Dead Time Reduction with a Variable Rate Broadband Receiver – Applications to Zero Echo Time Imaging

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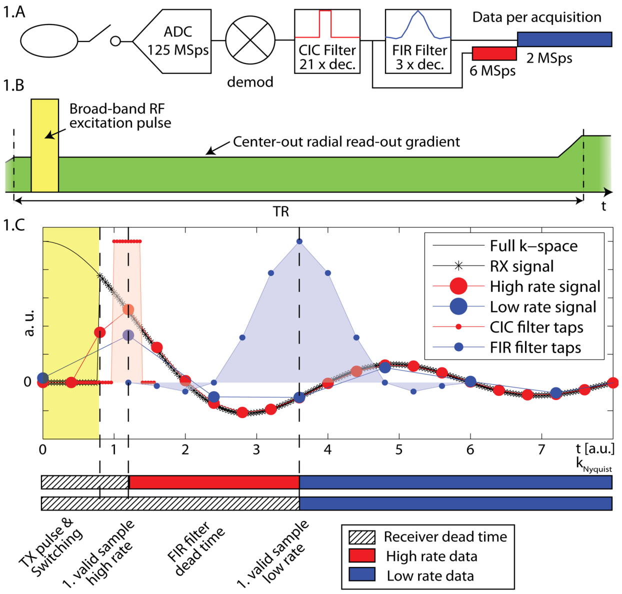

Figure 1:A system and signal processing schematic. B ZTE sequence diagram. C timing diagram of the signal acquisition and filtering showing the temporal extent of the filters by their shadings.

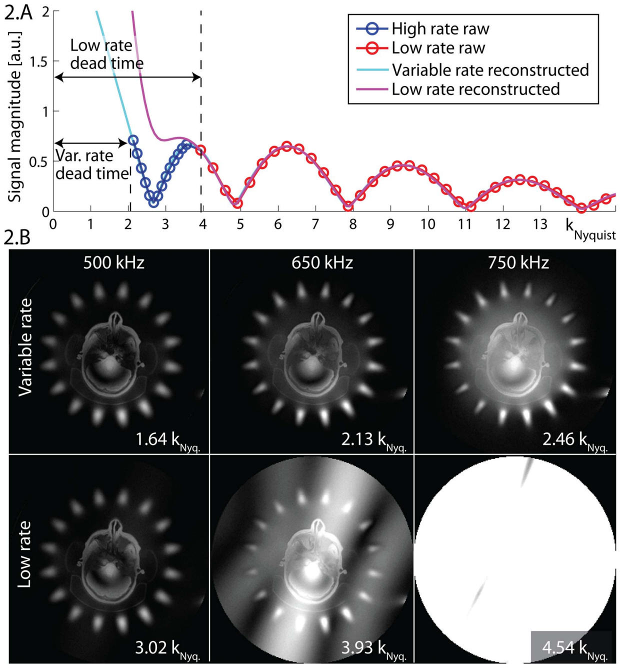

Figure 2: A time domain data comparison. B Comparison of in-vivo 7T high bandwidth ZTE images reconstructed with the variable rate data and with 2 MHz sampling rate solely.

Introduction: For imaging of ultra-short T_2/T_2^* (~100 µs) coherences several techniques such as UTE [1], SWIFT [2], PETRA[3], stochastic resonance [4] and ZTE [5] have been presented that benefit greatly from acquiring the NMR signal with minimal dead time between the short transmission pulses and the sampled recordings. This acquisition dead time is determinant for the achievable imaging bandwidth (iBW) [2, 5] and hence for the achievable localization of short T_2 species as well as for its tolerance towards strong off-resonances. The gap in the acquisition is composed by the excitation pulse itself, the transient time of the TR switch and the group delay of the narrow band filtering performed on the received signal. The associated downsampling of the acquired data to the acquisition bandwidth (aBW) is required for keeping the data flow in manageable realms, however using state-of-the-art switches (with transitions below 1 µs [7]) the settling time of these filters is typically the dominant contribution (4 to 10 µs depending on the filter performance, i.e. width and ripple of pass and transition band). The settling time is required by the filter to distinguish the pass and stop frequencies from each other after the start of the acquisition for which all taps of the filter have to be filled (see Fig. 1C) and can only be reduced by less selective filter designs which come at either large data overheads or increased noise due to aliasing effects. However, the excess sampling rate is only required at the borders of the acquisition window which represent a broadband event on the elsewhere band limited analytic k-space signal. Therefore a variable rate acquisition scheme is proposed oversampling the beginning (and in principle the end) of each acquisition window. It will be shown for the example of high bandwidth ZTE imaging with up to 750 kHz that this reduces the sampling dead time due to filtering by almost an order of magnitude at a very minor expense of additional memory requirements.

Methods: ZTE images were acquired on a 7T magnet (Philips Healthcare, Cleveland, Oh., USA) and a custom built broadband RF receive chain. 3 µs 2 kW transmit pulses were sent to a 10 cm, proton free surface coil and a commercial volume resonator (Nova Medical (Willmington, MA, USA) through custom built TR switches with sub-microsecond transient time. The excited NMR signal was acquired using a custom analogue to digital converter sampling at 125 MHz and 14 bits depth. The primary samples were digitally down converted on a dedicated FPGA (Xilinx, Spartan 6) to 6 MSps by a numerically highly efficient Cascaded-Integrator-Comb (CIC) filter (320 ns group delay) and subsequently to 2 MSps by a FIR filter (3.1 µs group delay) . Bursts of 2.8 µs of 6 MSps are incorporated into the reconstruction after the excitation pulse until the FIR filter is settled. The reconstruction was performed in full analogy to Ref. [8] by a profile-wise algebraic finite support extrapolation of the missing k-space centre followed by iterative 3D gridding.

Results: Fig. 2.A shows measured data from a single profile acquired from an oil phantom with 650 kHz BW showing the portion that were acquired with the high and low rate. The reduction of the gap by 50% shows significant improvement of the finite bandwidth extrapolation performed by the reconstruction of each profile (including the diametral spoke acquisition). Fig. 2B shows in-vivo data sets acquired with iBWs from 500 kHz to 750 kHz. As expected, the spatially correlated noise amplification and distortion of the spatial response due to the increasing ill-conditioning of the finite support approximation with large gap sizes [6, 9] is clearly reduced for the variable rate scheme. The remnant centre brightening at higher bandwidths is believed to stem from RF transmission signal ringing down into the acquisition and can potentially be further suppressed by an appropriate subtraction scheme. The extra data amount acquired was between 12% and 9% compared to the 2 MHz acquisition rate.

Discussion & Conclusion: Broadband MRI RF receivers in conjunction with high speed programmable computing engines enable flexible and sequence dependent access to the full information acquired. The presented scheme of variable rate sampling practically halves the receiver dead time due to power RF transmission and switching and enhances by this the image quality and achievable bandwidth of ZTE acquisitions at a very minor increase of excess memory and data streaming requirements which is of crucial importance for future high channel count approaches. The presented sampling scheme can analogously by applied in all cases with interrupted acquisitions of a signals with band limited analytic continuation requiring fast switching from transmission to reception such as in UTE, gapped SWIFT acquisitions, gapped decoupling and labelling sequences but also for rapidly re-excited field monitoring probes.

References: [1] Bergin, Radiology (1991), [2] Idiyatullin, JMR (2006), [3] David M. Grodzki, MRM (2011), R. Ernst, JMR (1970), [5] Weiger, MRM (2011), [6] Weiger, Proc. ISMRM p. 747 (2011), [7] Weiger, MRM (2013), [8] Weiger, eMagRes 1 p. 311 (2012), [9] Weiger, Proc ISMRM p. 2632 (2013)