QUANTIFICATION OF IMPERFECT PHASE CYCLING IN MULTI-BAND IMAGING: MATHEMATICAL MODEL AND PROOF OF PRINCIPLE

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Target Audience MRI physicists and engineers.

Purpose Multi-band[1] based imaging techniques require phase cycling between the different slices when the sensitivity maps are not sufficiently distinct[2]. The phase cycling, intended as a linear phase modulation along the phase encoding direction in a Cartesian acquisition, has the effect of shifting the image by a fraction of the FOV. For instance, a phase cycling $(0,\pi)$ meaning that every other read out line has a π phase shift results into a FOV/2 shift of the corresponding image. This leads to a much better posed parallel imaging reconstruction problem[2]. The phase difference is therefore fundamental for the successful application of this kind of techniques. In previous studies, the negative effect of signal leakage and cross talk between simultaneously excited slices has been shown[3,4]. In this work, we show that inter-slice leakage can be partially caused by an imperfect phase cycling and we derive a mathematical model to quantify it. Based on the model, correction of imperfect phase cycling could be done.

Methods The effects of imperfect phase cycling is demonstrated for a single slice and $(0,\pi)$ phase cycling, which results into a FOV/2 shift. The derivation for other phase cycling schemes is analogous. Suppose that a phase cycling suffers from a δ imperfection, i.e. the read out lines are modulated with phase $(0, \pi\text{-}\delta)$. Ideally: $\delta=0$. The resulting *k*-space data, $g(k)$, along the phase encoding direction, k, becomes $f(k)$ for even k and $f(k)*\exp(i(\pi-\delta))$ for odd k where $f(k)$ is the Fourier transform along the phase encoding direction of the un-cycled acquisition (no phase differences between read out lines). From this, it can be shown that the cycled data can be written as

$$g(k)=f(k)*[\cos(\delta/2)*\exp(-i\pi k)+i*\sin(\delta/2)]*\exp(-i\delta/2)=\exp(-i\delta/2)*[\cos(\delta/2)*\exp(-i\pi k)*f(k)+i*\sin(\delta/2)*f(k)].$$

Note the linear phase component $\exp(-i\pi k)$ in the first term between brackets. Applying inverse Fourier transform, the first term will be shifted by FOV/2 to obtain the image $G(x)=\exp(-i\delta/2)*[\cos(\delta/2)*F(x\text{-FOV}/2)+i*\sin(\delta/2)*F(x)]$. F denotes the inverse Fourier transform of f and thus, the original image. The new image, G, is now a composition of two images: a) the original image weighted by $\cos(\delta/2)$ and shifted by FOV/2 and b) the leaked image weighted by $\sin(\delta/2)$. For $\delta=0$ no leakage is present, while for $\delta=\pi$ the whole image is leaked, that is, there is no FOV/2 shift. Note that the distance between the two images is always FOV/2, independent of δ. We would like to point out that our model for the imperfect phase cycling has in case of MB=2, a strong link with the appearance of N/2 ghosting in EPI imaging.

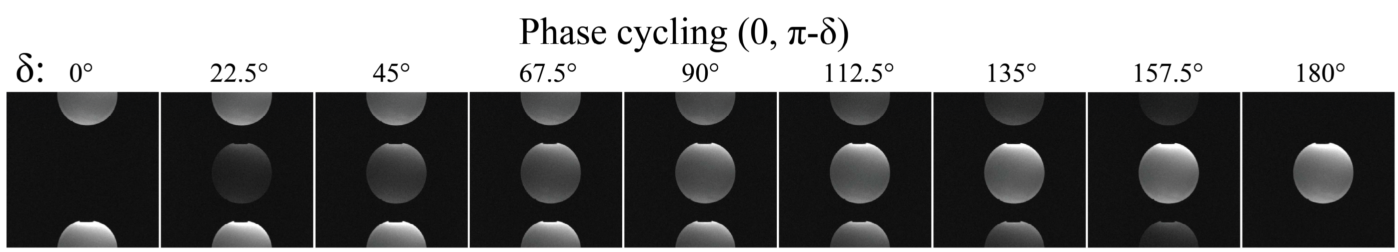

Fig 1: *Leaked (center) and shifted (FOV/2 shifted) image for (0,π-δ) phase cyclings. δ is reported on top of each frame.*

To demonstrate and quantify the leakage effect, we performed 9 single slice experiments, with phase cycling $(0,\pi\text{-}\delta)$ over the readout acquisitions, with $\delta = 0^o, 22.5^o, 45^o, \ldots, 180^o$. This is achieved by employing two different RF slice selective pulses, one with 0 phase for the even read out lines, and the other with $\pi\text{-}\delta$ phase for the odd lines. Subsequently, we measured the average signal value over the two non-shifted and shifted images. The FOV is chosen twice the phantom diameter to prevent overlapping of two images. Measurements were performed on a 1.5T MR scanner (Achieva, Philips Healthcare, Best, The Netherlands), with a cylindrical water phantom.

Results The images obtained for each phase cycling are shown in Fig. 1. Note that, as expected, the geometric shift is always FOV/2. Also, note the difference in intensity between the images. The average value for each image intensity as a function of the phase cycling is plotted in Fig. 2. Note the consistency between the mathematical model and the measurements (error=2.3%).

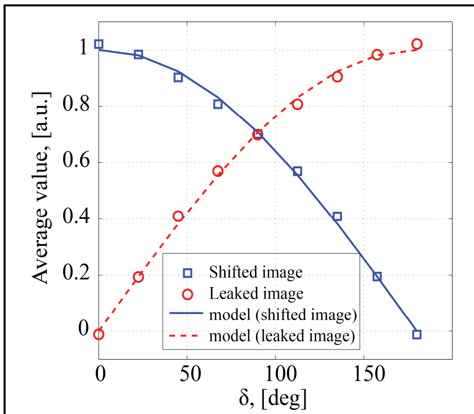

Fig 2: *Leakage experiment. Average values from images A and B (squares) and predicted values (continuous lines)*

Discussion The leakage due to phase imperfection is mathematically explained and experimentally proven. Our results imply that although visual inspection may indicate a nicely shifted image, considerable leakage may be present as well that is hard to see in a multiband case. For example at $\delta = 10^o$ the loss in signal is less than 1% whereas the leakage is already 10%.

To avoid the leakage, the phase cycling could in principle be calibrated at forehand of the experiment by testing the phase cycling for two readout lines and comparing their mutual phase. Any observed phase error δ could then be compensated in the RF pulse design. Such a calibration is especially important for CAIPIRINHA MB imaging[2] because the leaked image would overlap with the non-shifted slice image. By the here proposed phase correction, cross talk and leakage between slices would be avoided, leading to better image reconstruction for CAIPIRINHA MB methods.

Conclusion A model that explains and quantifies the leakage due to imperfect phase cycling is derived. Experimental data confirms the mathematical model. This insight our model provides, motivates performing a quick calibration scan just prior to any CAIPIRINHA MB experiment to minimize slice leakage due to imperfect phase cycling.

References [1] Glover GH, JMRI 1991 , [2] Breuer FA et al, MRM 2006, [3] Lee KJ et al, MRM 2005, [4] Xu J et al, Neuroimage 2013