# Slight Modification of Reconstruction Improves the Isotropy of non-CPMG.

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## Introduction

The non-*CPMG* sequence [1] is a spin echo sequence which permits to obtain a full magnitude signal even in the presence of initial phase variation. It already has had some clinical application in the realm of diffusion imaging [2]. But if the signal is maintained, there is still a slight amplitude modulation, in the order of +-3%, when the initial phase varies. This defect impedes true quantitative diffusion imaging and may also explain the discrepancy between non-*CPMG* and EPI based diffusion imaging found in [3]. It is proposed here a slight modification of the reconstruction process reducing this anisotropy to an acceptable level of +-0.5%.

## Method

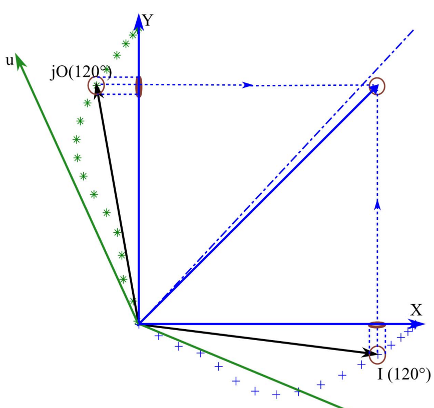
We represent 2D real vectors by bold letter, but also admit that this notation pertains equally to its representation by a complex number in the 'complex plane' $\mathbf{M} = x\mathbf{X} + y\mathbf{Y} \equiv x + jy$ , where **X,Y** are the unit vectors of the 2D rectangular coordinate, x, y the abscissa and ordinate, and $j=\sqrt{-1}$ .

<u>Position of the problem</u>: The non-*CPMG* sequence uses a quadratic phase modulation of the RF refocusing pulses train. By a suitable change of the carrier receiver phase one can, in case of a 180° refocusing pulse, make the magnetization stays constant, along the axis **X**, when the initial is along $\mathbf{X_0}$ after the flip pulse ('in-phase' condition) Then, when the magnetization is aligned with $\mathbf{Y_0}$ ('out-of-phase' condition) after the flip pulse, it will change sign every other echo, flip-flopping from $\mathbf{Y}$ to $-\mathbf{Y}$ . For nutation angle below 180°, a similar behaviour is obtained if the second order derivative $\Delta$ of the phase modulation is well chosen, and if an adapted catalyzation period is able to put the magnetization into a certain state (see [1]). The figure 1 pertains to $\Delta = 1.2$ radians and a perfect catalysing. For this value of $\Delta$ the integral of magnetization in one voxel conserves a high value, even for small nutation angles. In the figure, the crosses represent the voxel magnetization at each echo if the magnetization is initially 'in-phase' and of magnitude 1 (arbitrary unit). Each cross corresponds to one definite nutation angle, and this angle was varied from 10° to 180° by step of 10°. The corresponding complex gain is called **I** (for 'in phase'). Similarly, stars represent the voxel magnetization, at even index echo, for the out-of-phase condition. The position at odd index echo is symmetric around the origin and has not been represented. We denote by j**O** the corresponding even echo position and call **O** the out of phase gain vector. There is a moderate but significant difference of behaviour, between the in phase and out phase vector gains when the nutation is between 90° and 150°. The 'in phase' complex gain **I** is significantly larger (by 6%) in modulus or by its real component, than the 'out of phase' gain, **O**. This can be ascertained from the example **I**(120°) and j**O**(120°) shown in Figure 1. Also figure 2.a shows directly the curves real(**I**), and real(**O**), for nutations between 0 and 180°. This discrepancy produces a reconstructed image whose modulus varies when the initial phase varies, leading to a slight but visible anisotropic behaviour, not to mention a less visible concomitant phase error. Now, about the reconstruction, the figure 1 recalls the process exposed in [1]: two successive echoes are acquired with the same phase encoding; the signal of these two echoes are added, leaving only the influence of the steady magnetization **S**=**I**.$x_0$. Concurrently, a subtraction of the two successive signals is performed, leaving only the influence of the flip flopping signal **D**=j**O**.$y_0$. This is repeated for all value of **k** but only for one half k-space augmented by a small number of **k** lines. This is to permit to correct for the phase of the receiver $\varphi$ , and thus after a now classical homodyne reconstruction [4], to obtain two images. One is representing the estimate x of the initial 'in phase' magnetization $x_0$, the other one is representing the estimate y of the 'out-of-phase' magnetization, $y_0$. We note that the last step of a homodyne reconstruction is a projection along the local reference axis, $\mathbf{X}\exp(j\varphi)$ for the in phase image, or $\mathbf{Y}\exp(j\varphi)$ for the out of phase image ( $\varphi$ has been ignored in figure 1 for clarity). This projection, performed before combining the two images into the final complex image $x\mathbf{X} + y\mathbf{Y}$ , collapses one component of the noise. This is an important step for keeping the noise at the normal level (see the noise represented by circles and line segments in fig. 1) …but this step may also be used to solve the problem of anisotropy.

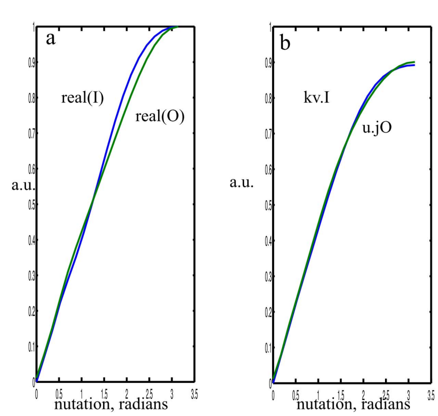
<u>Solution to the problem of anisotropy:</u> we intend to use more general estimators! What estimators of $x_0$ and $y_0$ are permissible? Because in 2D imaging, the signal is the integral of magnetization through the slice, one cannot isolate *directly* the signals coming from different sub-slices or different nutation angles. This restricts the choice of estimator to linear estimators only, so that the estimator can commute with the integral. Also as there is no a priori knowledge of the initial phase, the choice is even more restricted to two independent linear transformations, one on signal **S** only, and one on signal **D** only (a mixing of the two signals would not be controlled). Hence the most general form of possible estimators is composed of two scalar products, which can always be written (again the receiver phase $\varphi$ is ignored for clarity, the scalar product is represented by the dot symbol)

$$x = k\mathbf{v}\cdot\mathbf{S} = k\mathbf{v}\cdot\int \mathbf{I}(\theta)x_0(\theta)\mathrm{d}\theta, \quad y = \mathbf{u}\cdot\mathbf{D} = \mathbf{u}\cdot\int j\mathbf{O}(\theta)y_0(\theta)\mathrm{d}\theta\ .$$

These forms are more general than the two projections on vectors **X**, or **Y** used so far, because they are projections on general vectors **v** and **u**, of norm 1. Besides, a scaling of one of the estimators by a factor k can follow these projections. This factor must be inferior to 1, so that the noise is not increased. Of course, once x and y are obtained, the final complex image will still be reconstructed by $x\mathbf{X} + y\mathbf{Y}$ , and thus the noise will not be increased. The question is now: can one find a set of three parameters, **u**, **v**, k such that for any nutation angle the two reconstructed real values x and y are almost equal when $x_0=y_0=1$? Otherwise stated is it possible, according to the estimator's definition above and after commuting there the integral and dot product operators, to have $k\mathbf{v}\cdot\mathbf{I}(\theta) \approx \mathbf{u}\cdot j\mathbf{O}(\theta)$ , $\forall\theta$ ? The answer is that, when $\Delta = 1.2$ , one can indeed find such values. For instance the set of parameters, **u** at an angle 25.71 degrees from **Y**, **v** at an angle -21.07 degrees from **X**, as depicted on figure 1, and k= 0.956, gives the reconstructed components shown in figure 2b. The error between the two estimators $x/x_0$, $y/y_0$ is always less than 0.01, for all nutation angles $\theta$ . The price to pay is a 10% reduction of the signal, which is acceptable.




<u>Figure 1</u>




<u>Figure 2</u>

## References

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2. Oner A.Y. et al. *AJNR*, 28: 575-580, 2007;
3. Bastin, M.,*Magn. Reson. Med.* 48:6-14 (2002);4. Noll D.C.et.al. IEEE Trans. Med. Imaging,10,154-163,1991.