THE MOVEMENTS OF BONES AND JOINTS

4. The Mechanical Structure of Articulating Cartilage*

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When the joint is in motion its articulating surfaces are separated by a film of synovial fluid, but when it is at rest the surfaces are in contact. They are pressed together by a combination of muscular and gravitational forces; the resulting force across the joint is always equal to the weight of the part that has come to rest (MacConaill 1949); this weight includes that of any object which is carried by the limb. Since the area of contact across which the force acts is seldom the whole area of the joint surfaces the force per unit area is often great. Cartilage is deformable, and when the force is great the deformation may be considerable. The cartilage is compressed in the direction of action of the force, and dilated

Deformation of articulating cartilages at rest. Figure 1 shows the theoretical conditions with intrinsic and extrinsic forces eliminated. Figure 2 shows the effect of combined muscular and gravitational forces acting in the direction of the arrow. The effect of these forces is to cause vertical compression and lateral dilation, as shown by the network of lines, the origins and insertions of which are the same in the two diagrams.

in the direction perpendicular to the line of action of the force (Figs. 1 and 2). Dilation implies tension in the direction of dilation. The deformation of the cartilage is brought to an end when the dilation is brought to an end—that is, when tension-resisting mechanisms within the cartilage come into effective action. The normal tension-resisting substance of the body is collagen. Consequently the amount and manner of distribution of collagen fibres is a matter of importance for an understanding of joint mechanics.

It is the purpose of this paper to show that the amount of collagen in hyaline cartilage is much greater than has been commonly supposed, and that its distribution is exactly that called for by the impact of stress upon the articulating surfaces.

Historical note—About a hundred years ago the matrix of hyaline cartilage was thought to be a homogeneous substance (Hassall 1849). Schäfer (1891) noted that fibrous tissue was prolonged from the periosteum and joint capsule into the marginal (non-articulating) part of articular cartilage, but stated that the matrix did not contain fibres elsewhere. He mentioned that calcium salts might be found in the deepest layers of the cartilage of joints. Shipley (1928) denied the existence of fibres in hyaline articular cartilage. Ramón y Cajal

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(1933) reported that cartilage had a ground substance "composed of numerous collagen fibres embedded in a jelly of chondromucin," but that, because the chondromucin had an index of refraction equal to that of the collagen fibrils, they were invisible unless treated by special reagents such as potassium permanganate or potassium hydroxide. Ruth (1946), using potassium hydroxide, showed that the articular cartilage of the new-born contains numerous fine fibrils of collagen. Benninghoff (quoted by Murray 1936) studied the problem extensively: he believed that the collagen fibres of hyaline cartilage, including articular cartilage, limit the deformation of the individual cartilage cells, and that their arrangement is such that they form capsules for these cells, and for specific groups of these cells ("chondrones"). That is, each cartilage cell functions as a "bursal cyst," which is prevented from bursting under deformative pressure by the resistance to tension of its collagen capsule. Benninghoff's views will be discussed at a later stage; they appear in his *Lehrbuch* (1939).

MATERIAL AND METHODS

An account of the material and methods used in the present study will be presented in the form of directions to those who may wish to repeat it. The material used was taken from the ox (four years old) and from adult human cadavers, fresh and preserved. The structure of the cartilage was essentially the same in all.

FIG. 3

Different ways of sectioning a slice of articular cartilage. Free surface above, juxta-osseous surface below. RR', a radial section. TT', a tangential section. PP', a paratangential section. OO', an oblique section. A paratangential section is an oblique section taken near the free surface.

Method—Cut slices of articular cartilage from a joint surface; they should be parings taken as near to the bone as possible without including osseous tissue. Fix in 5 per cent formaldehyde solution, and embed in wax. Cut sections at 8μ . Some should be radial, some oblique sections (Fig. 3). The oblique sections display the essential arrangement of the collagen fibres much better than the radial sections. Mount the sections in Canada balsam or other suitable medium. Examine them 1) in plain light (transillumination); 2) by phase-contrast illumination; and 3) by polarised light. (If "polaroid" polarising glass is used to make the polariser and analyser, the use of a green filter between the polariser and the slide, or of green light for illumination, will give better contrast than does the use of white or yellow light.) A rotating stage—or its equivalent—is needed in order to see all the details of structure.

Treat other sections with 1/1000 potassium permanganate solution, immersing them for about one hour in the case of human material and slightly longer for bovine material. Wash the sections; mount some directly and stain others with collagen stains (acid fuchsin; aniline blue). The unstained sections will show the fine fibres and the general arrangement most clearly: collagen stains require an acid medium to make them "take," but the acid turns the collagen into a jelly, and the stains show the *locus* rather than the arrangement and form of the fibres. The depth of staining by collagen stains depends upon the length of time that the sections have been immersed in the permanganate bath.

RESULTS

The results obtained will be described in detail, so far as they bear upon the mechanical structure of articular cartilage.

The lamina splendens—Sections untreated and examined by ordinary illumination are uninformative. When they are examined by phase-contrast illumination they show a thin bright line at the articular surface of the cartilage. This is so conspicuous that it merits the name of *lamina splendens* (Fig. 4). It is to be remembered that what is a line in a section is a lamina in the whole specimen. The lamina splendens is devoid of collagen fibres. It is wholly composed of hyaline cartilage in the strict sense of the term and it is the only part of the articular cartilage that is purely hyaline.

Chondrousia—The component of articular cartilage that is neither collagenous nor cellular will be termed here *chondrousia* (Greek "cartilage substance"), a terminology which avoids biochemical presuppositions as to the precise nature of the non-collagenous component of

FIG. 4

A section of articular cartilage (8μ) mounted in clarite but otherwise untreated, viewed by phase-contrast illumination. 16 millimetre objective. L.S.—lamina splendens.

the chondromatrix. The chondrousia of the lamina splendens stains more lightly with stains such as lead haematoxylin than does the chondrousia elsewhere. The chondrousia is either removed by potassium permanganate or altered in such a way that the collagen fibres become visible in polarised light. It seems correct to say that the length of time taken by any given part of a section (of standard thickness) to be cleared by potassium permanganate is a measure of the amount of chondrousia in that part. Using this criterion we can make some estimate of the relative chondrification of different parts of one and the same articular cartilage.

The collagen fibres—In ordinary illumination permanganate-treated sections show some large fibre-bundles (Fig. 5). In polarised light, the polariser and analyser being "crossed," these appear far more numerous, and those seen in ordinary light are seen more distinctly (Fig. 6). The direction of the fibres will depend upon the orientation of the section to the beam of polarised light passing through it: we must rotate the section in order to get the complete structure of the collagenous mass. But very often bundles of collagen at right angles to the

FIG. 5

FIG. 6

Figure 5—Section of articular cartilage (8μ) treated with potassium permanganate and viewed by ordinary transillumination. 25 millimetre objective. Figure 6—Same section as in Figure 4 viewed by polarised light. The collagen bundles are clearly seen. Those not lying in the appropriate direction are, however, invisible.

FIG. 7

A section of articular cartilage from the lower end of the femur (human) viewed as in Figure 6 but through a 4-millimetre objective. The network of collagen fibres is seen; some fibres crossing, some anastomosing. The inset shows diagrammatically the arrangement of a phorm-anastomotic network (see text). Some fibre-bundles interlace, some anastomose. The cartilage columns (here seen in transverse section) lie in the interstices of the network.

visible bundles reveal their presence by their "darkness" (Fig. 7). When stained by aniline blue, or by acid fuchsin, the fibres that are visible in ordinary light take the stain more deeply than those that are invisible. This observation suggests that the potassium permanganate actually removes the chondrousia, probably by oxidizing it. Two facts may be recalled in this connection: 1) that articulating cartilage is not normally in direct contact with that chief oxidizing agent, the blood; and 2) that soft, mushroom growths are most common in the non-articulating parts of the articular cartilage, where the overlying synovial membrane provides an abundant blood-flow.

The collagenous fibres of "hyaline" articular cartilage are arranged in bundles as large as those of articular fibrocartilage and as large as those of individual constituents of tendon

FIG. 8

FIG. 9

Figure 8—The deployment of pressure in a compressed articular cartilage. The curved lines are the isobars of pressure generated by the travel of the compressing force (W) from the free surface to the osteochondral junction. T and T' are two lines tangential to an isobar of pressure: they represent lines of tensile stress. Figure 9—The disposition of some of the collagenous fibres that take tensile stresses consequent upon the deployment of pressure (as in Fig. 8). T and T'—two lines of fibre, each tangential to a potential curved isobar. G.A.—the *galea aponeurotica* of the cartilage formed by conjunction of the juxta-synovial ends of the collagenous fibres (see text).

or ligament. Thus hyaline cartilage (of joints) is white fibrous tissue impregnated with chondrousia and the articular surfaces are truly part of the fibrous joint capsule. Equally, the lamina splendens—in which cells may be found—is a hardened, or chondrified, continuation of the synovial membrane of the joint. The illustrations (Figs. 6 and 7) show how great a proportion of the articulating masses is formed by fibrous tissue. The arrangement of the articulating fibrous tissue is, however, more definite and regular than is that of the capsular fibres (Fig. 7). The individual fibres are not only interlaced but also anastomose with each other at intervals. Such an arrangement may be termed a *phorm-anastomotic network* (Greek *φορμος*=plaited mat or basketwork). The anastomosing elements unite the several networks at different levels of one and the same cartilage. The cartilage cell-columns lie in the interstices of the phorm-anastomosis, and the collagen fibres (in part) take a spiral course around these columns. This arrangement confers great strength against tensile stresses upon the fibre mass and converts that mass into an effective whole.

THE MECHANICAL PROBLEM AND ITS SOLUTION

The mechanical problem to be solved within the joints is essentially this. When the joint comes to rest a force is taken by a relatively small area of cartilage and transmitted to a wider area of bone, the osteochondral junction (Fig. 8). This means that the force is "deployed" across the cartilage in the form of a pressure-wave; the diameter of the

wave-front increases as the wave nears the osteochondral junction. The wave is, of course, a surface, but appears as a line in section. This surface is an *isobaric* surface; that is, the pressure has the same value at every point (instantaneous wave-front). The strain (deformation) of the cartilage, however slight, is a shear-strain. At every point of the pressure wave-front there will be a tension stress of equal magnitude but at right angles to the lines, that is, tangential to it. In terms of physics, the tension lines are the orthogonal trajectories of advance of pressure. Two such tension lines are shown in Figure 8. The mechanical problem, then, is to arrange tension-resisting fibres in such a way that they will always be orthogonal to a pressure wave-front, from whatever direction it may come; or, at least, that a sufficient number of them should be so disposed at any one time.

The solution of the problem depends upon the existence of a network of tension-resisting collagen fibres. This network must have its fibres disposed obliquely rather than radially (for the most part, anyway) for the tension stresses will not run in the shortest line from the lamina splendens to the bone, nor conversely. This means that the network will consist of fibres which are parts of laminae tangential to the possible wave-fronts (Figs. 8 and 9). The laminae nearest to the free surface of the cartilage will form a virtual *galea aponeurotica* beneath that free surface. This galea will be tense during maximal deformation, and it will then act as a reflector of an oblique (or transverse) pressure-wave—for this wave, like the stronger shock-wave of a bomb-blast, can be reflected.

DISCUSSION

The observations which have been recorded above are not in conflict with previously expressed views upon the structure of cartilage, except, of course, those of Shipley (1928). They are supplementary to earlier positive observations: they suggest that the mass of collagenous tissue in articular cartilage is greater than was formerly believed; and they define its arrangement more explicitly. In the writer's opinion the ultimate structure of cartilage is essentially fibrous, as is that of bone; the difference between bone and cartilage lies in the nature of the impregnating substances. The cells exist to produce the fibres and the chondrousia; the fibres do not exist for the cells. That is, the protection afforded to the cells by the fibres is a secondary result of their coming into full tension, not a primary result. This is, perhaps, the chief difference between the writer's views and those of Benninghoff. The difference in viewpoint centres mainly on the "necessary" disposition of a tension-resisting mechanism in such structures as cartilage. Benninghoff (1950) laid great stress upon the inferences he had drawn from the results of experiments in which the free surface of the cartilage was pierced with a fine awl. From these he argued to a predominantly vertical disposition of the fibres in the cartilage. Against this view the present writer would urge two facts: 1) that such a vertical disposition cannot be seen histologically in radial sections using the technique described, which shows fibres plainly in oblique sections; 2) that such a vertical disposition cannot be predicted from mechanical principles analogous to those invoked in comparable problems in civil engineering, while the oblique disposition can be so predicted. There are of course many vertical (radial) strands of collagen in articular cartilage; but they are not the predominating mass.

Some support appears to be lent to the general thesis of this paper by the disposition of collagen fibres in the menisci of the knee and in other intra-articular fibrocartilages. These, like the articular cartilages proper, have both articulating and non-articulating areas: the former are central, the latter are peripheral. The central parts are never under great pressure when the parts are at rest. But whatever the degree of such pressure, its effect upon the meniscus is to produce a "hoop-tension"; that is, a tension disposed in curved lines, like the tension in a segment of a wine barrel. This tension will be more marked peripherally than centrally, for the curved meniscus, under stress, can be compared to a bent beam: such a beam has one part (of smaller mean radius) a principal seat of pressure strain, and the

other part (of larger mean radius) a principal seat of tension strain. It is in the outer part (of greater mean radius) that we find the principal collagenous mass and it is disposed "circularly," as is well known.

The orientation of the collagenous fibres in articular cartilage is probably the consequence of the strains to which the cartilage is subjected during post-natal development. There is a Law of Collagenisation: *As iron filings are to a magnetic field so are collagen fibres to a tension field*. Its truth can be demonstrated experimentally (Huxley and De Beer 1934); and it has been applied to elucidate the precise structure of the fascia lata femoris, and the significance of the coraco-acromial ligament (MacConaill 1944). Ruth (1946) has shown that the cartilage of the distal femoral epiphysis of the human new-born contains fine collagen fibres; but they are not arranged in any "functional" direction as are the adult fibres. Clearly there is much work yet to be done with profit in this field.

The writer's conclusions may be briefly stated thus: all articulating cartilages are fibrocartilages, and the density of fibrous material is normally proportional to the customary stresses on the part.

SUMMARY

1. All articulating cartilages are fibrocartilages.
2. The articular cartilages of the synovial joints are largely composed of collagen fibres.
3. These fibres form a dense network, the fibres of which run obliquely between the articular surface and the bone.
4. This network is operative when the parts are at rest and in contact under pressure. It takes the tensile component of the resultant shear stress, and is a postural mechanism of the joint.
5. The articular cartilage is most heavily chondrified at its centre, between the juxta-synovial and juxta-osseous parts.
6. The technique for demonstrating the fibrous structure is described.

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REFERENCES

- BENNINGHOFF, A. (1939): *Lehrbuch der Anatomie des Menschen*. Band 1. Munich: J. F. Lehmanns Verlag, *passim*.
- BENNINGHOFF, A. (1950): Personal communication.
- HASSALL, A. H. (1849): *The Microscopic Anatomy of the Human Body*. London: Samuel Highley. Vol 1, 285.
- HUXLEY, J. S., and DE BEER, G. R. (1934): *The Elements of Experimental Embryology*. Cambridge: University Press.
- MACCONAILL, M. A. (1932): The Function of Intra-articular Fibrocartilages. *Journal of Anatomy*, **66**, 210.
- MACCONAILL, M. A. (1944): The Mechanical Anatomy of the Acromio-clavicular Joint of Man. *Proceedings of the Royal Irish Academy*, **50-B**, 7.
- MACCONAILL, M. A. (1949): The Movements of Bones and Joints: 2. Function of the Musculature. *Journal of Bone and Joint Surgery*, **31-B**, 100.
- MURRAY, P. D. F. (1936): *Bones*. Cambridge: University Press.
- RAMÓN Y CAJAL, S. (1933): *Histology*. London: Baillière, Tindall and Cox, 203.
- RUTH, E. B. (1946): A Note on the Fibrillar Structure of Hyaline Cartilage. *Anatomical Record*, **96**, 93.
- SCHÄFER, E. A. (1891): *in* Quain's *Anatomy*. London: Longmans, Green & Co. Vol. 1, part 4, 246.
- SHIPLEY, P. G. (1928): *in* *Special Cytology*. Edited by E. V. Cowdry. New York: Paul B. Hoeber Inc. Vol. 2, section 20.
- WALMSLEY, T. (1928): Articular Mechanism of the Diarthroses. *Journal of Bone and Joint Surgery*, **10**, 40.