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, $\alpha$ and 2$\alpha$ (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 $\pi$ 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 $\pi$ 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 $\phi$ following the application of a $\pi$ HS pulse in a spin-echo sequence varies with $B_1$ and static field inhomogeneities ($\Delta B_0$). In the case of a $\pi$ 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 $\phi$ increasing as the peak of AM function ($B_1^{\text{max}}$) 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 $\phi$ decreasing as $B_1^{\text{max}}$ increases. This dependence of $\phi$ ($\Delta B_0$, $B_1$) still exists when HS pulses are used for $\pi/2$ excitation and $\pi$ 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 of the $\pi$ HS pulse, i.e., $T_{p,1} = 2T_{p,2}$ (Below, subscripts of 1 and 2 indicate excitation and refocusing, respectively). Thus, $\phi$ 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 $B_1^{\text{max}}$ 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 $B_1^{\text{max}}$ needs to be obtained from Bloch simulation (Fig.3). The maximum $B_1^{\text{max}}$ of a HS pulse was 1.34 kHz for $B_1$ mapping method. For better demonstration, the background was scaled to be a half of the maximum $B_1$.

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.


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

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

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 $B_1$.  