B_1 Mapping Using Phase Information Created by Frequency-Modulated Pulses

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Introduction: The spatial distribution of the radiofrequency field (B_1) must be assessed for a number of MRI methods, including parallel imaging. Although many techniques have been developed to map B_1, the most straightforward and common approach is probably the double-angle method, in which the B_1 map is obtained from the ratio of two images acquired with different flip angles, α and 2α (*1*). A disadvantage of the double-angle method is the need to use a repetition time (TR) much greater than a longitudinal relaxation time (T_1) to obtain an accurate B_1 map. Recently, several alternative methods have been proposed to shorten TR and, thus, acquisition time. Some of them are variants of the double-angle method utilizing a driven recovery or saturation of magnetization with fast sequences (*2-4*). Others acquire two images from a single scan (*5-6*). Here, a new time-efficient method is introduced to obtain B_1 maps from multiple 2D slices. This spin-echo sequence exploits the unique properties of frequency-modulated (FM) $\pi/2$ and π pulses to create phase maps that depend monotonically on B_1. With this method, it is not necessary for TR >> T_1, and the $\pi/2$ and π pulses are based on the frequency- and amplitude-modulation (AM) functions of the hyperbolic secant (HS) pulse which produces excellent slice profiles (*7*,*8*).

Rationale: The basic idea of the new method originates from the observation that the magnetization phase ϕ following the application of a π HS pulse in a spin-echo sequence varies with B_1 and static field inhomogeneities (ΔB_0). In the case of a π HS pulse with the FM function sweeping from $BW/2$ to $-BW/2$ (BW = pulse bandwidth), $\phi(\Delta B_0)$ has a concave shape, with ϕ increasing as the peak of AM function (B_1^{max}) increases (Fig.1). In contrast, when the FM function sweeps from $-BW/2$ to $BW/2$, $\phi(\Delta B_0)$ has a convex shape, with ϕ decreasing as B_1^{max} increases. This dependence of $\phi(\Delta B_0, B_1)$ still exists when HS pulses are used for $\pi/2$ excitation and π refocusing in 2D spin-echo imaging. According to our previous work (*8*), when the HS pulses are applied for both excitation and refocusing, the $\phi(\Delta B_0)$ dependence is removed if the pulse length ($T_{p,1}$) of the $\pi/2$ HS pulse is twice that ($T_{p,2}$) of the π HS pulse, i.e., $T_{p,1} = 2T_{p,2}$ (Below, subscripts of 1 and 2 indicate excitation and refocusing, respectively). Thus, ϕ depends only on B_1, and the phase difference ($\Delta\phi$) of two images acquired using HS pulses with frequency sweeps in opposite directions can be used to calculate a B_1 map. The relationship between $\Delta\phi$ and B_1^{max} is obtained from Bloch simulation.

Method: The two images are acquired with multi-slice 2D spin-echo imaging, satisfying the condition for non-linear phase compensation across slices, i.e., $T_{p,1} = 2T_{p,2}$ (*8*). In the first image acquisition, HS pulses with frequency sweep from $-BW/2$ to $BW/2$ are used, and in the second acquisition, HS pulses with frequency sweep from $BW/2$ to $-BW/2$ are used. The pulse sequence diagram is shown in Fig.2 for better understanding. The two image datasets are divided to determine $\Delta\phi$. For a proper calculation of a $\Delta\phi$ map, it is recommended to isolate the object of interest and apply phase unwrapping only to the object itself, in order to avoid the phase contribution from background noise. To convert the $\Delta\phi$ map to a B_1 map, the plot of $\Delta\phi$ versus B_1^{max} needs to be obtained from Bloch simulation (Fig.3). The maximum B_1^{max} of a HS pulse was 1.34 kHz for $\pi/2$ excitation. Quadratic fitting was performed to derive an equation which specifies the relationship of $\Delta\phi$ versus B_1^{max}, that is, $\Delta\phi = 2.8(\gamma B_1^{max})^2 - 0.21(\gamma B_1^{max}) + 0.015$. The $\Delta\phi$ map is to be rescaled to fit the range of $\Delta\phi$ from simulation.

Experiment: For demonstration, an experiment was performed using a TEM head resonator at 4 T. The phantom consisted of a cylindrical container (diameter = 9 cm) of water with a trace amount of Gd ($T_1 \approx$ 1s). In the presence of same slice-selective gradients, $\pi/2$ and π HS pulses of the same BW (= 2.5 kHz) were used with $T_{p,1}$ = 8 ms and $T_{p,2}$ = 4 ms, respectively. Other parameters were: FOV = 20×20 cm^2, matrix = 128×128, TE/TR = 20 ms/0.5 s, acquisition time = 66 s, and slice thickness = 5 mm. In the obtained B_1 map (Fig.4), the maximum B_1 occurred in the center of the phantom, and B_1 intensity was gradually decreasing when approaching the periphery of the phantom. The maximum B_1 variation was ~31.4 %.

Conclusion: The new B_1 mapping method presented here is obtained by calculating the phase difference between two spin-echo images obtained with HS pulses having opposite frequency sweeps. Unlike the original double-angle method in which TR >> T_1, the new method can reduce scan time by shortening TR because of its use of phase, not signal magnitudes, and it can avoid a possible problem due to different slice profiles caused by using different flip angles (6). It can also be applied to both a volume coil and a surface coil, and 2D multi-slice B_1 map can be obtained..

References: (1) Insko EK et al, JMR 1993:82-85 (2) Stollberger R et al, MRM 1996:246-251 (3) Wang J et al, MRM 2005: 666-674 (4) Cunningham CH et al, MRM 2006:1326-1333 (5) Pan JW et al, MRM 1998:363-369 (6) Yarnykh VL, MRM 2007:192-200 (7) Park J-Y et al, MRM 2006:848-857 (8) Park J-Y et al, ISMRM 2006

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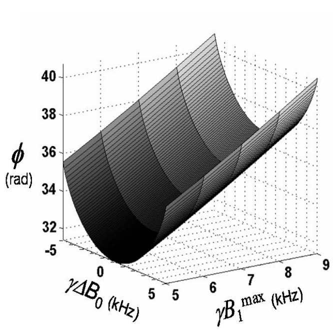

Fig.1 A 3D plot showing $\phi(\Delta B_0)$ shifts in ϕ magnitude as B_1^{max} increases, where $\phi(\Delta B_0)$ was produced by a π HS pulse whose frequency sweeps from $BW/2$ to $-BW/2$ for a given B_1^{max}.

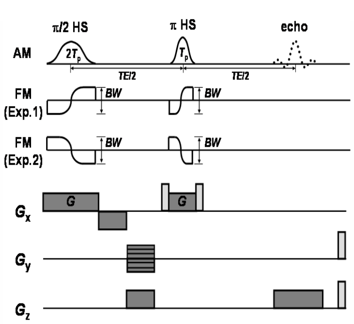

Fig.2 Multi-slice 2D spin-echo sequence diagram. In experiment 1, HS pulses with frequency sweep from $-BW/2$ to $BW/2$ are used. In experiment 2, the frequency-sweep direction must be opposite.

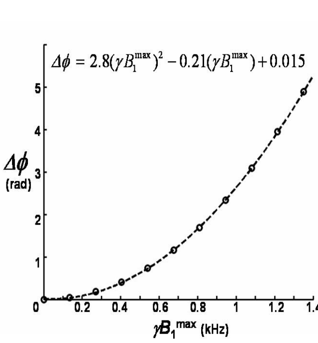

Fig.3 A plot of $\Delta\phi$ versus B_1^{max} which was obtained from Bloch simulation. Quadratic fitting was performed to determine the equation which specifies the relationship of $\Delta\phi$ versus B_1^{max}.

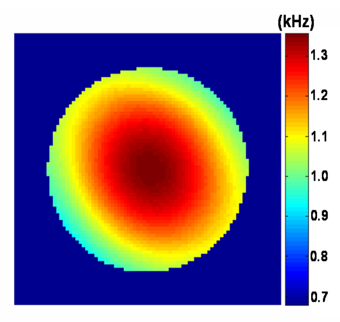

Fig.4 The B_1 map obtained from the new B_1 mapping method. For better demonstration, the background was scaled to be a half of the maximum B_1.