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Realistic phantoms for quantitative MR: the need and a proposal (the B_1 sleeve)

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ABSTRACT

Quantitative MR (qMR) has offered direct access to *in-vivo* biology and physiology for over three decades, yet it has failed to translate into the clinic. Why is this? The development of suitable phantoms is a key stage in the evolution of qMR, and here a systematic categorisation is proposed. Currently there is much attention paid to creating simple head phantoms containing materials with metrologically traceable values of MR quantities. However these are usually unrealistic; many of the disrupting phenomena present in clinical imaging are absent. Good performance with a simple traceable phantom is a necessary but not sufficient requirement for the establishment of good *in-vivo* measurement performance. There is therefore a premium on developing *realistic* phantoms. A proposal made for a more realistic body phantom that includes RF B_1 imperfections. It consists of lossy annuli placed around a standard head phantom. Other confounding phenomena could be identified, possibly built into an appropriate annulus around a simple head phantom, to form realistic phantoms; these would enable validation of qMR methods and translation to the clinic. The concept is probably applicable to other quantitative diagnostic imaging modalities.

Introduction

The concept of quantitative MR (qMR) has existed for over three decades, offering direct access to biology and physiology [1–7], yet its implementation is still not straightforward or widespread. It has failed to translate into the clinic. Thus it is important to understand why this might be. Multi-centre studies can show large differences between MR machines, often due to differences in sequences and vendors [8]; good and convenient accuracy (closeness to the true value) and precision (repeatability) remain elusive.

The development of suitable phantoms is a key stage in bringing about the acceptance of qMR. Currently there is much attention paid to creating phantoms containing materials with metrologically traceable values of MR quantities. [5–7,9]. However these simple phantoms are usually unrealistic; many of the disrupting phenomena present in clinical imaging are absent. These include RF nonuniformity and incorrect gradient magnitudes, and are a particular problem in body (as opposed to head) imaging, and at fields of 3T and above.

Thus there is a premium on developing *realistic* phantoms, as a crucial step in the evolution of qMR. Here the concept is explored, and a proposal made for a realistic body phantom that includes RF B_1 imperfections. The concepts explored here are most likely applicable in general terms to other diagnostic imaging modalities that are actually or potentially quantitative.

Types of phantom

Phantoms (test objects) for qMR, particularly head MRI, now have an evolved design and are quite widely available. Often they contain materials whose quantitative parameters (e.g. relaxation times, mean diffusivity) are traceable to metrology standards [5–7,9]. Thus the performance of a qMR procedure in phantoms can be regularly monitored, accuracy and repeatability can be measured, and a variety of machine failures can potentially be detected, thus aiding the use of qMR. If a measurement procedure can produce good performance in phantoms, it is tempting to deduce the procedure is good.

Good phantom performance is however a *necessary* but not *sufficient* criterion to establish the validity of *in-vivo* measurements. A measurement procedure could perform perfectly on a phantom yet fail *in-vivo*. This is because there are often other imperfections in *in-vivo* measurements which may be absent or different in phantoms (e.g. flip angle errors – see next Section below). Thus it is important to develop and use

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realistic phantoms (i.e. those which contain the imperfections encountered *in-vivo*) – see Table 1*;* if a procedure works well on a *realistic* phantom, in principle this proves it works *in-vivo* (provided that the phantom really is realistic). Realistic phantoms are therefore a key to increasing the performance, acceptance and use of quantitative MR methods; a key to translating qMR into the clinic

B_1 imperfections

B_1 imperfections are probably one of the most important factors in degrading in-vivo measurements (depending on what qMR parameter is being estimated); here an approach to making a phantom that is realistic with respect to B_1 imperfections is presented. They vary according to the tissue composition, the size of the subject being imaged, and the location being examined. They may be more of a problem for body imaging than head imaging, and for higher values of static field B_0. Probably no single phantom can replicate the variety of encountered B_1 imperfections.

B_1 imperfections arise from two distinct phenomena. Firstly, RF penetration of the more central tissue is limited by eddy currents in the more superficial (conducting) tissue. The effect of this is to reduce the transmitted RF field B_1^+ [10]. An opposing (second) phenomenon is that dielectric resonance [11] can increase B_1^+ near the centre of the object (independent of any electrical conductivity effects); this phenomenon is most pronounced in large non-conducting aqueous phantoms, and largely absent in the small bottles used in a head phantom. The effect of these two phenomena is to produce a range of incorrect values of flip angle FA within the subject [12,13] (see Fig. 1); the effect is more pronounced at 3T [11]. This defect can be mitigated by the vendor's procedure to set the FA inside the subject, although it cannot be accurate at all locations. The 2nd effect is that the RF signal B_1^- from the precessing magnetisation inside the subject may have difficulty in 'escaping' to the receive coil; then the observed signal and SNR will be reduced.

The primary consequence of incorrect FA is in Variable Flip Angle (VFA) T_1 and DCE measurements; a 1 % error in FA directly translates to an error of 2 % in the estimated T_1 value [14]. The loss of SNR is often less serious, although in T_2 and ADC measurements the attenuated signal value may be difficult to estimate (and biased) in the presence of noise. Thus B_1 imperfections can be significant *in-vivo* measurements whilst being absent in phantom measurements.

Proposal for a B_1 sleeve

It is proposed here to place a set of annular cylinders (rigid sleeves) one at a time around an established head phantom to give a variety of unknown B_1 imperfections, and thus a set of realistic (virtual) body phantoms (Fig. 2). The sleeves would contain aqueous NaCl solutions of various concentrations, thus giving a range of unknown B_1 attenuations. The performance of a well-designed measurement procedure (pulse sequence) would give correct values of T_1 even in the presence of several different B_1 values.

Each B_1 sleeve could be made from two concentric plastic cylinders. It should be large enough to contain a typical head phantom (200 mm diameter), and small enough to fit inside the body transmit coil with enough clearance to place a wrap-around receive coil around the sleeve. Diameters of 350 mm (internal) and 400 mm (external) would enable the head phantom to be placed at different positions with respect to the magnet isocentre (Fig. 2). The length should be at least twice the diameter, to prevent B_1 access through the ends of the sleeve; thus a length of 800 mm might be appropriate. If a set of say three sleeves was to be made, they could perhaps be made to slide inside each other for more convenient storage.

To establish suitable values for the NaCl concentration, some experimental MRI measurements would be needed at several B_0 values to determine i) how much B_1^+ is altered in body imaging, for a range of locations and body types (although published studies [12,13] give guidance), and ii) what values of concentration provide a comparable range of B_1^+ values. Alternatively, published models [13] could perhaps be used to estimate both of these.

Table 1
Establishing the validity of an *in-vivo* quantitative MR procedure using phantoms.

Phantom type	Testing for *in-vivo* validity in presence of imperfections	Role of good phantom performance[c] in establishing validity of *in-vivo* procedure
#1 simple traceable[a]	some imperfections	necessary
#2 realistic[b] traceable	all imperfections	necessary and sufficient

[a] traceable: true value of parameter is known (measured in a metrology lab).
[b] to establish realism the types of imperfection in the *in-vivo* measurement procedure have to be identified, then (ideally) replicated in the phantom (see discussion).
[c] to demonstrate good phantom performance the measurement procedure should be: 1. accurate (close to true value) 2. reproducible (at different centres) and repeatable (at one centre) and 3. sensitive (accurate over a range of true values).

Discussion

Realistic phantoms could provide the pathway to establishing the accuracy of clinical measurements, the stability of serial measurements, and the ability to carry out high-quality multi-centre studies. Imaging of human controls will probably also have role to play. Maybe the B_1 sleeve will play a part in creating the perfect body qMR machine [15].

Note that the proposed B_1 sleeve is not designed to calibrate the measurement procedure in any way; it is to validate an existing procedure. 'Loading rings' have been used for some time to load the transmission coil during phantom imaging, and the construction of a B_1 sleeve could be similar, although its purpose is different. An existing loading ring (or its casing) could perhaps be used without the need for any further construction.

So called 'System Phantoms' can be used for QA on the MR machine, to characterize performance and detect degradation in aspects such as RF coils, SNR, slice thickness and geometric distortion [5,7]. With the use of traceable materials, such a phantom can show that qMR measurements made in phantoms are correct. However it cannot show the validity of a clinical measurement procedure, since it is not realistic. It is a *simple traceable* phantom (see Table 1).

The search for *realistic* phantoms that mimic the human body has included a prostate phantom [illustrated in [6] Fig. 1]. These have an array of test substances usually in an aqueous bath; thus RF dielectric effects will be present [11], probably different from those in the body. Mimics will never be completely accurate, and cannot capture the range of properties encountered in different subjects. The proposal here is fundamentally different: instead of attempting to mimic, it identifies a confounding factor (here unknown B_1^+ effects) and provides a range of values (using the B_1 sleeves) to challenge the measurement procedure. These sleeves can use existing head phantoms and are relatively cheap and simple.

The approach proposed here (of surrounding a metrology core with a sleeve) can probably be extended to address other imperfections in qMR, although to identify and replicate them will require considerable further analysis and work. It is probably impossible to identify all of these with certainty. In this note B_1 imperfections are a convenient place to start exploring the concept of the realistic phantom. Additionally, other quantitative diagnostic imaging modalities could probably benefit.

Summary

In summary, the importance of designing realistic phantoms is

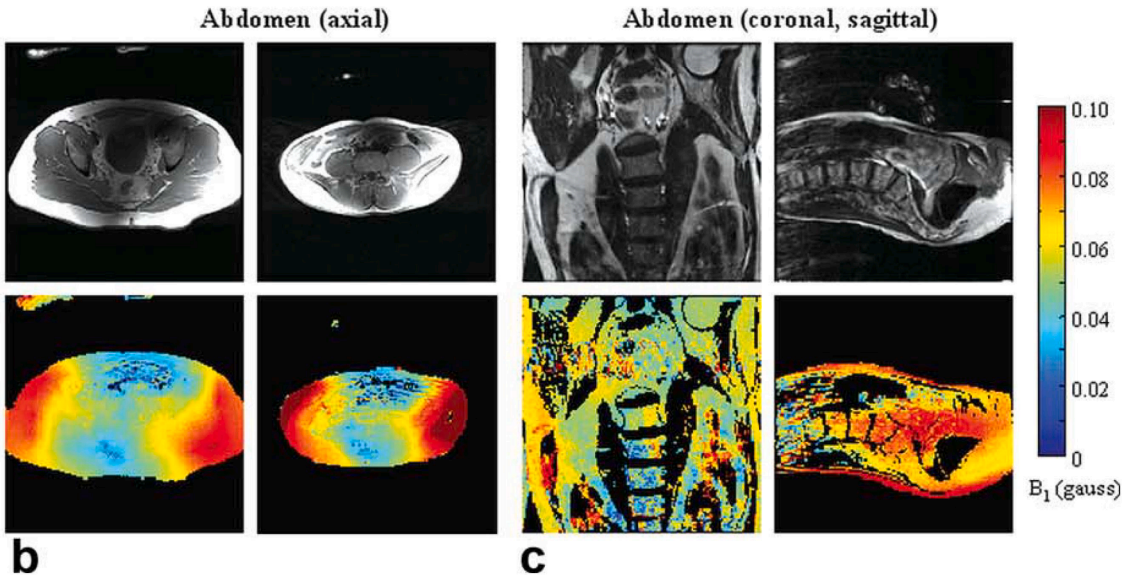

Fig. 1. An example of B_1^+ distribution in the body at 3T (from Sacolick et al. [11] figure 10 parts b and c). The colour images (lower row) show B_1^+ values with an approximate range from 0.04 to 0.09 gauss.

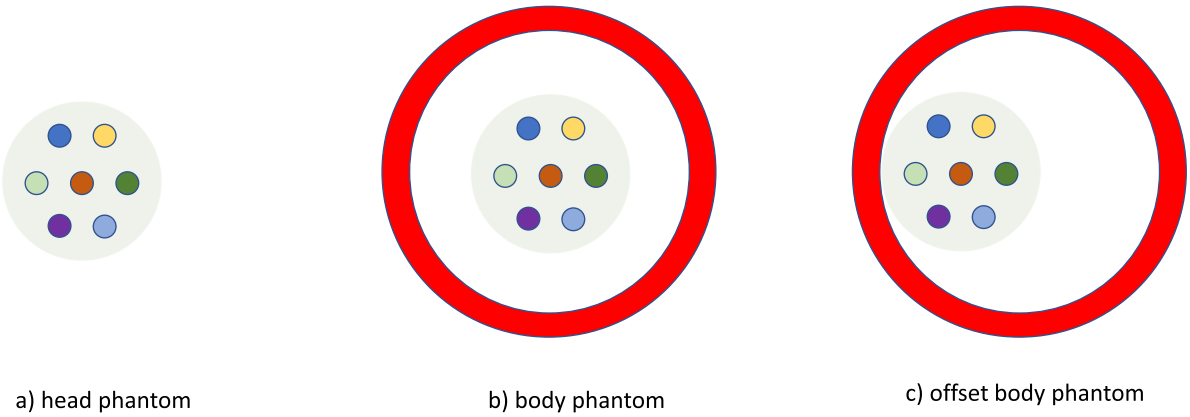

Fig. 2. An existing simple head phantom (a) can be converted to a realistic body phantom (b) by the addition of a concentric cylinder containing NaCl solution (**red**). Measurements offset from the isocentre are possible (c). Suggested dimensions are: head phantom 200 mm, concentric cylinder internal diameter 350 mm.

stated. It is proposed that a set of B_1 sleeves be used in routine QA for qMR. These would be cheap and simple to manufacture, and could be used widely. Existing head phantoms could then be used to validate measurement procedures in a realistic way.. It could then be established how a measurement procedure performs under a variety of B_1 imperfections.

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Ethical approval

Not required.

Declaration of competing interests

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References

[1] R. Damadian, Tumor detection by nuclear magnetic resonance, Science (1979) Science (1979) 171 (issue 3976) (1971) 1151–1153.
[2] S. Wray, P.S. Tofts, Direct in vivo measurement of absolute metabolite concentrations using 31P nuclear magnetic resonance spectroscopy, *Biochim Biophys Acta* 29 886 (3) (1986) 399–405, https://doi.org/10.1016/0167-4889(86)90175-8.
[3] P.S. Tofts, G. Brix, Estimating kinetic parameters from dynamic contrast-enhanced T(1)-weighted MRI of a diffusable tracer: standardized quantities and symbols, J. Magn. Reson. Imaging 10 (1999) 223–232.
[4] M. Cercignani, N.G. Dowell, P.S. Tofts, Quantitative MRI of the Brain: Principles of Physical Measurement, CRC Press, 2018 second ed.

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[5] K.E. Keenan, Quantitative magnetic resonance imaging phantoms: a review and the need for a system phantom, Magn. Reson. Med. 79 (2018) 48–61, https://doi.org/10.1002/mrm.26982.
[6] K.E. Keenan, Recommendations towards standards for quantitative MRI (qMRI) and outstanding needs, J. Magn. Reson. Imaging 49 (2019) e26–e39, https://doi.org/10.1002/jmri.26598.
[7] Stupic, A standard system phantom for magnetic resonance imaging, Magn. Reson. Med. 86 (2021) 1194–1211.
[8] N. Stikov, On the accuracy of T1 mapping: searching for common ground, Magn. Reson. Med. 73 (2) (2015) 514–522.
[9] Hall M.H. et al. (2023) The perfect diagnostic imaging machine and what it means for quantitative MRI reproducibility *IPEM translation* 10.1016/j.ipemt.2023.100019.
[10] P.A. Bottomley, E.R. Andrew, RF magnetic field penetration, phase shift and power dissipation in biological tissue: implications for NMR imaging, Phys. Med. Biol. 23 (4) (1978) 630–643.
[11] P.S. Tofts, Standing waves in uniform water phantoms, J. Magn. Reson. Ser. B 104 (1994) 143–147.
[12] L.I. Sacolick, F. Wiesinger, I. Hancu, M.W. Vogel, B1 mapping by Bloch-Siegert shift, Magn. Reson. Med. 63 (5) (2010) 1315–1322.
[13] W. Liu, C.M. Collins, M.B. Smith, Calculations of B1 Distribution, Specific Energy Absorption Rate, and Intrinsic Signal-to-Noise Ratio for a Body-Size Birdcage Coil Loaded with Different Human Subjects at 64 and 128MHz, Appl. Magn. Reson. 29 (1) (2005) 5–18.
[14] R. Deichmann, R. Gracien, T_1 : iongitudinal relaxation time, in: M. Cercignani, N. G. Dowell, P.S. Tofts (Eds.), Quantitative MRI of the Brain: Principles of Physical Measurement, CRC press, 2018, p. 78.
[15] P.S. Tofts, The perfect qMR machine: measurement variance much less than biological variance, EJMP 104 (2022) 145–148.