Travelling wave parallel imaging

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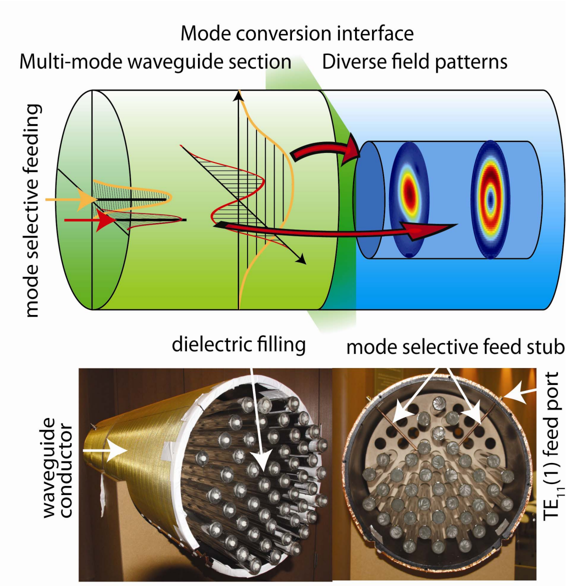

Figure 1: *(Top) Schematic of the setup showing the waveguide whose modes couple to the sample as indicated by arrows. (Bottom) Pictures of the bore extension filled with a variable number of water-filled rods to enhance its mode diversity.*

Introduction: Spatial degrees of freedom offered by radiofrequency (RF) electrodynamics form the basis of parallel MRI [1,2]. Conventionally, the RF encoding in these approaches is provided by diverse sensitivity patterns of different elements in a close-coupling coil array. However, RF coupling across greater distances is often observed at very high Larmor frequencies when the signal wavelength becomes comparable to object and bore sizes. This effect has recently been exploited to implement MRI with transmission and reception by travelling RF waves [3]. There has been doubt, however, if such distant detection could also serve for parallel imaging. In the present work it is shown that the necessary diversity of sensitivity patterns can indeed be achieved, enabling accelerated imaging with distant detection.

Theory: In a waveguide, orthogonal RF modes can propagate ideally, maintaining their unique transverse field distributions along the propagation axis. In a sample to be imaged, placed at the proximal end of such a waveguide, each mode gives rise to a distinct sensitivity pattern (Fig.1, top). It is hypothesized that the spatial degrees of freedom of this coupling can be used for parallel imaging, provided a sufficient number of propagating modes and selective detection through a corresponding number of ports at the distal end of the waveguide.

Methods & Results: To provide the necessary mode diversity a dielectrically filled, shielded bore extension was used (Fig.1, bottom), which fits into the bore of a 7T Philips Achieva whole-body scanner (Philips Healthcare, Cleveland, OH). When fully filled with 52 water-filled rods the eight-port extension carries up to 17 RF modes. The design and transmit properties of this device are reported in a separate contribution. Its ports were equipped with T/R switches and connected to the eight-channel MultiX transmit system and the spectrometer of the 7T system. Receive sensitivity maps were recorded in a transverse plane of a cylindrical phantom (Ø = 20 cm, length = 30 cm) filled with tissue-simulating liquid ($\varepsilon_r = 58$, $\sigma = 0.78\ ^{S}/_{m}$) and are plotted in Fig.2A.

From the receive sensitivities g-factor maps (Fig.1B) were calculated for a series of reduction factors R, showing that the field diversity is readily sufficient for parallel imaging with up to 3-fold acceleration. For concern of volunteer safety, initial imaging of a natural sample was limited to a water melon. Figure 1C shows receive sensitivity maps from a transverse slice through the melon. Gradient-echo imaging with full Fourier encoding and Roemer reconstruction [4] based on the sensitivity maps yielded the image shown in Fig. 1D (left), which also relied on RF shimming for uniform excitation. Travelling-wave parallel detection was then used for SENSE imaging [2] with 2.5-fold and 4-fold acceleration in the same plane. The resulting images in Fig. 1D (right) show spatially varying noise enhancement as expected from the g-factor maps but otherwise match the full-Fourier counterpart, thus proving the feasibility of parallel imaging.

The dependence of the parallel imaging performance on the mode diversity of the waveguide was studied by gradually decreasing its dielectric filling. The number of dielectric rods was reduced from 52 (17 modes) to 36 (13 modes), 24 (10 modes), and 12 (5 modes), maintaining a maximum degree of symmetry in the transverse plane. Without any filling the ports of the empty waveguide could no longer be matched and no MR signal could be observed, reflecting the expected lack of any propagating mode. However, as the plots in Fig.1E show, as few as 12 rods, enabling 5 modes, were sufficient for reasonable parallel imaging with common acceleration rates. Higher acceleration factors eventually exceed the mode diversity, leading to disproportionate g-factor increases whose onset is indicated by arrows in the graph.

Conclusion: Parallel imaging can readily rely on travelling-wave detection if a sufficient number of propagating modes is available. The mode diversity depends on the bore width, the Larmor frequency and the amount of dielectric filling. For a Larmor frequency of 300 MHz and a typical whole-body bore width a small amount of dielectric filling has been found sufficient to support parallel imaging with common acceleration rates. This filling took up less than 5 % of the bore cross section. It is thus relatively easy to mount and manipulate and is expected to have little effect on the comfort of human subjects. The use of travelling-wave coupling enables parallel imaging with detection across substantial distances (2m in this case) and without the need for a close-coupling receiver array. It is most feasible in ultra-high-field conditions and will benefit from even higher Larmor frequencies and larger waveguide diameters. Important open questions concern the dielectric filling configuration and the placement and nature of the waveguide ports. Both have been implemented based on basic simulation results in the present work but can likely be improved by design optimization. An important limitation of travelling-wave detection is its limited sensitivity, which stems from intrinsic long-range RF coupling to lossy materials in the setup and which thus makes it an alternative to body resonators rather than local receiver arrays.

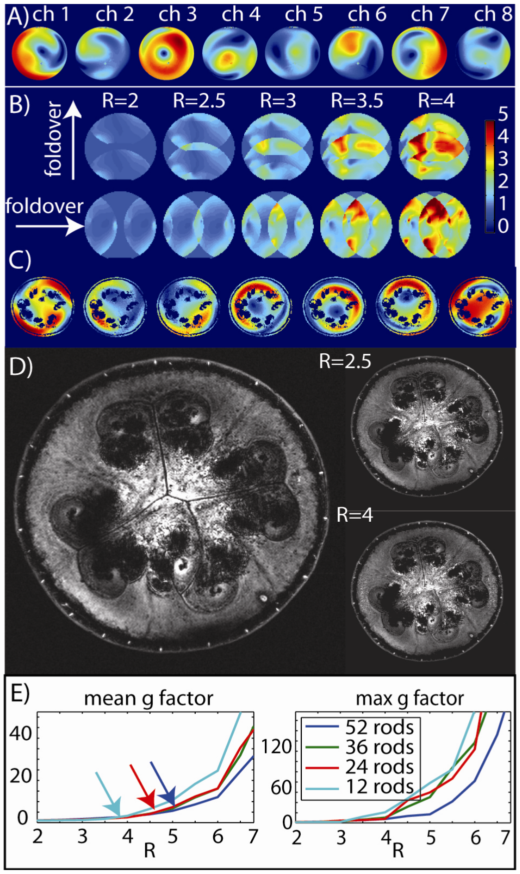

Figure 2: *A) Receive sensitivities of the eight waveguide ports. B) g-factor maps for Cartesian SENSE imaging with varying acceleration factor R. C) Receive sensitivities in a water melon. D) Full-Fourier (left) and SENSE imaging (right) of the melon. E) mean and maximum g-factors as the dielectric filling of the waveguide is gradually reduced.*

References: [1] Sodickson et al. MRM 1997 [2] Pruessmann et al. MRM 1999, [3] Brunner et al. Nature 2009. [4] Roemer et al. MRM 1990