Investigation of Eddy Current Effect on Phase Contrast Imaging

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Abstract

We introduce a theoretical model and a testing procedure that can be used to identify the relationship between the error in phase contrast (PC) measurements and the eddy currents of the system. The results show that for typical clinical protocols the phase error is very sensitive to the eddy current with time constant on the order of the echo time (TE). The sensitivity drops significantly for eddy currents with very short or very long time constant.

Introduction

Phase contrast (PC) imaging is commonly used in quantitative measurements of volume flow rates (VFR). In PC imaging, spins are imparted with a phase that is proportional to their velocity. Typically the phase-difference from two acquisitions with different flow sensitivities is used to minimize the phase accumulation from other sources. However, phase changes induced by eddy currents are different between these two acquisitions and cannot be completely eliminated through simple phase-difference processing. As a result, in the presence of significant eddy currents the phase-difference images do not accurately reflect the true VFR and may introduce a clinically significant error in the flow measurement. This becomes a serious problem for cardiac related application in which the tolerance for error is low [1] while there is very little stationary tissue that can be used for reliable background correction. This problem exists on modern MR systems with pre-emphasis eddy current compensation and has been reported on scanners from various manufacturers. Here we identify and quantify the eddy current effects on phase error in PC imaging through theoretical modeling and measurement. We have found that for a given protocol, the phase error is particularly sensitive to the eddy current that has time constant close to TE and sometimes the default eddy current compensation is not adequate to eliminate the error.

Methods

The nature of the phase error caused by the eddy current is explained by the pulse diagram in Fig 1. The flow sensitizing bipolar gradient pulses G(t) induces eddy currents which have linear components $G_e(t)$. This leads to a shift in the echo and results in a phase ramp across the object (Fig 1A). Similarly eddy currents can cause B_0 shift that results in overall phase offset in the object (Fig 1B). We can model the eddy currents as the convolution of the time derivative of the primary bipolar gradient pulses G(t) and an exponentially decaying kernel function with a time constant τ, $G_e(t) = A\cdot e^{-t/\tau}\otimes G'(t)$, in which *A* is a coupling constant related to the mutual inductance between the various gradient coils and metallic structure. For a simple bipolar pulse shown in Fig 1, the phase due to the eddy currents can be written in a closed form:

$$\phi_L(x) \propto \int_0^{T_e} x\cdot G_e(t)dt = A'\cdot x\cdot R\cdot \tau^2 \cdot e^{-T_e/\tau}\cdot\left[1-e^{T_a/\tau}\right]\cdot\left[1-e^{(T_a+T_p)/\tau}\right]\cdot\left[1-e^{(2T_a+T_p+T_d)/\tau}\right]$$

In the above equation *R* is the slew-rate and the other timing parameters are shown in Fig 1. Similar result can be obtained for non-ideal bipolar pulses, such as the pulses combined with flow-comp pulses [2]. A simple relation can be derived from the above equation by fixing all parameters except T_e, the delay between the bipolar pulse and the readout pulse: $\phi(T_e) = \alpha\cdot e^{-T_e/\tau}$. This relation can be used to measure the τ of very short time constant eddy current that is typically difficult to measure using free induction decay (FID) based techniques.

In order to measure the PC background error, a spherical phantom filled with $CuSO_4$ solution was placed at the iso-center of an Lx Signa 1.5T scanner (GE Medical Systems, Milwaukee, WI). The phantom was allowed to stabilized for 15 minutes to eliminate any residual flow. The body coil and standard clinical PC imaging protocols were used to acquire the phase images of the static phantom. The imaging parameters were: receiver bandwidth ±31.25 kHz, slice thickness 8 mm, FOV 20 cm, acquisition matrix 256 × 128, flip angle 30°, Venc=50-250 cm/s TR=8.5-7.4 ms, TE=4.2-3.1 ms. Orthogonal imaging planes and flow encoding directions were used to isolate effect from individual gradient axis. The phase images were corrected for gradient non-linearity and concomitant fields [3] and background suppressed with magnitude threshold. They were fitted to a second order polynomial: $\phi(x,y) = a + b\cdot x + c\cdot y + d\cdot x^2 + e\cdot y^2 + f\cdot x\cdot y$ in which *a* is the DC phase offset, and *b* and *c* are the phase ramp associated with the linear eddy currents. Higher order terms *d*, *e*, and *f* were used to obtain better fit but not for further analysis. The amplitude of specific eddy current components in the pre-emphasis compensation system was adjusted to simulate the eddy current effect.

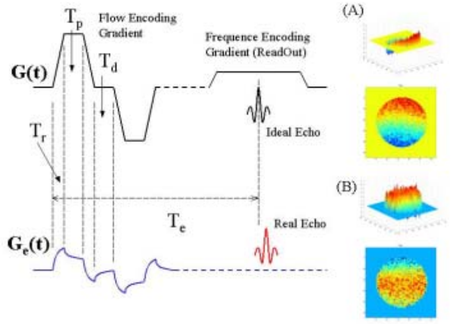

Figure 1 Pulse diagram and Timing parameters

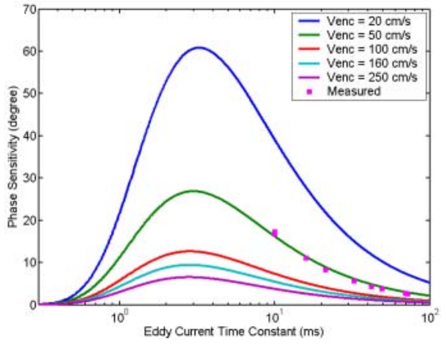

Figure 2 Calculation and measurement of phase sensitivity with various Venc values.

Results and Discussion

The phase sensitivity, which is defined as the phase change for a given amount of change in the eddy current amplitude, as a function of the eddy current time constant is calculated for waveforms with varying Venc (Velocity Encoding) values. Results are shown in Fig 2, which compares the theoretical response with the measured value. The lower Venc value corresponds to larger bipolar gradient pulse, which generates more eddy currents. This is reflected by the larger phase error shown. The measured result agrees well with the calculated values. The measured short term eddy current shown in Fig 3 has a time constant τ=0.864±0.055 ms. We have found that the phase error can be attributed to each individual component of the different type of eddy currents, i.e. various on-axis or cross terms of the scanner.

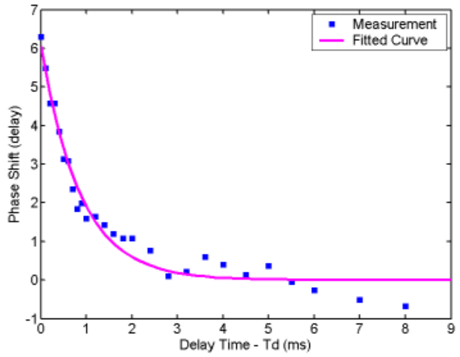

Figure 3 Result of measuring τ by varying T_e.

Conclusion

We have proposed a methodology that can be used to determine the dependency of the background phase error in PC imaging on the system eddy currants. We have proposed a theoretical model that can predict the phase error based on the knowledge of the eddy currents and waveform timing. This provides a better understanding of the nature and extent of the error, which may be used to minimize the effect of the error in future hardware design and pulse sequence programming. The model can also be extended to systems with more complex eddy currents, i.e. eddy currents with multiple time constants.

References

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