Estimating the short-time elastic modulus of cartilage using $T1_\rho$ and T2

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Introduction: The ability to use MRI to estimate cartilage material properties could improve both clinical diagnosis and subject-specific modeling. Cartilage material properties have been shown to correlate with macromolecules: glycosaminoglycans (GAG) and collagen [1]. Cartilage macromolecules, in turn, have been shown to correlate with MR parameters (T2, T1ρ, dGEMRIC, sodium, gagCEST) [2-6]. Equilibrium material properties have been shown to correlate with T2 and dGEMRIC parameters [7], but initial elastic modulus (E_0) has not been studied in this context. The purpose of this study was to determine if there are individual relationships between initial elastic modulus and T1ρ and T2 relaxation times.

Methods: Patellae from 19 human cadavers (20-90 years old, median age=56) were used in this study. Patellae were affixed to an acrylic plate and were stored in PBS with protease-inhibitors to minimize the natural degradation process. Specimens were not artificially degraded for this study.

Specimens were imaged in a transmit/receive wrist coil at 3T. A 2D spiral sequence was used to acquire T1ρ (spin locking frequency 500 Hz) [8] and T2 images [9] with 3.0 mm slice thickness, 0 mm spacing, 10 cm field of view and 5 identical echo/spin-lock times: 7, 21, 36, 65, 124 ms. The 5th echo was not used to determine the T2 relaxation time because the cartilage signal was not distinguishable from the background noise. If ROIs contained any artifact, the data point was excluded from the remainder of the study. Fig. 1a shows an MR image of one slice of a specimen.

After imaging, creep indentation tests [10] were performed at 7 locations across the surface of the patella. E_0 was determined using the Hayes approximation [11] (t=0.15 s, assuming near-incompressibility ν_0=0.47). Following mechanical testing, 3 mm plugs were removed near the mechanical test sites. DMMB [12] and hydroxyproline assays [13] were used to measure the sulfated GAG and collagen content per 3 mm diameter plug. A mixed effects model was used with knee nested within specimen as the random effect; statistical analyses were performed using Stata (stata.com).

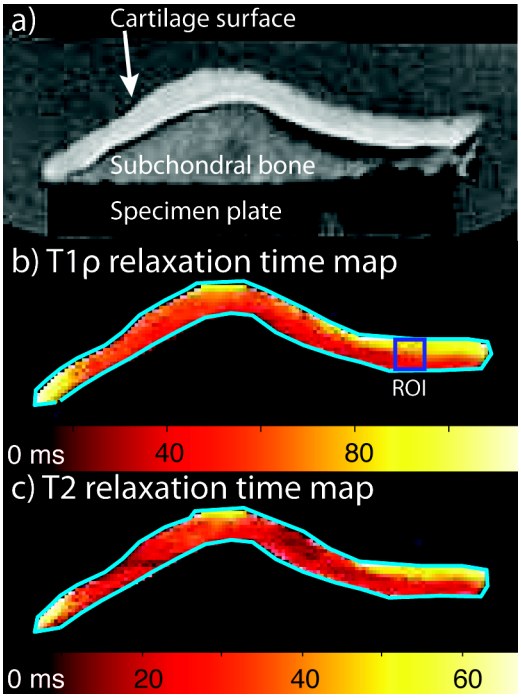

Figure 1: MR image of patella specimen. MRI and biochemical measurements were made from the same ROI, located near each mechanical testing site.

Table 1: Univariate mixed effects models relating T1ρ and T2 relaxation times, sGAG and collagen to E_0. Regression r^2 was calculated by squaring the linear correlation between model predictions and observed values. A value of p<0.05 was considered significant. (N=85)

	T1ρ	T2	sGAG	Collagen
E_0	p=0.48	p=0.27	p<0.001 r^2=0.47	p<0.001 r^2=0.55

Results: T1ρ and T2 relaxation times did not individually correlate with E_0 (Table 1). However, sGAG and collagen were individually correlated with E_0 (Table 1). sGAG also correlated with T1ρ (p<0.01, r^2=0.73), while collagen did not correlate with T2 (p=0.781). T1ρ and T2 relaxation times were significantly correlated with each other (p<0.001, r^2=0.57, Fig. 2), and T1ρ and T2 maps of a slice of a patella specimen were qualitatively similar (Fig. 1b,c).

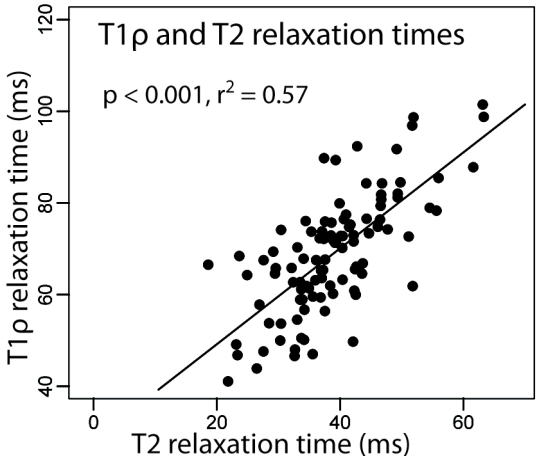

Figure 2: Linear regression of T1ρ and T2 relaxation times.

Discussion: There was no univariate correlation between T1ρ and E_0, nor between T2 and E_0. As reported previously, T1ρ and T2 relaxation times were highly correlated [14,15]; the correlation here (r^2=0.57) was substantially stronger than that found by Taylor et al. (r^2=0.06). Cartilage macromolecules were related to E_0, in agreement with previous work [1]. Collagen did not correlate with T2, in contrast to what has been reported previously [2]. Collagen content was assessed without regard to its structure, which may explain the lack of correlation with T2. Previously, prediction of equilibrium modulus improved when both GAG and collagen imaging parameters were used in a multivariate regression model [7]. In this study, it was not possible to incorporate T1ρ and T2 relaxation times in a multivariate model to predict E_0 due to the multicollinearity [16] of T1ρ and T2 relaxation times.

References: [1] Guilak et al., 1994 [2] Nieminen et al., 2000 [3] Duvvuri et al., 1997 [4] Bashir et al., 1999 [5] Shapiro et al., 2002 [6] Ling et al., 2008 [7] Nieminen et al., 2004 [8] Li et al., 2005 [9] Foltz et al., 2003 [10] Keenan et al., 2009 [11] Hayes et al., 1972 [12] Farndale et al., 1982 [13] Smith et al., 1992 [14] Taylor et al., 2009 [15] Vogelsong et al., ISMRM 2010 [16] Slinker and Glantz, 1985
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