The structural organization of cartilage and the habituation hypothesis

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Learning Objectives:
1. Understand how the structure of cartilage influences the appearance of routine cartilage histology.
2. Understand how the complex three dimensional organization of the cartilage matrix is displayed the MR image.
3. Consider the habituation hypothesis which posits that through the repeated application of appropriate biomechanical forces it may be possible to “condition” cartilage in such a way that it is more resistant to injury.

The form and physical properties of any connective tissue are largely determined by the structure of the extracellular matrix. Consider as a case in point the relatively simple example of a tendon, a tissue which resists the forces generated by muscle contraction. Its composition - parallel arrays of collagen - is ideally organized to withstand tensile forces. This interrelationship between form and function should also be a characteristic feature of articular cartilage structure. It is therefore reasonable to predict that the structure of articular cartilage would have the following properties:

a. The structure of articular cartilage should be ideally suited to provide the unique physical properties of cartilage including remarkable resistance to compression and a nearly frictionless surface.
b. The structure of cartilage should vary from one joint to another, reflecting differences in the biomechanical forces experienced at different joint surfaces.
c. Similarly, differences in the biomechanical demands placed on different regions of a joint surface should be associated with variability in cartilage structure within a given articular surface.
d. To the degree that cartilage has an ability to remodel, a change in the prevalent stresses within a joint should lead to changes in cartilage structure and biomechanical properties.

Cartilage histology
- Water, Type II collagen, proteoglycan, chondrocytes
- Aneural and avascular

Biomechanical properties
• The compressive stiffness of cartilage is the product of the tensile forces of collagen resisting the swelling forces created by proteoglycans drawing water into the tissue.
• Nearly frictionless surface
• Durable, able to withstand extremely high compressive loads for many years.
• Anisotropic tensile strength implies an anisotropic structure. (1)

Collagen organization
• Polarized light microscopy (PLM)
  o Depth dependent variations in birefringence reflect the curved orientation of collagen within the matrix – thought by Benninghof and others to represent arcades of collagen radiating from the subchondral bone to the joint surface and curving back 180 degrees to the bone. (2)
  o PLM is limited by the use of routine sectioning which cuts through the three-dimensional organization of cartilage.
• Scanning electron microscopy (SEM)
  o Fracture sectioning reveals a fibrous structure radiating from the bone and curving through an arc of 90 degrees into the plane of the joint surface. (3)
  o Curvature of the fibrous structure correlates with the transitional zone of PLM studies.
• MRI
  o MR techniques are capable of both directly and indirectly visualizing cartilage structure. If one accounts for the limitations inherent to MR imaging the technique provides a noninvasive means of evaluating the internal structure of the cartilage matrix.
  o Depth dependent variability in T2 causes a characteristic layered appearance on MR images of cartilage. (4,5)
  o T2 anisotropy is due to the influence of matrix structure on water mobility.
  o Changes in T2 correlate with changes in the matrix orientation as displayed on fracture sectioned cartilage. (6)
  o Changes in T2 correlate with changes in PLM. (7)
  o Therefore T2 is neither uniform nor constant. It is determined in large part by the orientation relative to B₀ of both the joint surface and the internal structure of the matrix. This creates predictable challenges to interpreting the significance of T2 measurements.

Joint specific matrix architecture
• Surface split lines created by puncturing the surface of cartilage with a round awl are oriented in predictable patterns which are characteristic for different joint surfaces. This implies that each joint surface has a typical organization and that this organization is biomechanically significant. (8)
The biomechanical properties of cartilage, such as the compressive modulus, vary from one region of a joint surface to another. (9)

Split lines are oriented perpendicular to the plane of matrix curvature revealed by fracture sectioning.(3) The joint specific organization revealed by split line orientation therefore reflects an underlying organization of the matrix.

Regional variation in the structure of the matrix correlates with regional differences in the depth dependent variability of T2.(10) These variations are predictable for a given joint surface. For example, the tibial plateau is ideally suited to resist compression while the more obliquely curved structure of the femoral condyle more efficiently resists shearing injury.

The habituation or “conditioning” hypothesis

- Cartilage injury occurs when local mechanical forces exceed the tissue’s failure threshold.
- The extracellular matrix adapts in response to local biomechanical forces which do not exceed that threshold.
- Proteoglycans may increase though there is limited capacity for collagen to adapt following maturity.
- It may therefore be true that the threshold at which cartilage fails is regulated by prevalent stresses arising in the joint.
- Cartilage surfaces which are not typically stressed are more likely to be injured when stress is applied, e.g. superior medial facet of the patella
- Exercise during childhood may influence cartilage volume. (11)
- Modeling of cartilage with exercise regimen may be possible. (12)

REFERENCES