Simultaneous Estimation of T_2 and ADC in Human Articular Cartilage In Vivo with a Modified 3D DESS Sequence at 3 T

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INTRODUCTION: Evaluation of articular cartilage with MRI during the progression of osteoarthritis (OA) or other diseases is aided by methods that show morphological and biochemical properties of tissue including T_2 and ADC mapping[1]. Standard Spin-Echo (SE) methods for these mappings require long acquisitions, are SAR limited, or may suffer from distortion and artifacts.

The Double Echo Steady State (DESS) sequence[2] (also called FADE or MENSA) consists of two echoes (a "FISP" or S^+ echo and a "PSIF" or S^- echo) with significantly different contrast. It has been used to generate morphological images and segment cartilage in the OA Initiative protocol[3], and to generate approximate T_2 maps[4]. Here we modify the 3D DESS sequence to increase its flexibility with respect to the diffusion weighting, extending the work on [5] to develop, validate, and demonstrate an accurate quantitation of ADC and T_2. We acquire two data sets with this sequence with different diffusion weightings and fit the resulting four images to the signal equations to solve for T_2 and ADC values simultaneously and without artifacts or distortion. We validated the accuracy of our method in phantoms and demonstrated it *in vivo*.

METHODS: DESS is a balanced SSFP sequence where the readout gradient is prolonged to unbalance the gradients and separate the echoes. We modified DESS by separating the unbalancing spoiler gradient from the readouts (Fig. 1) to allow flexibility to modulate the diffusion sensitivity. To quantify T_2 and ADC, we acquired two modified 3D DESS data sets with different spoiler gradient amplitude and flip angle (FA) while maintaining the timing parameters. We fitted the S^-/S^+ ratios for each acquisition and the ratio of the S^+ echoes from both acquisitions to the corresponding equations[6] to estimate T_2 and ADC values for each pixel. We generated a morphological image by summing the echoes of a single acquisition.

We acquired data on a 3T MR750 whole-body scanner (GE Healthcare, Waukesha, WI) with a commercial 8-chanel knee coil. All modified 3D DESS images were obtained with: TR=26ms, spoiler gradient duration=2ms, 256×256 matrix, receiver bandwidth=±62.5kHz, FOV=16×16cm^2, slice thickness=3mm, and TE for the S^+ readout=9ms (the effective TE for the S^- readout is calculated from the RF pulse of the previous TR and is 43ms). We obtained a first data set (with lower diffusion sensitivity) with FA=35° and spoiler gradient amplitude=0.5G/cm on all axes, and a second data set (higher diffusion sensitivity) with FA=18° and spoiler gradient amplitude=4.0G/cm on all axes. Each acquisition of 40 slices was 4 min.

To validate our method we scanned phantoms consisting of different concentrations of agar in water, dish soap, egg whites, and peanut oil. We compared the values estimated with our method with those obtained with the standard 2D SE technique for a single slice: multiple SE acquisitions for T_2 (TEs = 10, 20, 30, 40, 50, 60, 70, and 80 ms), and multiple SE-EPI images for ADC (b = 0 and 400 s/mm^2 in each direction). We calculated mean and SD for the values estimated within a ROI consisting of the entire phantom in a single slice and performed a linear regression of the estimates of our method to those calculated with the SE methods, forcing the y-intercept to 0. The Pearson coeff. (R) and slope of the regression were our metrics.

We scanned 6 volunteers with the 3D DESS acquisitions with the same parameters described above in order to demonstrate the method *in vivo*.

RESULTS and DISCUSSION: Modifying the spoiler gradient and FA change the diffusion and T_2 weighting as expected. The phantom results show excellent correlations between methods. For the ADC measurements: R=0.997, slope=0.99. For the T_2 measurements: R=0.984, slope=1.02 (Fig. 2).

The 3D ADC and T_2 values estimated *in vivo* in cartilage with our method are within the ranges of previously published values, mean T_2 = 40 ms, and mean ADC = 1.5x10^{-9}m^2/s[1]. While in DESS the echoes are usually added to produce a single image, there is a lot more information available in these images, as evidenced in [4] and here. In this case the two sum images obtained have high SNR and different contrasts, and can be used for segmentation or morphological analysis. These 3D datasets require two scans of about 4 min. each. A sample set of morphological images and T_2 and ADC maps obtained *in vivo* are in Figs. 3 and 4. There are changes in T_2 across the cartilage (Fig. 4) as expected and magic-angle T_2 changes are evident (Fig. 3). Further studies of patients with lesions are needed to verify that our method can effectively detect the related changes in tissue parameters.

CONCLUSION: Using two modified DESS acquisitions we can produce high-resolution 3D morphological images suitable for segmentation and with different contrast, together with highly accurate T_2 and ADC maps in 8 minutes, with high SNR and no distortion or blurring.

REFERENCES: [1]Glaser C, *Radiol. Clin. N. Am.*, **43**:641-653, 2005 [2]Redpath TW *et al.*, *MRM*, **6**:224-234, 1988 [3]Peterfy CG *et al., Osteoarthr. Cartilage.* **16**:1433-1441, 2008 [4]Welsch GS *et al., MRM*, **62**:544-549, 2009 [5]Staroswiecki E et al., *Proc. ISMRM* **18**:824, 2010 [6]Wu EX *et al., JMR*, **90**:243-253, 1990
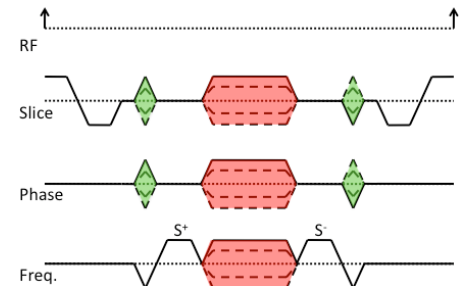
Figure 1: Modified 3D DESS. The spoiler gradient is separated from the readout gradients, allowing it to be played with arbitrary direction, duration, and amplitude, resulting in greater flexibility to manipulate the contrast of the resulting images.
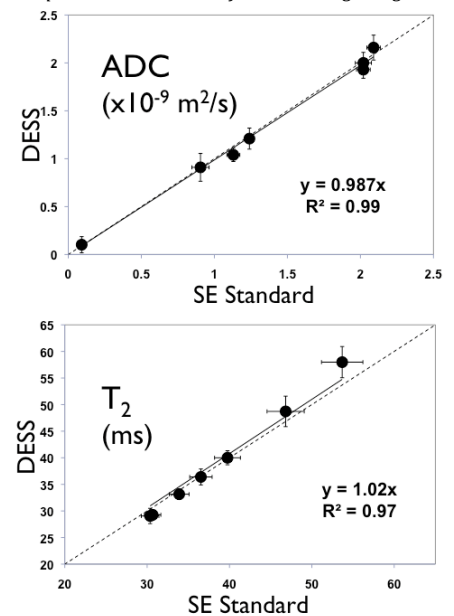
Figure 2: Comparison of ADC and T_2 values obtained with DESS for several phantoms, to those measured with standard SE techniques. The results correlate very well, with high R values and slopes within 2% of unity.
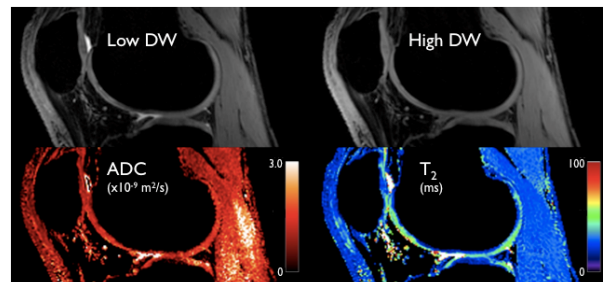
Figure 3: Detail of a single slice of a 3D sagittal dataset obtained from two modified 3D DESS acquisitions obtained in 8 min. Sum images from acquisitions with low and high diffusion weighting; ADC and T_2 maps.
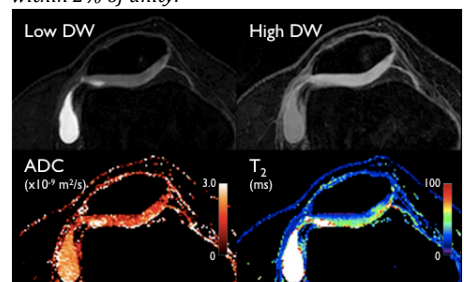
Figure 4: Detail of a single slice of a 3D axial dataset obtained from two modified 3D DESS acquisitions obtained in 8 min.