Fast characterization of higher-order shim dynamics by impulse response measurements with a dynamic field camera

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Introduction: New dynamic shimming methods open up possibilities of shaping the field within an object more in line with specific requirements on field homogeneity for different applications [1,2]. This however puts demands on the dynamic characteristics of the shim system, which were previously not as significant. One immediate problem are the eddy currents induced by shim switching [3,4], but for faster dynamic use of the shims, also other effects such as the characteristics of the shim amplifiers and mechanical vibrations of the shim coils could become important. This motivates research into methods that can be used for comprehensive characterization of shim field dynamics, within reasonable time windows. As technical development advances towards increasing numbers of shim channels, the time per channel required for characterizing a system also becomes more significant. The purpose of this work was to investigate measurements of the shim impulse response function (SIRF) with a dynamic field camera, as a method for generally characterizing the dynamic properties of a shim system [5]. With the SIRF, the response to any input within the linear range of the system could be predicted according to the following equation:

$$\int in(\tau)\cdot sirf(t-\tau)d\tau = out(t) \quad \xleftrightarrow{\text{Fourier Transform}} \quad IN(\omega)\cdot SIRF(\omega) = OUT(\omega) \qquad (1)$$

Knowledge of the SIRF could thus serve as a basis for sequence design, for choosing pre-emphasis settings, and for system diagnostics.

Methods: All measurements were performed on a 7T Philips Achieva system (Philips Healthcare, Cleveland, USA) with full 2nd- and 3rd-order spherical harmonic shim sets. The shim amplifiers were dynamically controlled via a digital interface (Load&Go, Resonance Research Inc., USA) synchronized with the scanner through a TTL trigger signal. Field responses to the shim pulses were measured with a dynamic field camera as described in Ref. [6]. Two sets of boxcar functions, with pulse lengths of different ranges (0.1, 0.3 & 0.5 ms vs. 0.3, 0.5, 0.9 & 1.5 seconds), were used as inputs and the response was measured over 26 ms for the short pulses and 6.5 seconds for the long pulses. A boxcar transforms into a sinc function in the frequency domain, with equidistant zeros spaced depending on the length of the boxcar. The conditioning of the response measurement depends on the amplitude of the input functions at each frequency. The used pulses were thus chosen to complement each other in their pattern of sensitivity to different frequencies. The set of short pulses were more suitable to probe the response within a wide bandwidth at moderate frequency resolution (~40Hz) ($SIRF_{wide}$), whereas the longer pulses yielded high sensitivity and frequency resolution (~0.15Hz) for low response frequencies ($SIRF_{centre}$). The SIRFs were least-squares fitted to the measured data according to Eq. (1). The real part of the response was fitted within ±20 Hz onto Lorentzians of three different time constants and amplitudes, using a Levenberg-Marquardt algorithm (curve fitting toolbox, Matlab R2009b). Here data from the X2-Y2 and X3 shims are shown.

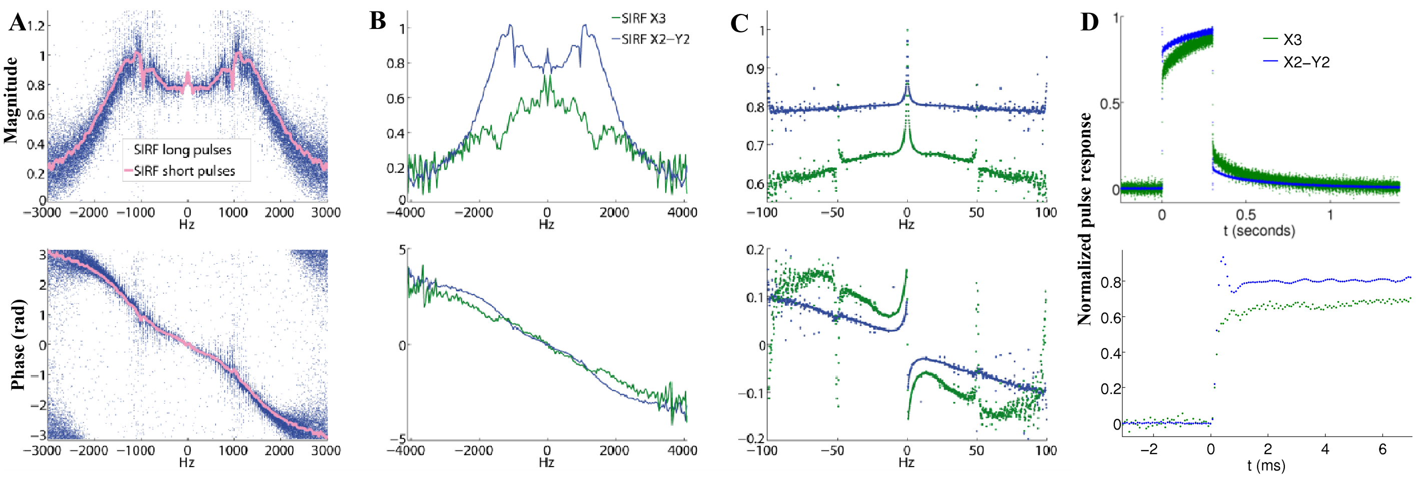

Fig 1: A) Comparison of SIRFs based on long vs. short set of pulses for X2-Y2. B) $SIRF_{wide}$ for X2-Y2 and X3. C) $SIRF_{centre}$ for X2-Y2 and X3. D) Response of one pulse in the time domain (top), zoomed to show initial overshoot (bottom).

Results: There was good agreement between the SIRFs calculated from the two different sets of input functions, though, as must be expected, the high-frequency data obtained with the long test pulses are very noisy (Fig 1A). The highly resolved data in $SIRF_{centre}$ reveal a sharp peak centred at zero, which drops to a nearly constant level (Fig 1C). The linewidth of this peak is ~0.9 Hz for X2-Y2 and ~1.2 Hz for X3. For both shims, the response tapers off at around ±4 kHz (Fig 1B). In X2-Y2 there is a prominent 'hump' centred at around 1 kHz, which cannot be seen in X3. Correspondingly, in the time domain there is an overshoot when switching X2-Y2, which is not seen in X3 (Fig 1D). The central peak of the SIRFs could be fitted well by three Lorentzian terms for both X2-Y2 and X3, suggesting eddy currents as its source. For X2-Y2, the inverted response (1/SIRF) was fitted in the same way to obtain time constants and amplitudes that could be used for pre-emphasis. Setting these in the shim interface resulted in the desired flat response at the centre (±4‰ deviation from 1, within ±15 Hz), and for higher frequencies the impulse response was raised by about 24% (Fig 2).

Discussion & Conclusion: The impulse responses of higher-order shims can be readily determined by probing them with suitable sets of boxcar test functions and measuring the field responses with a dynamic field camera. Long-term eddy current effects are clearly seen at the centre of the SIRFs, whereas the exact origins of other observed features remain to be elucidated. Their sources certainly include the characteristics of the shim coils as well as shorter-lived eddy currents and potentially mechanical vibrations. Field camera measurements yield the responses of all spherical harmonics simultaneously. Therefore, the data and methods presented above can straightforwardly be used also to obtain and analyze SIRFs for shim cross-terms. In conclusion, the results of this study indicate that SIRF measurements could serve as a fast and reliable technique to obtain useful information for the development, quality assurance, and maintenance of shim systems. It may also serve as a basis for choosing pre-emphasis settings.

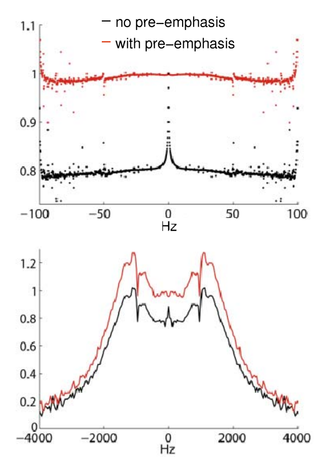

Fig 2: Measured $SIRF_{centre}$ (top) and $SIRF_{wide}$ (bottom) of X2-Y2, before and after setting the pre-emphasis.

References: [1] Koch et al., JMR 2006, 180:286-296 [2] Poole et al., Magn Reson Mater Phy 2008, 21:31–40 [3] Juchem et al., Proc. ISMRM 2010, p.222 [4] Vannesjö et al., Proc. ISMRM 2010, p.145 [5] Vannesjö et al., Proc. ISMRM 2010, p.1536 [6] Barmet et al., 2008 Magn. Res. Med 60:187-197