusion

The importance of RF non-uniformity correction for quantitative imaging has been demonstrated in particular in the context of proton density imaging, where an accurate sensitivity correction is required. Experiments conducted at 3T indicate that dielectric resonance effects significantly affect the B_1 distribution in a sample of size comparable to the size of a head. Consequently, RF non-uniformity correction based on external field maps, as proposed at 1.5T field strength, is not a valid approach. The alternative consists in measuring the sample-dependent transmit-and-receive non-uniformity maps. The hypothesis of reciprocal maps has been tested in a simple but widely used model of the NMR signal. It is then shown that the measured maps actually exhibit reciprocal properties to within a precision of 2%, indicating that proton density mapping methods based on this method also give this precision at most. According to this study, the presently investigated model needs further refinement in order to reach higher precision measurements.

References

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