INTRODUCTION The tensile modulus of articular cartilage has been widely measured as a function of depth, orientation, and age (1-5). Collagen is believed to provide cartilage with its resistance to tensile loading, contributing to anisotropic effects which are observed as a dependence of tensile behavior on orientation with respect to the collagen ultrastructure (2,4,5). The Poisson's ratio is also required to fully describe the tensile behavior of articular cartilage, but has not been previously measured. The Poisson's ratio for bovine cartilage in unconfined compression has been directly measured with evidence for material isotropy in compression (6). Given the nonuniform and highly oriented ultrastructure of collagen in articular cartilage, we may expect the Poisson's ratio for cartilage to exhibit anisotropic effects in tension and to vary with spatial position. In this study, we directly measure the Poisson's ratio and tensile modulus of articular cartilage from the human patella and its variations with depth using a newly developed optical system. This is the first reported data for the Poisson's ratio of cartilage in tension, with evidence of significant anisotropy for the Poisson’s ratio throughout the tissue depth. This finding has important implications for predicting the stress-strain state within cartilage and suggests that volumetric changes, with associated fluid flow, may be a significant mechanical phenomenon in tensile loading of cartilage.

METHODS Test samples were prepared from articular cartilage on the lateral facet of non-degenerate human patella (n=4, average age 51). Samples were prepared from the surface and mid-zone (~1.5 mm below the surface). Planar strips of uniform thickness (0.47 ± 0.13 mm, mean ± sd, n=8) and width (2.01 ± 0.26) were prepared with the length (6.95 ± 3.71) oriented parallel to the split-line direction (7). Samples were tested in uniaxial tension in a 0.15 M PBS bath using a custom-built mechanical test system (8) with optical image analysis. A uniform distribution of enamel markers was applied to the sample surface with an airbrush. Samples were oriented with the length aligned with the axis of tensile loading and allowed to adhere under a light load (0.1 MPa). A digital image of the sample surface was taken at the equilibrium, deformed state. The protocol was repeated in 0.02 strain increments to εx = 0.16. The coordinates of the surface markers were recorded and the planar components of Lagrangian strain (εxi) were calculated at each strain increment for triads on the sample surface using a custom-written program (PV/Wave, Visual Numerics). The Poisson's ratio, νxy = -εy/x/εx, was calculated for each triad and for each strain increment, where x-y is defined in the plane of the sample surface. Values for νxy were found to be relatively constant with spatial position and with strain increment, so that an average value was calculated for each sample for all triads and for all strains from εx = 0.04 to 0.10 (i.e., the linear region). The equilibrium stress-strain response was modeled by an exponential law and the tangent modulus (E) was determined in the toe (zero strain) and linear region (Eyy = 0.10) regions, as described previously (8). A paired t-test was used to test for an effect of depth on the Poisson's ratio and modulus. RESULTS Values for Eyy and Eyy were measured at 20-30 triads per sample. This technique for local strain measurement is capable of detecting inhomogeneities due to stress concentrations, clamping effects, and edge effects. For the samples in this study, the strains were 0.2 ± 0.14 for the linear region. The strain values for Eyy and Eyy were highly correlated (r = 0.96, n=8), providing further evidence of a uniform value for νxy with amplitude of strain, Figure 1. The surface and mid-zone νxy were 2.2 ± 1.2 and 0.60 ± 0.22, respectively (Figure 2, mean ± sd, n=4). There was no evidence of a difference in Eyy and νxy with zone which was significant at p≤0.05 for the tensile modulus only (Figure 2).

DISCUSSION Values for the tensile modulus and Poisson’s ratio of patellar cartilage from the mid-zone were found to be 12% and 27% of their respective values at the surface. These findings are consistent with previous studies of human (1-3) and bovine cartilage (4.5) in which the tensile modulus of deep zone cartilage was ~15% of values at the articular surface (1.2). This trend is believed to arise from a higher collagen density and preferential collagen fiber orientation at the surface as compared to the deeper layers. Further support of this hypothesis is found in a higher tensile modulus for samples oriented parallel, compared to perpendicular, to the split-line direction (2.4.5), where split-lines correspond to collagen fiber orientation at the articular surface (7). It is likely that the trend for higher Poisson's ratio at the cartilage surface also arises from these zonal variations in the collagen ultrastructure.

Values for Poisson’s ratio greater than 0.5 indicate that anisotropy is significant in governing the tissue behavior of cartilage at the surface and mid-zones, and suggest that an isotropic model for the cartilage solid matrix may be insufficient to describe the material behavior in tension. Previous studies have directly measured the Poisson’s ratio of bovine cartilage for unconfined compression in the axial plane (i.e., the x-z plane using the convention in our study) with values for νy < 0.19, which are significantly lower than νyy measured in our study. These differences may partly arise from different tension-compression behaviors for cartilage (9), and also support the hypothesis that collagen fibers in the sample contribute to material anisotropy in tension but not compression. To fully assess the order of anisotropy for cartilage as suggested by the data in this study, additional material properties are required (e.g., Poisson’s ratio and moduli in the x-z and y-z planes). Finally, values for νyy greater than unity, where the transverse strain exceeds the axial strain, suggest that a negative dilatation may occur during uniaxial elongation. One mechanism for volumetric changes in articular cartilage could be through fluid exchange, as has been well-studied for cartilage in compresion (9). Material models for anisotropy with explicit representations of the collagen fibers (10-12), in combination with models of fluid-solid interactions, are promising for describing the tensile behavior of cartilage and other collagen-reinforced soft tissues.

ACKNOWLEDGMENTS Supported by a grant from The Whittaker Foundation and an NIH Pre-Doctoral Fellowship.


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DIRECT MEASUREMENT OF THE POISSON'S RATIO OF HUMAN ARTICULAR CARTILAGE IN TENSION


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4649