Abstract

Mechanics of articular cartilage can be represented using poroelastic theories where fluid and solid displacements are viscously coupled to create a time-dependent spatially heterogeneous behavior. In recent models of this tissue, finite element methods have been used to predict tissue deformation as a function of time for adult articular cartilage bearing a characteristic depth-dependent structure and composition. However, current experimental methods are limited in providing verification of these predictions. The current study presents an apparatus for imaging the radial displacement profile of cartilage in unconfined compression using an ultrasound technique called elastography. We acquired ultrasound A-scans across the lateral diameter of full-thickness cartilage disks containing a thin layer of underlying bone, during axial compression. Elastography was then applied to correlate temporally sequential A-scans to estimate the solid radial displacement profile in articular cartilage while it undergoes compression and stress-relaxation. Both time-dependent and depth-dependent solid radial displacement profiles were obtained with a precision better than 0.2 μm. The results generally agree with predictions of poroelastic models, demonstrating lateral expansion with an effective Poisson’s ratio just after completion of the compression phase of the mechanical tests reaching values from 0.18 to 0.4 (depending on compression speed), followed by contraction to lower values. A more restricted movement was observed at both the articular surface and near to the subchondral bone than at regions midway between these two locations.

Keywords: Cartilage; Ultrasound; Poroelasticity; Biphasic model; Elastography; Extracellular matrix

1. Introduction

The mechanical performance of articular cartilage reflects the composition and structure of its three main extracellular components: proteoglycans, collagen fibrils, and water. When cartilage is compressed rapidly, it initially deforms in a volume-conserving manner, after which internal solid matrix stress forces fluid to flow out of the tissue (Armstrong et al., 1984). Necessarily, solid matrix deformation evolves during this time since fluid and solid exchange occurs continuously. Therefore, when investigating cartilage mechanical behavior, and especially when comparing to predictions of theoretical models, the direct measurement of internal physical profiles such as solid deformation or fluid velocity would be of great utility. Novel instrumentation developed towards this goal could also be useful for clinical diagnosis.

In this study we describe a new technique and show that it is capable of imaging solid matrix displacement internal to articular cartilage during the dynamics of loading. The method uses high frequency ultrasound (US) techniques and is inspired by recent work in elastography. In this technique (Ophir et al., 1991), an ultrasound transducer is pulsed during tissue deformation and a series of echoes, named A-scans, is acquired. A-scans are signals representing the pressure applied on the face of the transducer by the reflected echoes as a
function of time and are related to the position of acoustic inhomogeneities, which in cartilage are at least partly related to collagen fibrils (Agemura et al., 1990). Thus, by cross-correlating consecutive A-scans, one can follow the displacement of the solid matrix of the tissue to obtain time evolving solid displacement profiles. We have previously described the apparatus and the success of this technique when applied to soft gel-like materials (Fortin et al., 2000). Furthermore, it has been recently shown that images of the effective local Poisson’s ratio in tissues may be obtained from elastographic estimations of the axial and lateral components of the strain tensor (Konofagou and Ophir, 1998). In this note we describe the application of elastography to articular cartilage attached to bone and show the time-dependence and depth-dependent heterogeneity of the internal solid radial displacement profiles in a cartilage/bone disk subjected to unconfined compression.

2. Methods

The apparatus has been described elsewhere (Fortin et al., 2000) and only a brief description will follow. The mechanical testing system is the Mach1™ (A-Class, Biosyntech Ltd., Laval, Canada) equipped with a chamber for unconfined compression of disk shaped samples (Armstrong et al., 1984). A high-frequency ultrasound (US) transducer (f/2, 8 mm focus, 50 MHz, VisualSonics, Toronto, Canada) can be positioned in 3-D and is oriented to pulse across the lateral diameter of the cylindrical sample (Fig. 1). The width of the ultrasound beam at focus is approximately the product of the f-number (focal length (8 mm)/crystal diameter (4 mm) = 2) and wavelength (~ 33 µm at 50 MHz) and is about 70 µm in our case. A separate pulser (Avtech ElectroSystems Ltd., Ogdensburg, NY, USA) and custom amplifiers are used. The US signal is digitized at 500 MHz through a PC oscilloscope board (Gage Applied Sciences, Inc., Lachine, Canada) for further processing.

Cartilage disks (n = 3) were isolated from the humeral head of 1–2 years-old steers in a manner that retained a thin layer of subchondral bone (Dumont et al., 1999). Disks were punched to ~1.7 mm diameter and placed in PBS in an unconfined compression testing chamber. The average disk thickness was 1.00 mm with a standard deviation of 0.09 mm and the average disk diameter measured with a calibrated optical microscope was 1.65 mm with a standard deviation of 0.13 mm. Mechanical contact was made with the disk inside the chamber by detecting a small 0.05 g contact with the load cell and then applying a 50 µm offset compression. After equilibrium was reached, 11 successive ramp compressions and releases of 15 µm amplitude were performed using a ramp time of 5 s and a relaxation time of 600 s between ramps. One additional (4th) sample was also tested using a shorter ramp time of 2 s. The position of the transducer was changed between successive ramps in order to sample lateral expansion at different vertical positions, starting at the articular surface and moving the transducer down by 100 µm after each ramp. The compression offset was returned to the initial 50 µm after each transducer movement, so that measurements...
at different transducer positions could be compared. Actuator position, total force and ultrasound data across a diameter were sampled at 1 s intervals.

The US data were processed off-line to obtain the displacement profile inside the sample using cross-correlation between pre- and post-compression signals performed on 256 point windows with parabolic interpolation and logarithmic signal compression (Ophir et al., 1991). This computation consists in isolating 256 data point windows in the pre- and post-compression signals and applying a logarithmic compression to the data using

$$\text{CompData} = \text{sign(Data)} \times \log(1 + C|\text{Data}|),$$

where Data is the acquired 256 points, sign denotes the sign (+ or −) of a data point, C is a compression strength” parameter and CompData is the compressed data. The cross-correlation function between these two windows is then computed and interpolated near its maximum. The argument of the function at its maximum, with interpolation, gives an estimate of the time delay between the two windows in the two signals. With this time delay, and using the speed of sound in cartilage, assumed to be 1666 m/s (Joiner et al., 2001), mechanical displacements inside the tissue can be computed. The effective Poisson’s ratio was calculated as the ratio of surface-to-surface lateral strain to axial strain, the former being obtained using the lateral displacement profile measured by US.

3. Results

The time-dependent behavior of the effective Poisson’s ratio averaged for three samples during compression was obtained (Fig. 2) indicating an initial lateral expansion followed by a retraction phase that is similar in pattern to that of the force profile. Poisson’s ratio measured at equilibrium is approximately 0.12, which is consistent with values found previously using microscopic techniques (Mizrahi et al., 1986; Jurvelin et al., 1997). The effective Poisson’s ratio for the sample tested with a faster 2 s ramp (in Fig. 2B rather than a 5 s ramp in Fig. 2A) reached a much higher maximal initial value of 0.4, nearer to the value indicating volume conservation.

Radial displacement profiles within the tissue, also displayed a time-dependence and space-dependence compatible with poroelastic behavior (Fig. 3). Taking the sample number (3 total), radial position, depth from the articular surface, and time as independent variables, ANOVA revealed that radial displacements were greatly dependent on radial position ($p < 0.001$) and time ($p < 0.001$) and weakly dependent on depth ($p < 0.1$). Thus during the course of the compression, the radial displacement increases with time, reaches a maximum when the ramp amplitude is attained and then decreases during the relaxation portion of the test (Figs. 2 and 3). The displacements 2 s prior to ramp completion are smaller than the displacements at the end of the ramps showing continual radial expansion during the compression ramp. Also, the displacements at equilibrium are smaller than the displacements at the end of the ramps. We note that all displacement profiles correspond to the ~100 µm thick slices of tissue that is sampled by the finite-width ultrasound beam width allowing visualization of depth-dependent behavior. Radial expansion appeared greatest in the zone midway between the articular surface and bone (Fig. 3B).

4. Discussion

In this study we have demonstrated that high frequency US elastography techniques can be successfully applied to dynamically image solid matrix displacement within articular cartilage. The effective Poisson’s ratio, representing average lateral expansion relative to axial compression, can be obtained, as has
boundary conditions, and possibly non-linear stiffening (Li et al., 1999) in order to stiffen the cartilage laterally in tension and create a relaxation time that is shorter than several seconds. Clearly any depth-dependent radial displacement profiles and their restriction at both the articular surface and the cartilage-bone interface can only be described by models incorporating depth-dependent proteoglycan concentration and collagen fibril orientation.

The combination of elastography and mechanical testing is capable of providing important detailed information regarding displacement of internal solid matrix that changes with time and spatial position inside poroelastic tissues. Both temporal and spatial variations in radial displacement can be observed with a resolution greater than 0.2 µm. Exploitation of this novel technique is continuing for fundamental and applied studies.

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References


