Optimized refocusing-flip-angle-train design for small peripheral nerve imaging with 3D TSE

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Target audience: Scientists working in 3D TSE and clinical researchers interested in imaging small peripheral nerves.

Purpose: 3D spin echo imaging based on a rapid acquisition with relaxation enhancement (RARE, also known as 3D TSE and 3D FSE) is a reliable and robust method for achieving isotropic high-resolution T_2-weighted imaging of the peripheral nerves [1]. 3D TSE sequences rely on the design of a refocusing-flip-angle train that balances relaxation-induced signal loss and blurring effects for a specific tissue. The Extended Phase Graph (EPG) formalism has been extensively used in 3D TSE to design tissue-specific flip-angle trains (Fig. 1a) [2] which maintain a signal plateau for long echo times (Fig. 1b). [3,4]. Flip-angle modulation in 3D TSE has been shown to yield in general satisfactory results in peripheral-nerve imaging in various regions [1,5]. 3D TSE flip-angle-trains for nerve imaging have been designed balancing the relaxation-induced signal loss (signal plateau level, Fig. 1b) and blurring effects (expressed as the Fourier transform of the modulation transfer function MTF) (Fig. 1b), by considering signal contributions only from the nerve. However, blurring effects in 3D TSE depend on the local geometry and need to consider the interface between fine nerve structures and the enveloping muscle tissue. The loss of small objects embedded in another tissue has been previously addressed in 2D RARE imaging [6] but no relevant experimental assessment in peripheral-nerve imaging has been performed. Therefore, the purpose of the present work is (i) to study the effects of flip-angle modulation on signal loss and k-space filtering of small peripheral nerves embedded in muscle and (ii) to develop an optimized flip-angle-train design which balances the needs of signal and sharpness required for the proper delineation of small nerves.

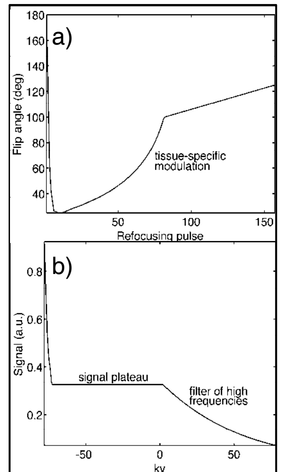
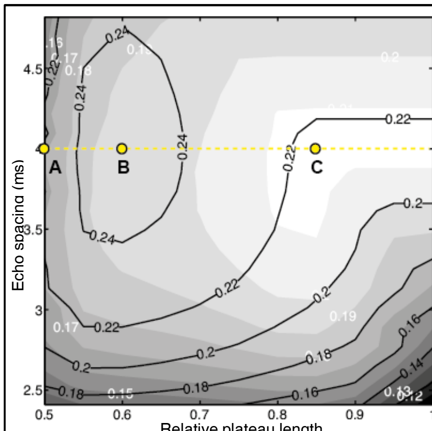


Fig. 1: EPG-generated (a) Flip-angle train and (b) MTF of nerve illustrating effects of flip-angle modulation on signal properties.

Methods: <u>Flip-angle train optimization:</u> Flip-angle schemes were generated based on the EPG formalism [3] for a subspace of sequence parameters, varying echo spacing and plateau length (relative to the echo-train length). The MTFs of nerve and muscle corresponding to those flip-angle trains were computed. A small nerve feature of 1 pixel in width embedded in a large region of muscle was simulated and each region was separately blurred with each of the generated MTFs corresponding to nerve and muscle. The amplitude and full width at half maximum (FWHM) of the integrated blurred profile, represented by the effective signal S_e and the effective blurring b_e, were measured (Fig. 2, right). The metric $Z = S_e/b_e$ was determined to simultaneously describe signal and sharpness resulting from the combined effects of the MTFs of the nerve and muscle. S_e and Z maps were generated as a function of echo spacing and relative plateau length to assess the effect of the enveloping muscle on the signal of the studied small-embedded nerve structure (Fig. 2, left).

<u>*In vivo* measurements:</u> Two healthy volunteers were scanned using a 32-channel torso coil on a 3 T Philips system. Coronal acquisitions of the lumbar plexus were carried out with 3D TSE using three different flip-angle-train designs, corresponding to MTFs having relative plateau lengths equal to 0.5, 0.6 and 0.85 (points A, B and C in Fig. 2). Echo spacing = 4 ms, maximum flip-angle values (defining a range between which modulation was kept linear) = [100˚, 125˚], 6 initial echoes to reach Pseudo-Steady-State (PSS). Relaxation parameters were $T_1 = 1010$ and $T_2 = 90$ ms for nerve and $T_1 = 1160$ and $T_2 = 45$ ms for muscle. FOV = 400×400×80 mm^3, acquisition voxel = 1.25×1.25×1.4 mm^3, reconstruction voxel = 0.63×0.63×0.7 mm^3, TR/TE = 2000/330 ms, TSE factor = 150, total scan duration = 4m26s.



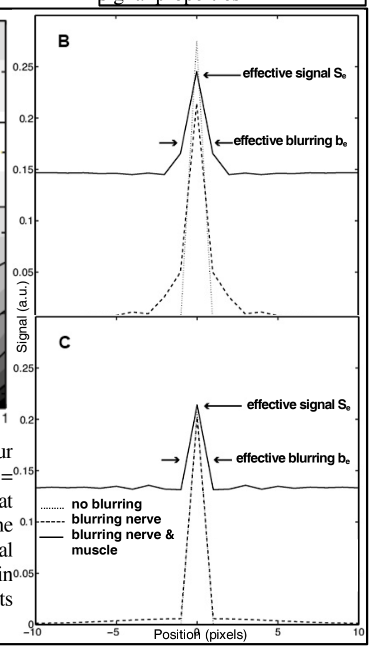


Fig. 2: <u>Top:</u> effective signal S_e (black iso-contour lines) is highest at short plateau lengths while $Z = S_e/b_e$ (gray filled contours) reaches its maximum at longer values. Z includes the loss in sharpness of the nerve due to the blurring of muscle. <u>Right:</u> signal profiles illustrating a small nerve embedded in muscle, shown for B and C above. C reflects optimized signal and sharpness of small nerves.

Results: Points A, B and C in Fig. 2 correspond to different rates of flip-angle modulation. A quickly varying flip-angle-train (points A, B) yields high nerve signal and may be desirable when imaging large features, less affected by blurring effects (red arrows, Figs. 3a, 3b). However, a quickly varying flip-angle-train implies higher blurring, which noticeably affects appearance of small nerve features. A slowly varying flip-angle-train with lower flip angles (point C) considerably decreases the combined blurring of muscle and nerve and thus provides much higher sharpness of fine nerve branches while preserving high signal (yellow arrows, Fig. 3c). Blurring effects are especially apparent in very narrow structures and can considerably restrict the ability of their delineation (Fig. 4).

Discussion & Conclusion: The present results show that the standard flip-angle modulation in 3D TSE used to enhance nerve signal does not yield the optimal image quality for viewing small structures. The combined blurring effects from nerve and the surrounding muscle, not traditionally considered when choosing a flip-angle-train design, have been shown to be significantly reduced with the presently proposed optimized design (point C), hence highly improving the delineation of small nerve roots and branches.

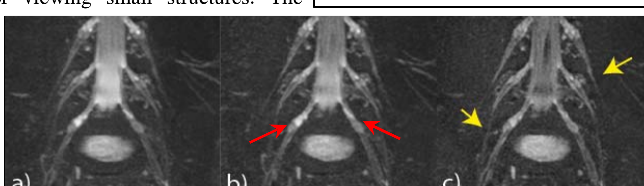


Fig. 3: MIPs of L3, L4 and L5 nerves with flip-angle schemes yielding (a) highest blurring, (b) highest signal and (c) optimized signal and sharpness (A, B and C in Fig. 2). Quickly varying flip-angle train in (a) leads to severe filtering of high frequencies. Nerve signal reaches its maximum at (b) but a considerable amount of blurring is still present. Signal in (c) is similar to that in (a) but delineation of fine nerves is highly improved due to reduced blurring in muscle.

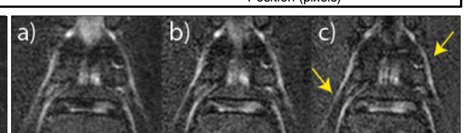


Fig. 4: Source images showing effect on signal and sharpness of L3 and L4 nerve roots with three flip-angle-train designs (A,B and C in Fig. 2). (a) Has the highest blurring, (b) exhibits highest signal and (c) uses the optimized design yielding the best compromise between signal and sharpness. Blurring of muscle degrades delineation of nerve roots in (a) and (b) compared to (c).

References: [1] Chhabra, AJR 196:583, 2011, [2] Busse, Magn Reson Med 60:640, 2008, [3] Busse, Magn Reson Med 55:1030, 2006, [4] Mugler, JMRI 00:00, 2014, [5] Yoneyama, Proc. ISMRM, 2011, p. 2721, [6] Constable, Magn Reson Med 28:9, 1992

Acknowledgment: The present work was supported by Philips Healthcare.