Very low SAR imaging of the lower leg using variable angle for uniform signal excitation (VUSE) and balanced SSFP without RF phase cycling

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Introduction: Variable angle for uniform signal excitation (VUSE) [1] has been used for balanced SSFP (bSSFP) with RF phase alternation (+α, -α, +α,…) [2]. Recently, the variable flip angle train has been calculated to achieve constant transverse magnetization (Mxy) during transient imaging using matrix inversion of the Bloch equation [2], $VUSE_{bSSFP}$. Herein, we iteratively calculate the flip angle required to provide constant M_{xy} for bSSFP without RF phase alternation ($VUSE_{noalt}$). The variable flip angle train calculated by matrix inversion of the Bloch equation results in a very low flip angle train (and concomitantly very low SAR) and high sensitivity to off-resonance. Lower leg imaging is performed and the deposited energy for $VUSE_{noalt}$ is compared with the constant flip angle b-SSFP and $VUSE_{bSSFP}$.

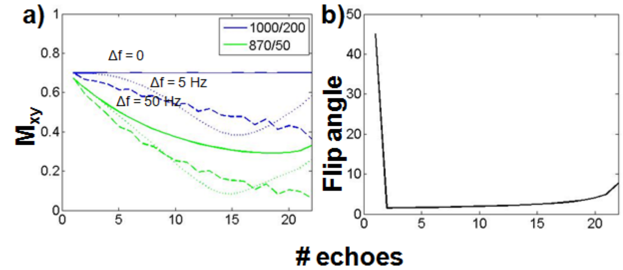

Figure 1: (a) Simulation of the transverse magnetization over the number of echoes for (b) the calculated flip angle profile.

Materials and methods: The variable flip angle profile for $VUSE_{noalt}$ can be calculated iteratively, similar to VUSE [2] using,

$$\tan\alpha = \frac{2\,G2\,G3 \pm \sqrt{(2\,G2\,G3)^2 - 4(H2^2 - G3^2)(H2^2 - G2^2)}}{2(H2^2 - G3^2)}$$

Where $G2 = E2\,Mxy$; $H2 = \frac{Mtxy}{E2}$; $G3 = E1 \bullet Mz + 1 - E1$; $Ei = e^{-\frac{TE}{Ti}}$.

M_{txy} is the desired transverse magnetization, M_{xy} and M_z are the current transverse and longitudinal magnetization. ***Simulation:*** Bloch equation simulations were performed in MATLAB. The flip angle train was calculated for a tissue with T_1/T_2=1000/200 ms, TR=5.24ms and M_{txy}=0.7. The resultant flip angle train was used to simulate a representative tissue with T_1/T_2 of 870/50 ms and off-resonance of 5 and 40Hz. ***Volunteer imaging:*** All the images were acquired on a 1.5T MRI scanner (Siemens, Erlangen, Germany). 2D multi-slice interleaved segmented images of the lower leg were acquired in two volunteers using single shot bSSFP, segmented interleaved $VUSE_{bSSFP}$ and $VUSE_{noalt}$ for appropriate comparison of SNR and energy deposition. The imaging parameters were FOV: 150x150, acquisition matrix: 512x512, #segments=10, #slices=15, TR=5.24ms, BW=558 Hz/px; and constant flip angle of 70° for b-SSFP, as shown in Fig. 1b for $VUSE_{noalt}$ and variable flip angle obtained for $VUSE_{bSSFP}$ with the same simulation parameters. The total acquisition duration for bSSFP, VUSE and $VUSE_{noalt}$ were 21s, 50s, and 50s respectively. ***Data analysis:*** ROIs were drawn over the artery, vein, muscle and fat regions on Fig. 2 and SNR was calculated as the ratio of the signal mean to the standard deviation of background noise.

Results: Fig. 1 shows the simulation results for M_{xy} and flip angle profile required to maintain constant M_{txy} for T_1/T_2=1000/200 ms. The required variable flip angle profile is very low, resulting in a low SAR acquisition. However, the off-resonance signal decays as a function of the echo-number for both tissues. Hence, we used a segmented acquisition. Fig 2 shows a single slice of the lower leg acquired with bSSFP, $VUSE_{bSSFP}$ and $VUSE_{noalt}$. The venous blood has a lower signal in $VUSE_{noalt}$ due to the lower T_2 [3] than arterial blood and its off-resonance sensitivity. $VUSE_{bSSFP}$ and $VUSE_{noalt}$ exhibit more T_2 weighting as a consequence of transient-state imaging, which results in brighter muscle signal compared to bSSFP. The deposited energy is indicated below each image (Ws=Watts•s). The energy deposited by $VUSE_{noalt}$ is ~14x times lower than b-SSFP despite the shorter imaging time for bSSFP. The SNR measured in the different regions are shown in Table 1. $VUSE_{noalt}$ provides SNR comparable to bSSFP with much reduced deposited energy.

Discussion and Conclusion: The very low SAR property of $VUSE_{noalt}$ may be beneficial to ensure the reduced heating of a device when scanning patients with implanted devices. The off-resonance sensitivity necessitates excellent shimming, but $VUSE_{noalt}$ can still be used to evaluate anatomy not immediately adjacent to the implant (eg head scan in a patient with a pacemaker). $VUSE_{noalt}$ may also be used for non-contrast arterial MR angiography owing to both the and low venous signal and inherent fat suppression.

References: 1.Priatna, et al., JMRI 1995; 5:421-427 2.Worters, et al., MRM 2010, 64:1405-1413. 3.Wright et al., JMRI 1991, 1:275-283

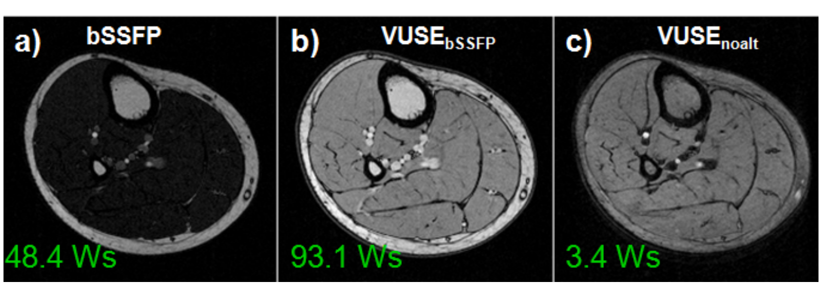

Figure 2: 2D a) bSSFP, b)$VUSE_{bSSFP}$ and c)$VUSE_{noalt}$ images of lower leg. Reduced venous and fat signal can be seen in $VUSE_{noalt}$. The energy deposited is indicated in green.

	bSSFP	$VUSE_{bSSFP}$	$VUSE_{noalt}$
Arterial blood	47.5	48.2	48.7
Venous blood	15.2	41.2	4.0
Muscle	6.7	29.8	24.9
Fat	32.1	29.2	20.0

Table 1: SNR measured over arterial blood, venous blood, muscle and fat for b-SSFP, $VUSE_{bSSFP}$ and $VUSE_{noalt}$.