A New Type of Gradient: The Detection Frequency Gradient. A New Capability: Retrospective Shimming

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Introduction: Conventional NMR detection results in detected signals having the same frequencies as the precessing spins. However for a time-varying B1 detector field this is not necessarily so, leading to the possibility of *retroactive shimming*, i.e. the detected signal appears shinned (spectrum has narrow lines) even though the spins themselves are precessing at different frequencies. The dynamic B1 detector field is synthesized retroactively by a time-dependent weighted combination of NMR signals from a receive coil array. This method exploits array element sensitivity variations within the target volume (as does SURE-SENSE (1)).

Introducing the NMR Detection Frequency: The NMR detector mediates between the RF field of the precessing spins (ωF) and the detected EMF signal (ωEMF). We will define the *detection frequency* as: ωF = ωEMF - ω0. Normally ω0 = 0, however not necessarily, and we will show that a spatial gradient in ω0 is possible.

B0 Field Errors: This is common for the B0 field to have an unwanted (‘error’) term: B0(r,t) = B00 + B0EXP(r,t) + B0ERR(r,t), which leads to mCORR = mACT e^{-j(ω0+ωERR)(t)}, where mACT is the actual magnetization, and mCORR = mACT e^{-j(ωEMF)(t)} the desired error-free (‘correct’) magnetization. The precession errors are given by: φERR(r,t) = -∫t0 tf(r,t)dt.

NMR Detection Process: The NMR detection process is governed by: emf = -2ζ(B0, m) = -2ζ(B0 || m | cos θ) where normally m is assumed to contain all the time-variation and B0 is static (2,3). Note especially that the B1 detector field does not have RF time-variation – if it did an EMF would arise from a static m!! However, these facts notwithstanding, note the complete symmetry between the two vectors in the equation.

A Modified Detection Process: By a modification of this detection process we can compensate the signal for magnetization precession errors. We write the sample magnetization as: mACT = |mACT|e^(iθm(r,t)), which includes the precession errors. Now, the precession errors in mACT would be counteracted, and mCORR recovered, if we had a time-dependent detection field B1 CORR(r,t) satisfying this condition:

emf CORR = -2ζ(B1 CORR(r,t), mACT(r,t)) = -2ζ(ζB1 STATIC(r),mCORR(r,t))

This states that B1 CORR(r,t) is the detection field that can yield the EMF field as a regular static detector field (B1 STATIC) detecting the error-free magnetization (the ideal situation). To satisfy this condition it is sufficient that the dot products be equal: B1 CORR(r,t) = B1 STATIC(r), mACT(r,t) = B1 STATIC(r), mCORR(r,t) Omitting the r dependence for clarity, this becomes: B1 CORR(r) = B1 STATIC(r) |mACT(r)| cos(θm(r) - θm(r) + φERR(r)) writing B1 STATIC = |B1 STATIC| e^iφ we can perform the dot product on the right hand side: B1 CORR(r) = |B1 STATIC| |mACT(r)| cos(θm(r) - θm(r) + φERR(r)) and rearrangement of the phase terms to associate the phase error term φERR with the B1 field (rather than m) the solution is:

B1 CORR(r) = B1 STATIC(r) e^(-jφ(r))

So our claim is that spin precession errors can be eliminated by a detection field that is the product of any static field and a spatial phase correction term.

Retrospective Shimming using a Detection Frequency Gradient: For the case of a linear gradient inhomogeneity: φERR = χ Gx(r) so φERR = -γχ Gx(r) and B1 CORR(r) = B1 STATIC(r) e^(-jχ Gx(r)) From our condition on B1 CORR(r) the error term has been eliminated from the EMF, so the detection frequency is:

ωF(r) = ωEMF(r) - ω0(r) = (ω0 + ω0 EXP(r)) - (ω0 + ω0 EXP(r) + ω0 ERR(r)) = -ω0 ERR(r) = γχ Gx(r) + χ Gx(r) has which the form of a linear detection frequency gradient Gx = ∂ω0/∂x = γχ Gx. In other words, the detected frequency depends upon the spin location within the sample. This is the mechanism for retroactive shimming.

Generation of the Time-Varying Detector Field: So given this requirement for a time-varying B1 CORR(r,t) detection field, how do we create it? It can be retroactively synthesized by a time-dependent weighted sum of a set of EMF signals acquired from multiple detector coils (receive array). This has many similarities with parallel imaging methods such as SMASH (5). An important difference however is that the weightings are not constant, but vary throughout the acquisition window.

Taylor Series Method: For a linear detection frequency gradient we need to create a receive field: B1 CORR = |B1 STATIC| e^iφ(r) [cos(γχ Gx(r) + βχ Gx(r))] which can be expanded as a power series in x: B1 CORR = |B1 STATIC| e^iφ(r) [1 - x^2(γχ Gx(r))^2/2 + ...] = [x(γχ Gx(r) - x^3(γχ Gx(r))^3/6 + ...)], where the powers of x can be regarded as the spatial response of the receive fields and the arguments as weighting factors. If we write: Φ = x Gx(r), then, for a given set of field polarization terms, there will be a value ΦMAX beyond which the approximation breaks down. So for example, when correcting an FID, the maximum available detection frequency gradient decreases linearly with time. Matrix Method: This is a more general method. The problem is to find the weights Wc, given the coil field maps An and the target field: Bp = An Wc, where P indexes the field point, and C indexes the coils. The inverse of A can be calculated: I = (A^T A)^-1 A^T, where Gamma provides regularization to control noise amplification (1,4). The coil weightings then: Wc = I Bp. The corrected EMF is obtained from the weighted sum of the acquired EMFs.

Results: Simulation results are shown for |Φ| < 135° and 4 terms in the Taylor series polynomial. The sample is a single spectral line with T2 decay. Fig.1: raw FIDs from the 4 RF Rx coils (uniform, χ x, y, χ); Fig.2: FIDs after weighting has been applied; Figs.3: un-shimmed FID (i.e. signal from uniform coil), corrected FID (i.e. complex sum of weighted FIDs); the ideally-shimmed FID; Fig.4: spectra corresponding to Fig.3.

Discussion: The corrected FID shows complete rephasing (dotted line in Fig.3) where the un-shimmed signal is a null. The correction is less effective at the end of the FID. The corrected line-width shows significant improvement, even though complete rephasing is not achieved. Conclusions: A new type of NMR field gradient has been introduced (detection frequency gradient). Simulations show that this enables retrospective shimming, a unique capability. In principle many types of B0 error (shimming, eddy currents, instabilities) are candidates for correction using this method. Because the method is retrospective each voxel can be corrected individually, which is a unique capability. The method is compatible with all other shimming methods. Implementation requires receive coils with different sensitivity distributions over the target volume (i.e., intra-voxel variations). Design of suitable coil arrays will therefore likely be key in determining range of applicability.