EE 591 Project

2D spatially selective excitation pulse design and the artifact evaluation

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Two-dimensional spatially selective excitation is used to excite a volume such as pencil beam or cylinder-like shape (1). It can also be used to obtain reduced FOV in slice selective excitation, which corresponds to a rectangular stick in the object domain (2). This study is to explore how to design RF and gradient pulses in order to excite a desired volume given gradient limitations, and to see how off-resonance and gradient delay affect the excitation profile. In the present work, echo-planar RF pulse with forward-backward design scheme is adopted (3).

MATERIALS AND METHODS

PULSE DESIGN

As Pauly et al. developed (4), the relationship between the spatial weighting deposited by RF pulse and the 2D excitation volume is Fourier transform formula.

$$M_{xy}(x,y) = i\,\gamma M_o \, integral \ \int_{kx}\int_{ky} P(k_x,k_y)\, e^{ixkx}\, e^{iyky}\, dk_x\, dk_y \qquad [1]$$

where $P(k_x,k_y) = W(k_x,k_y)\, S(k_x,k_y)$. $S(k_x,k_y)$ is a sampling structure that is determined by the k-space trajectory, and $W(k_x,k_y)$ is a spatial weighting function defined by $W(k_x,k_y) = B1(t)/|\gamma G(t)|$. Also,

$$k_x(t) = -\gamma \int_t^T G_x(s)ds \qquad [2]$$

$$k_y(t) = -\gamma \int_t^T G_y(s)ds \qquad [3]$$

More exactly,

$$P(k_x, k_y)=1/(2\pi\gamma)\, FT\{ M_{xy}(x,y) \} \qquad [4]$$

The desired excitation shape in the object domain is set to $rect(ax)cos^2(by)$ as shown in Fig.1 so that the spatial weighting function in the excitation k-space is $1/a\ sinc(1/a\ k/(2\pi))\ \pi^2\,(\delta(k_y+2b) + 2\delta(k_y) + \delta(k_y-2b)$, i.e.,

$$\prod(ax)cos^2(by) \quad \leftrightarrow \quad 1/a\ sinc(1/a\ k/(2\pi))\ \pi^2\,(\delta(k_y+2b) + 2\delta(k_y) + \delta(k_y-2b) \qquad [5]$$

which leads to 1-2-1 binomial weighting (5) with sub-pulses, as shown in Fig.1. The sub-pulses used here are only the main-lobe of sinc pulse which covers the k-space from -2π

to 2π in k_x-axis, and –2b from to 2b in k_y-axis as visualized in Fig.2. The truncation in the coverage of k_x-axis will cause blurring in x-axis in the object domain. Fig.3 shows the forward-backward design trajectory also known as non-flyback. Since Fourier relationship holds true mostly for a small tip-angle, the RF pulse amplitude should not be chosen too large. In this experiment, the parameter a and b are both set to 0.05, and RF pulse duration is 5.5ms. The designed RF and gradient pulses are shown in Fig.4, and the resultant excitation in Fig.5. In real MR scanner, the slew rate and maximum value in gradient pulse should be considered. Therefore, the gradient pulse should be trapezoid shape as opposed to rectangular due to the slew rate limitation, and the slope of transition should be designed making the most of the maximum slew rate in order to reduce the time duration. Also, the use of maximum limit value in the gradient strength will save the time duration, enabling the k-space scanning velocity fast. Pulse duration time is a critical issue because off-resonance and flow artifact show more impact in longer time duration. And longer TE degrades imaging quality as well.

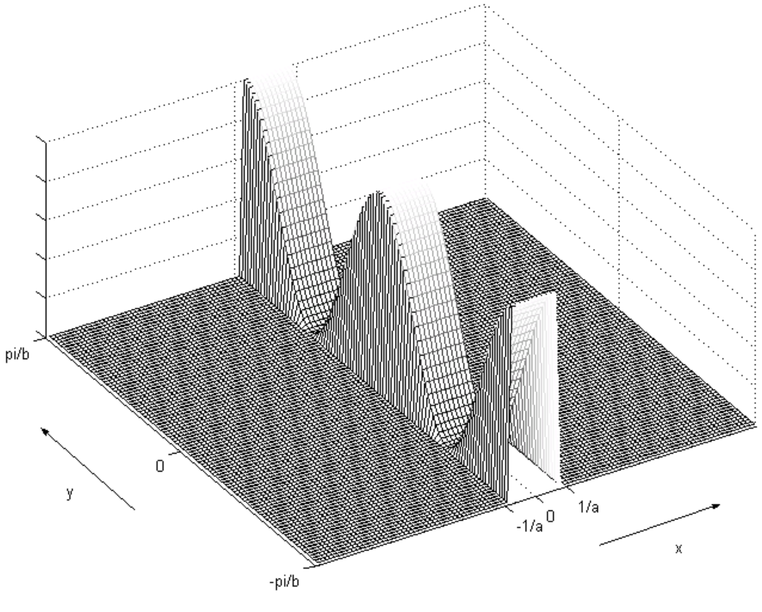


Fig.1. Desired excitation shape in the object domain.

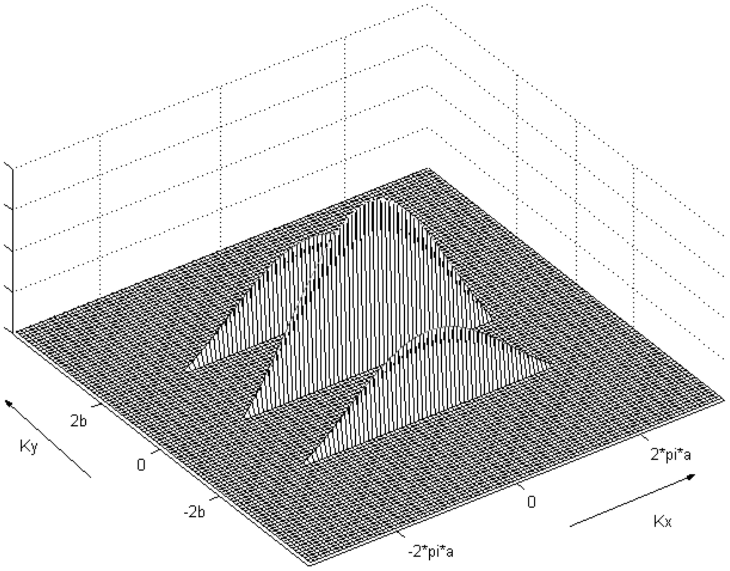


Fig.2. RF pulse deposited in the excitation k-space. Weighting function is truncated along k_x –axis.

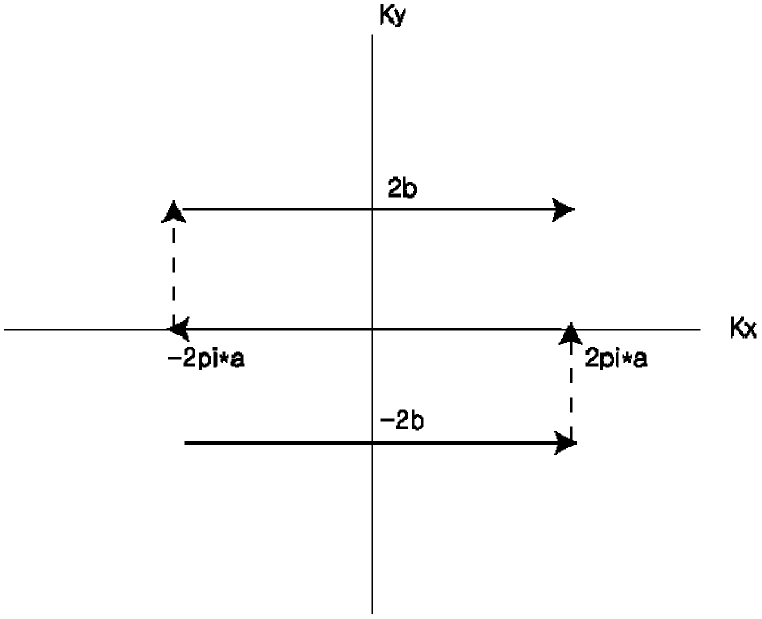


Fig.3. Echo-planar forward-backward trajectory in the k-space.

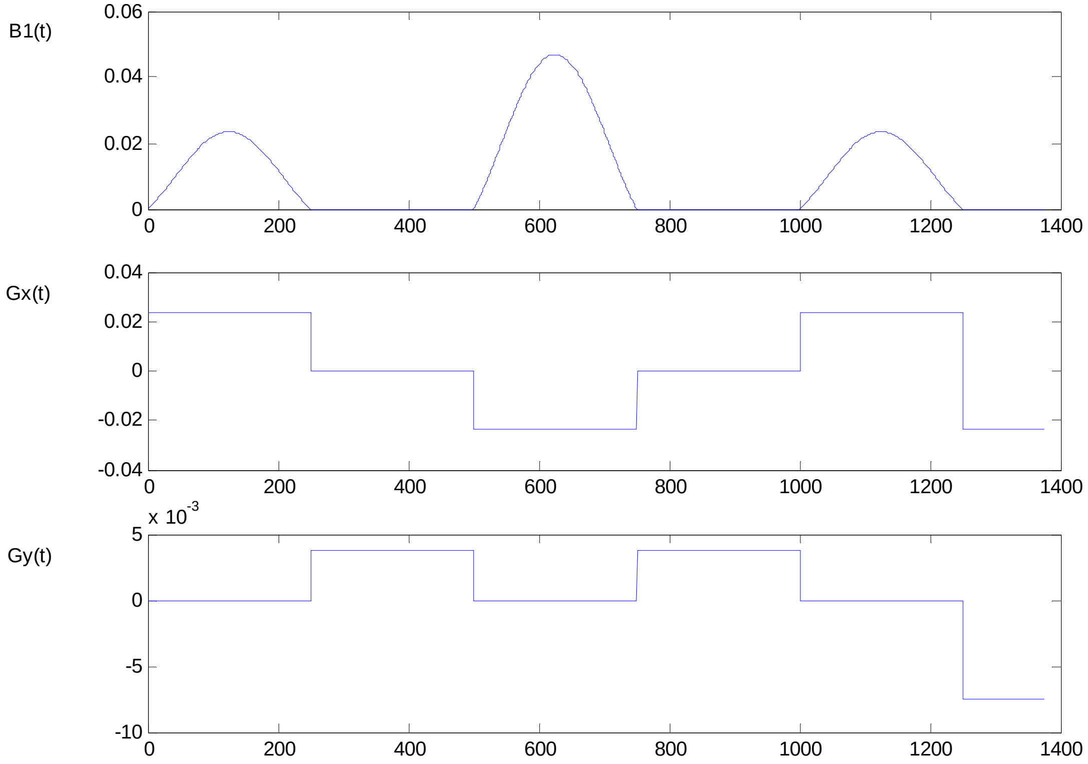


Fig.4. Designed pulse sequences. Sampling period is set to 4μs and total pulse duration is 5.5ms. Slew rate and maximum limitation of gradient is not considered in the simulation.

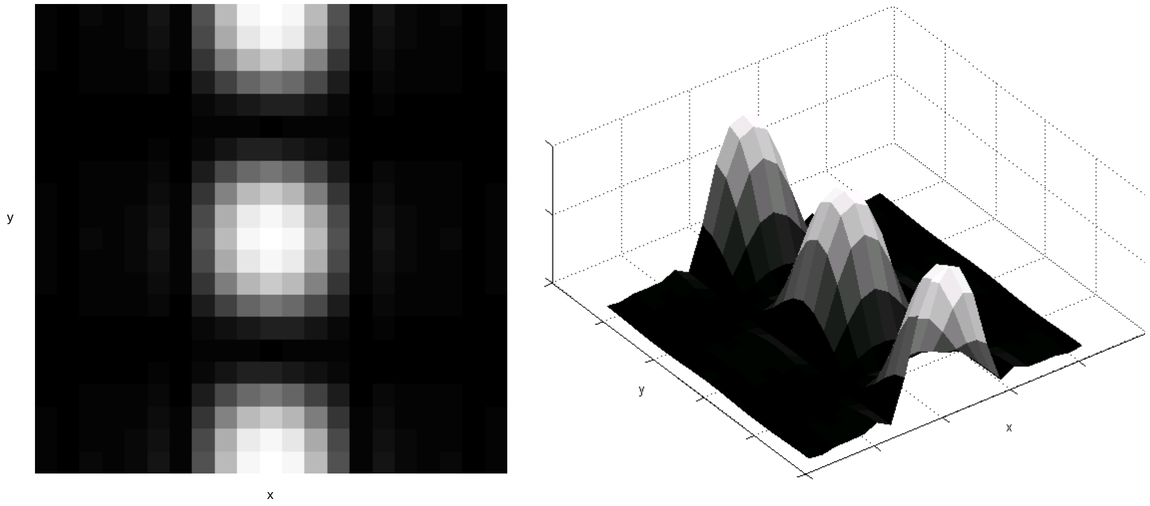


Fig.5. Numerically calculated excitation profile in the object domain. Since $\cos^2(y)$ is a period of π, two peaks can be seen within a FOV.

OFF-RESONANCE AND GRADIENT DELAY ARTIFACT

While the forward-backward scheme in echo-planar pulse helps to save the time duration, it also causes serious artifact in the presence of off-resonance and gradient delay compared to flyback design. A generic non-flyback echo-planar trajectory can be viewed as a sum of two flyback trajectory scans as shown in Fig.6 in which case, the off-resonance is a negative value. With halved amplitudes, the final object is shifted along x-axis as well as y-axis because there is a linear phase not only in x-direction but also in y-direction. The even line scan and odd line scan cause the opposite shift along x-axis due to the reversed scan direction while the shift along y-direction is the same. And also, odd line scan in the k-space causes alternating sign of replicas in object domain because of the shifted sampling. The final result is a sum of two excitation shapes. Matlab simulation shows the expected results in Fig.7. Off-resonance of –50Hz, -100Hz, and –440Hz are used here. For –50Hz and –100Hz, artifact in x-axis is not noticeable because the scan time along x-axis is short compared to y-axis scanning. Artifact in x-axis is more visible with off-resonance of –440Hz. The object is separated in x-direction and also, incomplete destructive interference shows up halfway between Nyquist replicas.

Phase inconsistency caused by eddy current, gradient imperfection or anisotropic gradient delay in echo-planar excitation also generates so-called N/2 ghosts as in echo-planar imaging. In a similar way to the above analysis, echo-planar trajectory can be thought of as a sum of even and odd line trajectories. Since gradient delay causes alternating shift in even and odd lines in the k-space, the corresponding object domain excitation has the opposite phase shift to each other as shown in Fig.8. As time delay gets greater, N/2 ghosts get bigger. Matlab simulation shows the consistent result as visualized in Fig.9.

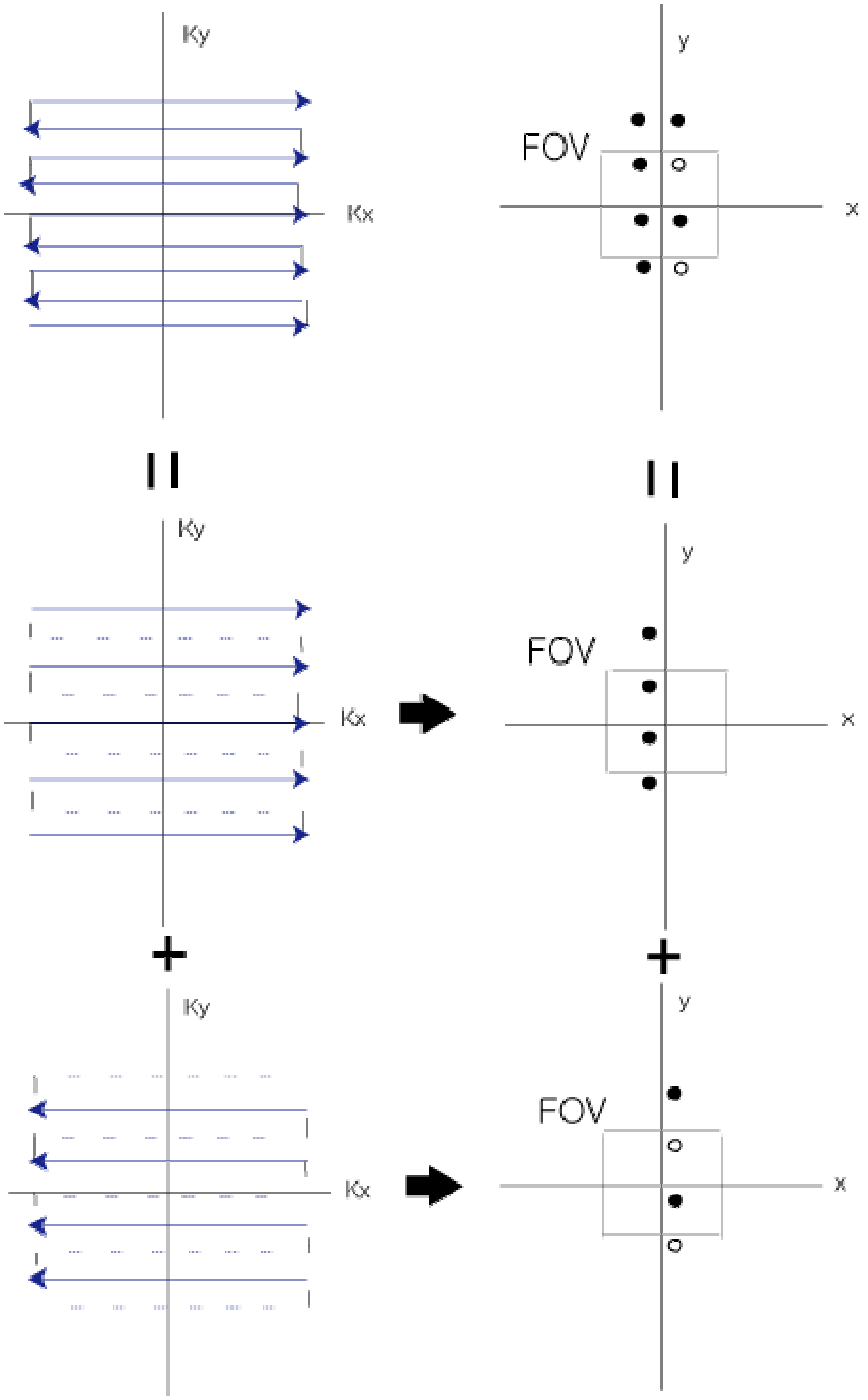
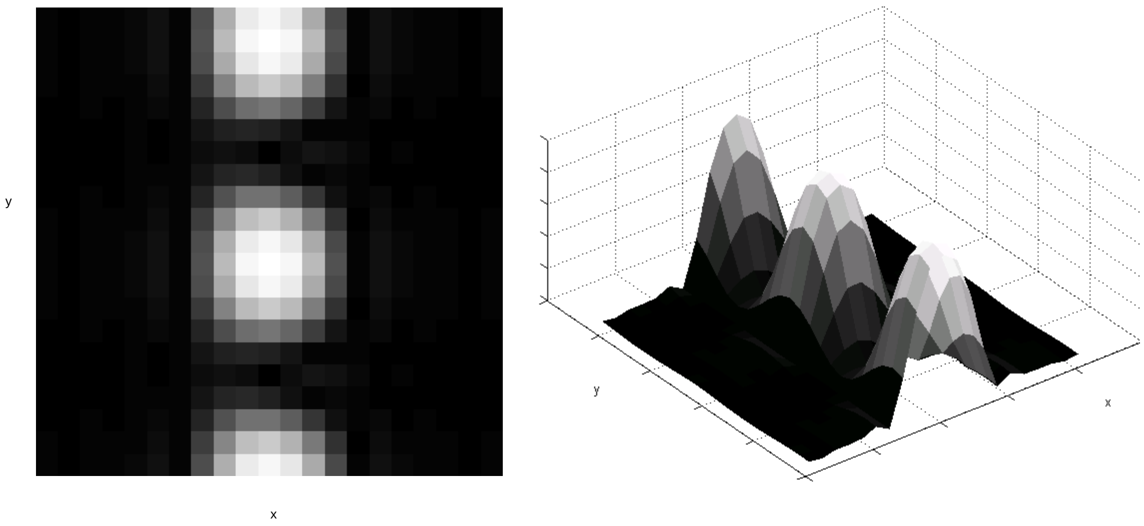
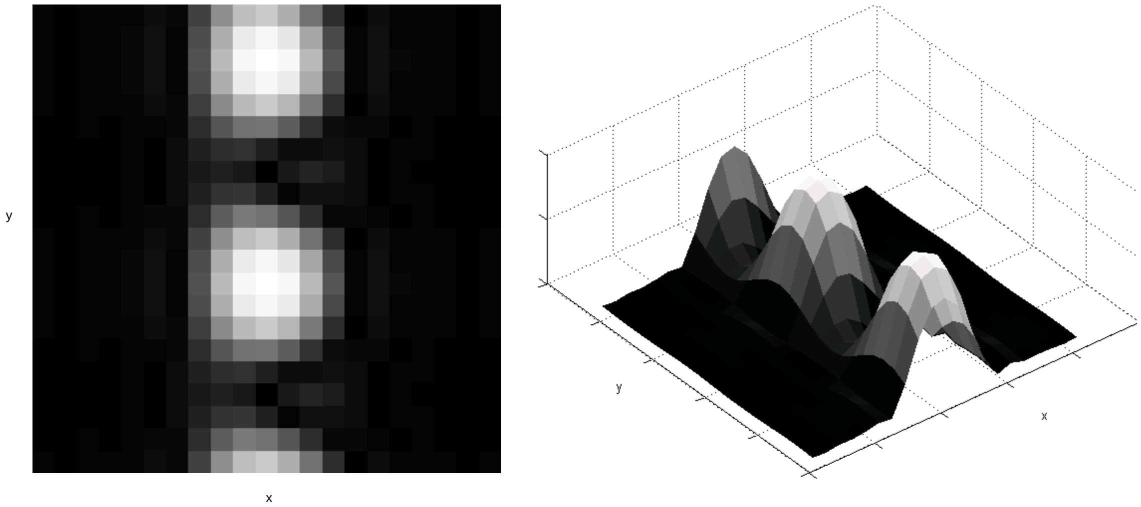


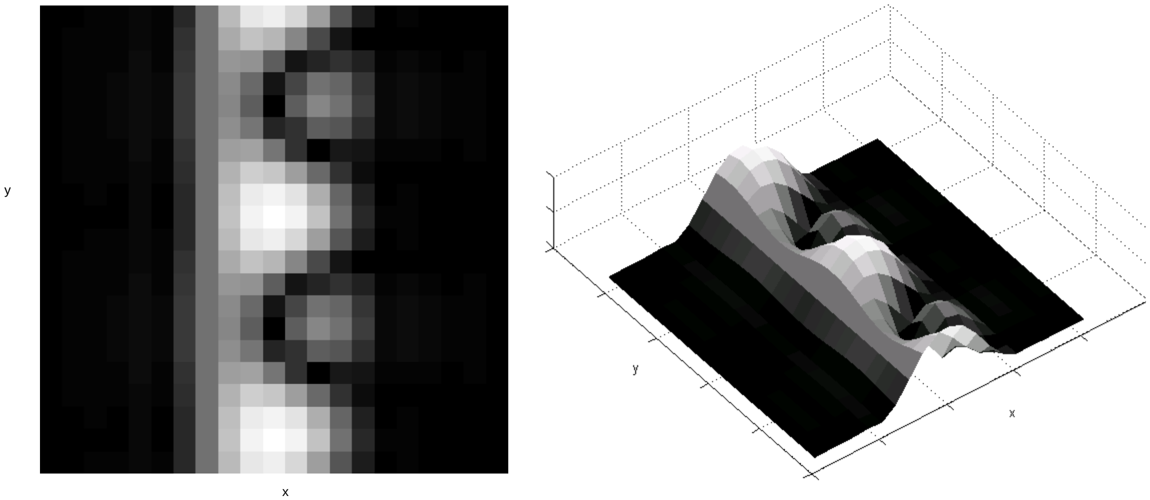
Fig.6. Off-resonance artifact analysis in non-flyback echo-planar design. White circle denotes the opposite sign of the back circle.



(a) For Δf = -50Hz



(b) For Δf = -100Hz



(c) For Δf = -440Hz

Fig.7. Excitation shape change in the presence of off-resonance of –50Hz, -100Hz, and –440Hz.

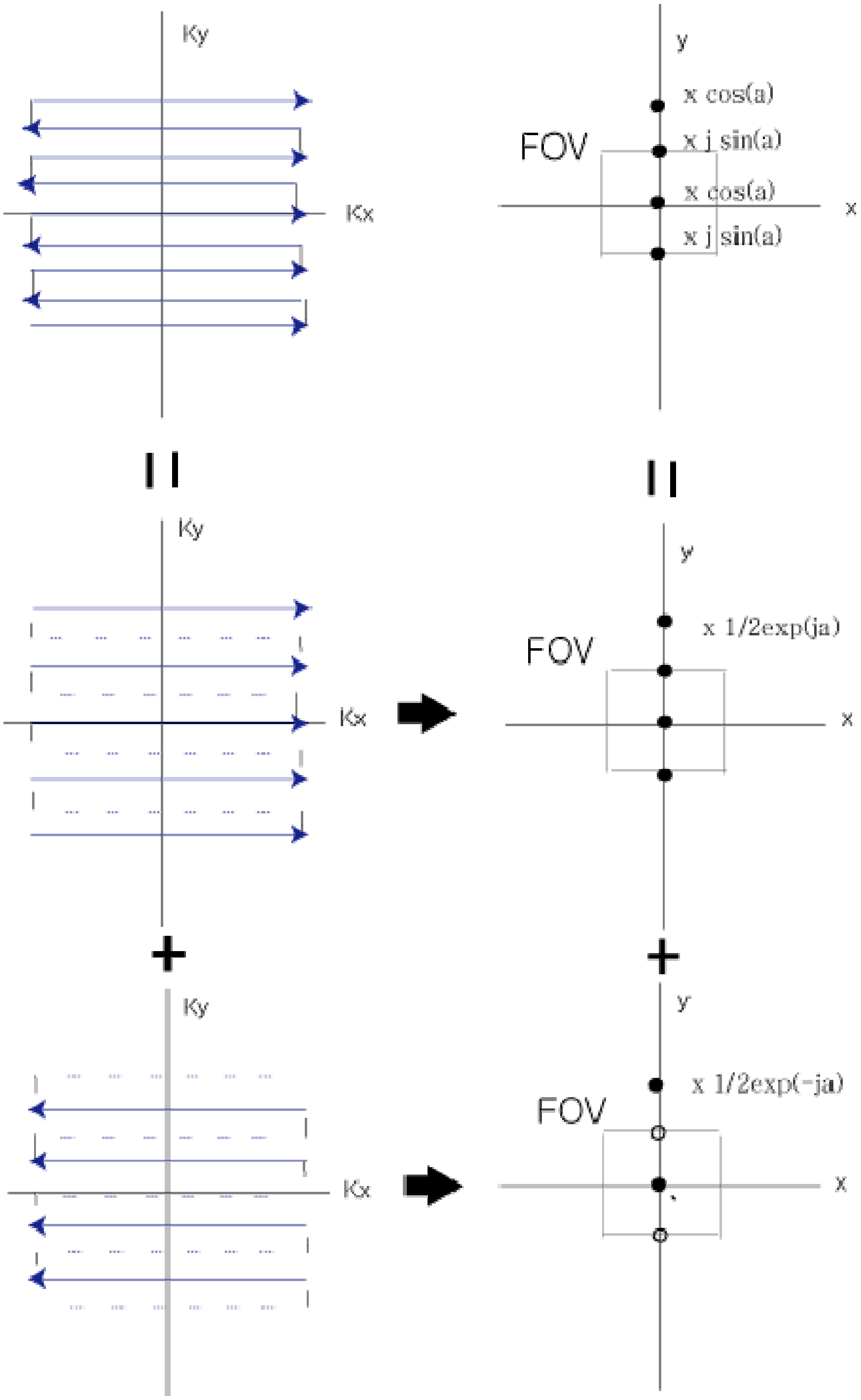
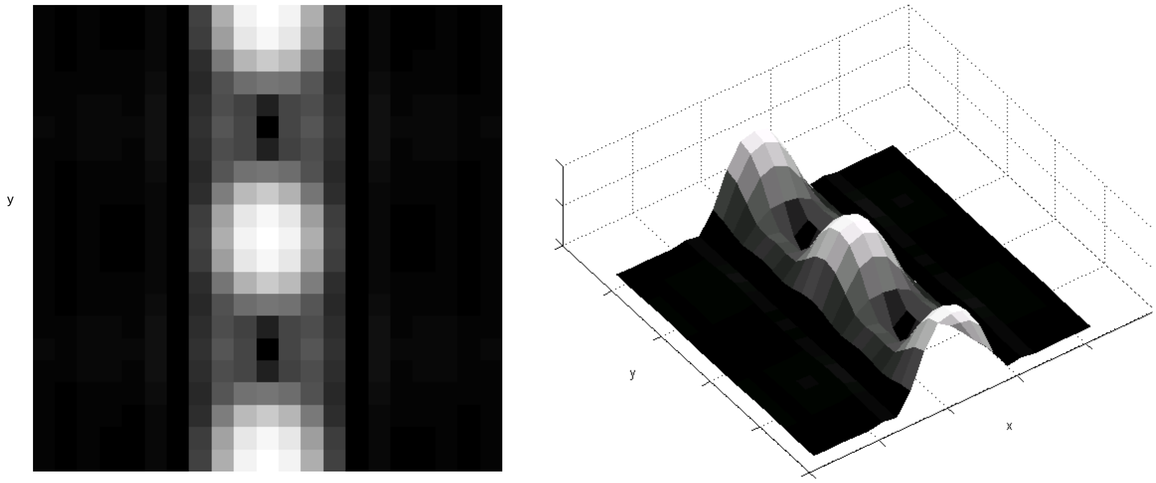
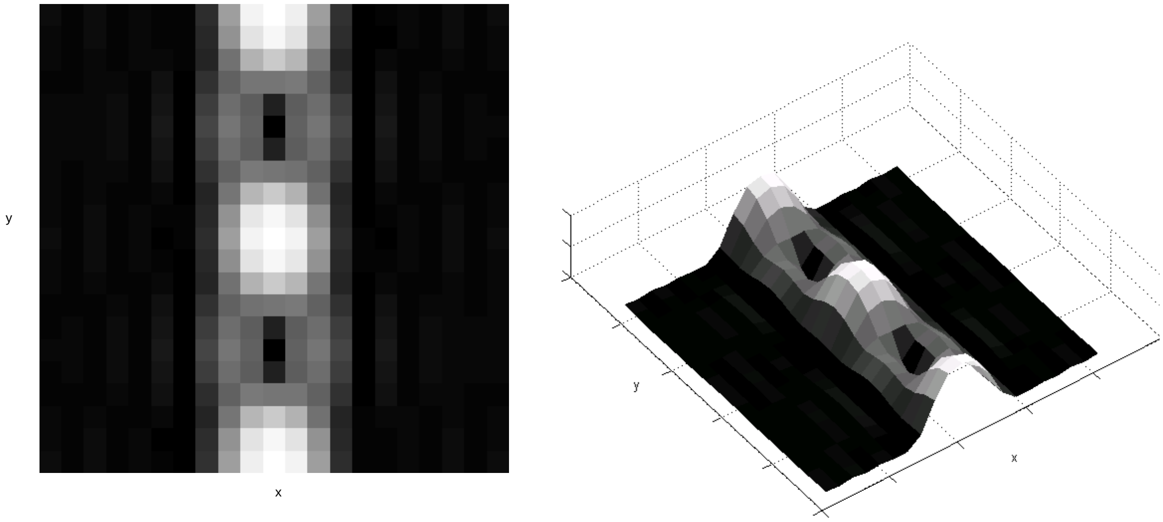


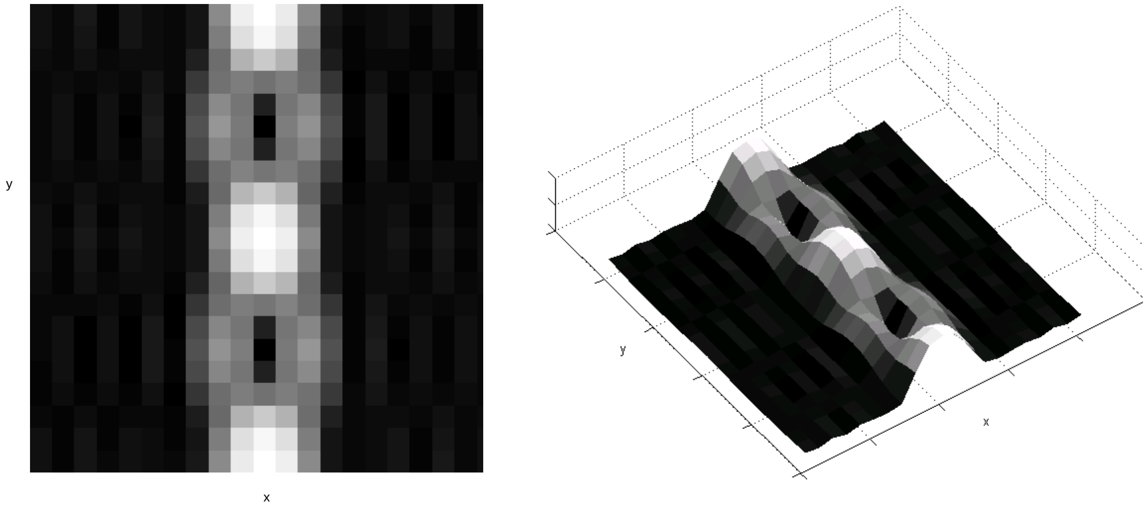
Fig.8. Gradient delay artifact analysis in non-flyback echo-planar design. For a small time delay *a*, *cos(a)* is almost 1 and *sin(a)* is close to 0. As the delay gets greater, N/2 ghosting grows up.



(a) When the gradient is delayed by 8% of the subpulse duration.



(b) When the gradient is delayed by 12% of the subpulse duration.



(c) When the gradient is delayed by 16% of the subpulse duration.

Fig.9. The artifact caused by gradient delay. With longer time delay, N/2 ghosting grows up.

DISCUSSION

The major drawback of 2D selective excitation is the longer RF pulse duration, which causes many artifacts in the presence of flow, motion, or off-resonance. To reduce the time duration, slew rate and maximum gradient limit should be utilized at the most, and echo-planar trajectory can be adopted. Especially, forward-backward scheme saves pulse duration twice as the flyback design because it deposits RF energy in the k-space during both positive and negative gradient lobes. At the same time, however, it is very susceptible to system imperfections such as off-resonance and gradient delay. In this study, how these artifacts affect the 2D excitation pulse in non-flyback echo-planar design has been examined. They show almost the same effect as in echo-planar imaging. Off-resonance imposes linear phase in the excitation k-space, which corresponds to shift in the object domain. Conversely, gradient delay generates shift in the k-space domain resulting in linear phase in the object domain. Due to the alternating shift (or linear phase) in the non-flyback k-space lines, the desired interference destruction in N/2 position of FOV becomes incomplete, and therefore produces unwanted excitation. These artifacts can be resolved by the similar solutions from echo-planar imaging, and could be improved in further study.

ACKNOWLEDGMENT

1-2-1 binomial weighting has been adopted in this work at Kyunghyun Sung's suggestion.

REFERENCES

1. Schroder C, Bornert P, Aldefeld B. Spatial excitation using variable-density spiral trajectories. J Magn Reson 2003;18:136-141
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4. Pauly J, Nishimura D, Macovski A. A k-space analysis of small-tip angle excitation. J Magn Reson 1989;81:43-56
5. Hore PJ. Solvent suppression in Fourier transform nuclear magnetic resonance. J Magn Reson 1983;55:283-300

APPENDIX : MATLAB CODE

```
close all;
clear all;

a=0.05;
b=0.05;
D=0;
df=0;
```

```
Morig=[0;0;1];
gamma=26752;
m=10^(-3);
T=5.5*m;
dt= 4*10^(-6);
N=T/dt;


%%%%% gx(t) generation

for k=1:N
        t=dt*k;
        if (0<t & t<=m) | (4*m<t & t<=5*m)
                gx(k)=4*pi*a/m/gamma;
        elseif (2*m<t & t<= 3*m) | (5*m<t & t<=5.5*m)
                gx(k)=-4*pi*a/m/gamma;
        else
                gx(k)=0;
        end
end


%%%%% gy(t) generation

for k=1:N
        t=dt*k;
        if (m<t & t<=2*m) | (3*m<t & t<=4*m)
                gy(k)=2*b/m/gamma;
        elseif 5*m<t & t<=5.5*m
                gy(k)=-4*b/m/gamma;
        else
                gy(k)=0;
```

```
    end
end


%%%%% b1(t) generation

for k=1:N
    t=dt*k;
    if 0<t & t<=m
        b1(k)= sinc((t-0.5*m)/(m/2)) * sqrt( gx(k)^2+gy(k)^2 );
    elseif 2*m<t & t<=3*m
        b1(k)= 2*sinc((t-2.5*m)/(m/2))* sqrt( gx(k)^2+gy(k)^2 );
    elseif 4*m<t & t<=5*m
        b1(k)= sinc((t-4.5*m)/(m/2))* sqrt( gx(k)^2+gy(k)^2 );
    else
        b1(k)= 0;
    end
end


%%%% gradient delay generation

if D~=0
    for k=1:D
        gxd(k)=0;
        gyd(k)=0;
    end

    for k=D+1:N
        gxd(k)=gx(k-D);
        gyd(k)=gy(k-D);
    end
```

```
        for k=1:N
                gx(k)=gxd(k);
                gy(k)=gyd(k);
        end
end


%%%% excitation process

x=-2/a: 4/a/20 :2/a;
y=-pi/b: 2*pi/b/20 :pi/b;

for i=1:length(x)
        for j=1:length(y)
                M=simpulse2(b1,gx,gy,dt,Morig,x(i),y(j),df);
                Mxy(j,i)=sqrt( M(1)^2 + M(2)^2 );
        end
end

%%%% pulses and Mxy plotting

figure(1);
subplot(3,1,1);
plot(b1);
subplot(3,1,2);
plot(gx);
subplot(3,1,3);
plot(gy);

figure(2);
dispimage(Mxy);
xlabel(’x’);
ylabel(’y’);
```