

Field of View reduction using Sinusoidal gradient Pulses in Combination with an O-space Gradient eNcoding field and reconstructing with SPACE RIP (VSOP COGNAC)

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Introduction: Recent work has shown that non-linear gradients allow a reduction of the FOV by dephasing parts of the spin ensemble [1]. Elsewhere it has been suggested to use non-linear gradients for more flexible encoding schemes and better adaption to the imaged anatomy [2, 3]. The imaging scheme presented here uses the advantages of encoding with non-linear gradients while intrinsically dephasing the spin ensemble in the center of the FOV. Applying phase encoding (PE) in the polar coordinate r with a z^2 -gradient, the number of PE steps necessary to fulfill the Nyquist criterion can be reduced. This potentially allows faster imaging e.g. of the cortex, when the central part of the FOV is of no interest. Using only the z^2 -gradient for PE, COGNAC [4] can be adopted for reconstruction and therefore the inversion of the full encoding matrix can be avoided to save reconstruction time. In VSOP COGNAC (Field of View reduction using Sinusoidal gradient Pulses in Combination with an O-space [3] Gradient eNcoding field and reconstructing with SPACE RIP [5]) sinusoidal gradient pulses are applied with Cartesian gradients for readout (RO).

Acquisition trajectory: The amplitude of the sinusoidal gradient pulses are set to acquire a circle that is the tangent to the edge of Cartesian k-space at a given resolution. For PE a z^2 -gradient ($B_z(x,y,z) \sim z^2 + 1/2(x^2 + y^2)$) is used. In order to obtain signal from a given voxel, the z^2 -gradient must be strong enough to compensate for the phase induced by the linear gradients. While this is easily fulfilled at the outer part of the FOV at some point of the trajectory, the z^2 -gradient is too weak in the central part due to its non-linearity. Therefore the center of the FOV is never rephased. Examined using the idea of a "local k-space" [6], the central area of the k-space is not acquired for the center of the FOV.

Reconstruction: The reconstruction takes place in polar coordinates. The raw data is Fourier transformed in r -direction. Thereafter it is interpolated in order to compensate for the non-linearity of the z^2 -gradient. Each "onion ring" is reconstructed separately. The signal equation in COGNAC is a generalized form of the SENSE [7] equation, where all signal on a ring folds onto one pixel. Furthermore the equation is supplemented with the phase induced by the field of the linear gradients and yields in matrix form

$$\vec{S} = \mathbf{C} \cdot \mathbf{G} \cdot \vec{\rho} = \mathbf{C}' \cdot \vec{\rho}$$

where \vec{S} is the signal of the n_r receiver coils in the folded pixel, \mathbf{C} denotes the coil sensitivity matrix and \mathbf{G} the phase induced by the phase gradient. $\vec{\rho}$ represents the magnetization. If the encoding matrices of all n_p phase encoding steps are combined, an encoding matrix \mathbf{C}' with $n_r \times n_p$ virtual coils is derived. The regularized reconstruction equation

$$\vec{\rho} = (\mathbf{C}'^H \mathbf{\Psi}^{-1} \mathbf{C}' + \lambda^2 \mathbf{I})^{-1} \mathbf{C}'^H \mathbf{\Psi}^{-1} \vec{S}'$$

follows out of the Tikhonov cost function. Here indicates H the transposed and complex conjugate. $\mathbf{\Psi}$ is the noise covariance matrix, λ the regularization parameter, \mathbf{I} the identity matrix and \vec{S}' contains the signal of all virtual coils in the folded pixel. The reconstruction equation is solved with the conjugate gradient method.

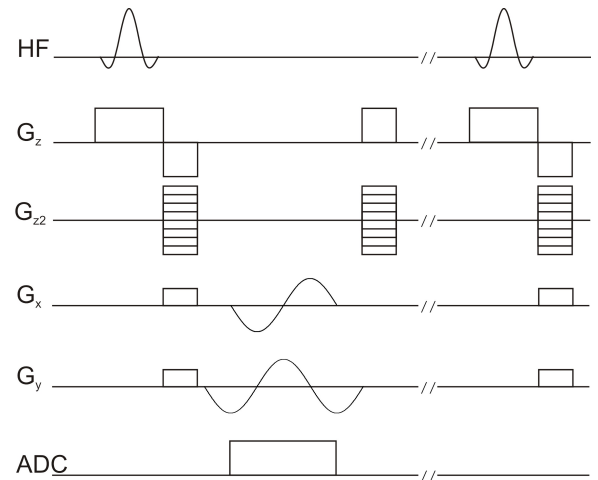


Figure 1: VSOP COGNAC sequence. G_{z2} is used for phase encoding, while Cartesian gradients are driven in sinusoidal shapes during readout. The trajectory of the Cartesian gradients is a circle that is the tangent to the edge of Cartesian k-space.

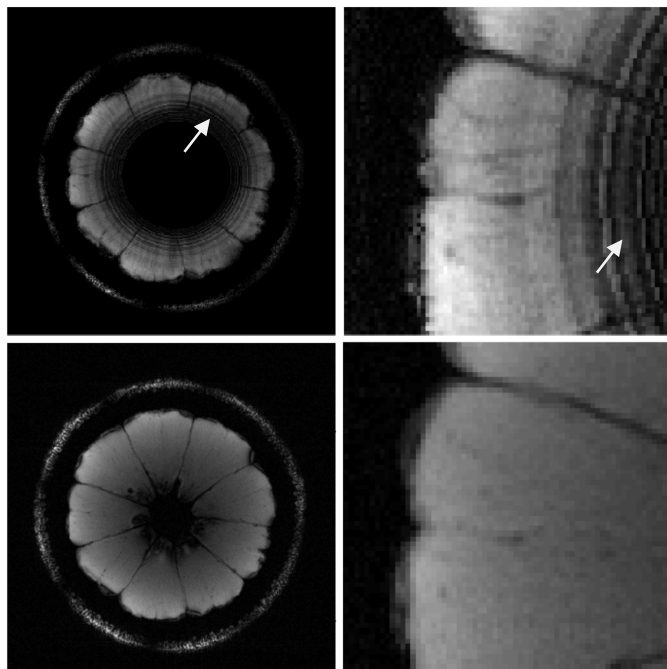


Figure 2: Top: VSOP COGNAC with 85 PE steps, reconstructed on a 384x384 grid. Bottom: Cartesian gradient echo, resolution 256x256 interpolated to 348x348 by zero filling. Left: Whole FOV, Right: Zoom. The FOV is reduced in r -direction. Thus 85 PE steps are sufficient to fulfill Nyquist while still gaining some resolution increase compared to the reference image. The arrows indicate artifacts caused by the interpolation.

Methods: Experiments were carried out with a 3T Siemens TIM TRIO (Erlangen, Germany) with a 12cm bore z^2 -gradient insert [8]. A custom-built 8 channel HF coil was used [8]. A VSOP COGNAC dataset was acquired with the Cartesian gradients set to gain a resolution of 256 pixels and a FOV of 100mm (TR = 1.5s; TE = 20ms (defined by the middle of the readout); dwell time = 7.5 μ s; flip angle = 30°). The z^2 -gradient was set to induce a phase of $\varphi(r) = 58.3/cm^2$ for the outmost PE line. 256 PE lines were acquired. Every third PE line was used for reconstruction, thus reducing the FOV in the desired way. The image was reconstructed on a 348x348 grid. A Cartesian gradient echo with a resolution of 256 and a FOV of 100mm was taken (TR = 1.5s; TE = 10ms; dwell time = 5.0 μ s; flip angle = 35°). This was interpolated to a resolution of 348x348 by zero filling and used both as a reference and for calculating the sensitivity maps.

Results and Discussion: Figure 2 shows a VSOP COGNAC reconstruction in comparison to a reference image. It can be seen that 85 PE steps are sufficient to fulfill the Nyquist criterion while still increasing the resolution slightly compared to the reference image. Coil sensitivities were used in the reconstruction only in angular direction, hence further speedup would be possible by undersampling in the radial direction. Reconstruction can then be done by inverting the full encoding matrix. After the Fourier transformation, the data has a rapidly changing phase in r -direction. This makes the interpolation difficult and causes ring like artifacts (arrows, Figure 2). A workaround is the inversion of the full encoding matrix.

Unlike in GradLoc [1], the FOV reduction in VSOP COGNAC is intrinsic. In this regard, the amount of reduction is given by the ratio of the strength of the z^2 - to the Cartesian gradients. Increasing the resolution in r -direction without increasing the amplitude of the pulses of the Cartesian gradients increases the FOV and vice versa.

It should be mentioned that the echo time, when defined as the time the spin ensemble is in phase, varies in angular direction.

To conclude, VSOP COGNAC is an imaging scheme that intrinsically reduces the FOV while also exploiting the advantages of imaging with non-linear gradients.

References: [1] Witschey W., et al., ISMRM, 2011, 2805; [2] Hennig J., et al., MAGMA, 2008, 21:5-14; [3] Stockmann J., et al., MRM, 2010, 64:447-456; [4] Assländer J., et al., ISMRM 2011, 859; [5] Kyriakos WE., et al., MRM, 2000, 44:301-308; [6] Gallichan D., et al., MRM 2011, 65:702-714; [7] Pruessmann K., et al., MRM, 1999, 42:952-962; [8] Stockmann J., et al., ISMRM, 2011, 717.