Surface structure of articular cartilage

Historical review

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In the previous paper it has been shown that the surfaces of articular cartilage in living mammals and birds are not smooth but are covered by a series of secondary irregularities and of 20 to 30 μm . tertiary undulations, both superimposed on the broad primary anatomical contours (Gardner and McGillivray, 1971). The experiments from which this evidence has been derived have drawn attention to a historical paradox: the conspicuous smoothness of articular cartilage, emphasized by William Hunter (1742–43), is evident grossly. Yet the scanning electron microscope quickly revealed that articular cartilage surfaces are irregular and that the surface irregularities are sufficiently large to be easily seen with a primitive compound microscope. Cartilage surfaces have been viewed with hand lenses since 1742 and with compound microscopes since 1820 or earlier. How is it that observers failed to note the small irregularities which exist upon all varieties of articular cartilage?

To examine this question and the historical development of knowledge of articular surfaces is the object of this short historical review which should be read in conjunction with the earlier report (Gardner and McGillivray, 1971).

Considerable effort was directed towards understanding the structure of articular cartilage by William Hunter (1742–43); the 19th century literature attests to a continued interest in this problem. The literature demonstrates clearly that early workers in cartilage histology were biased in their approach and that they were preoccupied with the questions: Is cartilage cellular? Is cartilage vascular or avascular? and Is the articular surface covered by a synovial membrane?

A substantial number of 19th century workers, armed with compound microscopes fitted with the new achromatic objective lenses introduced in the 1820s, made detailed studies of sections of mammalian articular cartilage cut freehand with a razor or with the early Rutherford microtome. Until 1845 or thereabouts, these investigators were mainly concerned to establish whether articular cartilage was

vascular, whether, as William Hunter (1742–43) and Benjamin Brodie (1813) believed, the cartilage surface was covered by synovial ‘membrane’, and whether cartilage possessed cells, a question which arose naturally from the promulgation of the cell theory (Schleiden, 1838; Schwann, 1847). Several of the early students of cartilage histology drew careful illustrations showing the detailed microscopic structure of hyaline cartilage. In a number of these illustrations, the cartilage surface, with its small tertiary undulations, was clearly depicted. The small prominences were shown to overlie zones in which flattened chondrocytes were situated immediately beneath the surface.

Why then did these observers make no mention of surface structure, or question the superficial smoothness of the surface first seen *en face* in the fresh preparation, or even draw attention to the undulations shown in their own drawings? The explanation, surely, is twofold. First, 18th and early 19th century students of cartilage structure were preoccupied with the debates on ‘Cartilage Vascularity’, on the ‘Role of Chondrocytes’, and, later, with ‘Mechanisms of Cartilage Injury’ (Axhausen, 1923; Pommer, 1927). Second, the surface of articular cartilage appeared and felt so smooth, and served its articulating function so efficiently, that to question this smoothness would have seemed the height of foolish scepticism. Hence the persistence of the view, restated as recently as 1969 (Davies, 1969), that the surface of articular cartilage is ‘strikingly smooth’.

Only one early author (Hammar, 1894) may be said to have offered explicit opinions which conform with those described in the previous report (Gardner and McGillivray, 1970). Hammar wrote ‘Die Gelenkfläche ist niemals glatt, er bietet aber übrigens ein sehr wechselndes Aussehen. Selten ist es ein und dasselbe auf der ganzen Fläche desselben Knorpels’. He went on to say: ‘It (the joint surface) is frequently covered with shallow depressions’. And ‘... the free edge of the cartilage is rarely smooth on vertical section’. In the older literature it is not always easy

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to distinguish between studies of the superior, articulating surface of cartilage and the inferior aspect of this cartilage. Since the latter is indented by vascular prominences closely recalling those of the rete pegs of the dermis, descriptive confusion is only too common. The older authors, in addition, do not always make clear whether they are studying cartilage sections or cartilage surfaces viewed *en face*.

Weichselbaum (1877) distinguished 'very small, rounded or angular, elevated white surface areas which alternate regularly with equally small, depressed, grey or grey-white areas'. Very many other observers, however, were less precise and failed to comment on the surface structure shown, with varying degrees of clarity, in their own drawings. A synopsis of the views given in the older papers surveyed for the present purpose is given in the Table.

Thus, Liston (1840), discussing the vascularization of cartilage, showed drawings in which the cartilage surface, seen in section, was irregularly undulating. Toynbee (1841) illustrated the broad shape of articular surfaces, which we call the primary contours, but not the secondary irregularities. He claimed that cartilage surfaces were smooth. In drawings of sections of normal and of diseased cartilage, Birkett (1848) clearly showed the secondary irregularities normally seen in these preparations but did not describe them. Leidy (1849) stated 'The free surface . . . is very smooth and shining . . .'. The drawings of Redfern (1849) depicted, without comment, primary contours and (probably) secondary surface undulations, but the simple stereotypic lithographs of Toynbee (1849) displayed absolutely smooth surfaces. In experimental studies of cartilage healing, Redfern (1850) made drawings of the undulating surface of an abnormal canine femoral trochlear, and the internal glenoid cavity, 'at a dimple-like depression', was shown to have (100–200 μm .) prominences (approximately 30 μm . high) [Author's brackets]. In these positions the surface cells were rounded instead of flattened, but Redfern did not speak of the surface irregularities. Goodsir (1868) made no comment on the smoothness of joint surfaces, apparently taking the question as self-evident. Nor did Reyher (1874) add any information of relevance in spite of his demonstration that cartilage cell processes could be shown in three dimensions in teased, silver-stained preparations. The drawings of Ogston (1875) included a series of very shallow undulations on the surface of an adult astragalus and similar appearances on the tibial surface of a boy aged 10; in neither case did he remark on the surface structure.

Modern accounts (written before late 1969) of the smoothness of articulating cartilaginous surfaces

concur with Hunter's (1742–43) opinion. Thus Barnett, Davies, and MacConaill (1961) wrote, 'articular cartilage is smooth, glistening, and compressible', while Davies (1969) repeated this opinion, emphasizing the point by stating that 'articular cartilage is strikingly smooth'. Bloom and Fawcett (1962) did not show illustrations of the articular surface, but Ham (1965) depicted a surface with conspicuous undulations about which, however, he made no comment. This state of affairs also obtained in the publication of Cruickshank, Dodds, and Gardner (1968); shallow surface undulations are clearly shown in a photomicrograph of human articular cartilage but no comment was made on surface structure.

We conclude therefore that recognition of the essential roughness of articular cartilage is a matter on which generations of observers have been misled; first because of the widely accepted and authoritative statements of authors such as Hunter (1742–43) and Goodsir (1868), and secondly, because of the invariable presence, on normal surfaces, of a highly reflective film of synovial fluid.

Two fundamental questions remain to be answered: How does the irregular surface of normal living cartilage combine with synovial fluid to give a lubricating mechanism of unbelievable efficiency? and: What part do changes in this mechanism play in the initiation of diseases such as osteoarthritis? Answers to these questions are likely to emerge from the extensive research now in progress in this field.

Summary

The historical literature relevant to the problem of joint surface structure is briefly reviewed.

The demonstration that articular cartilaginous surfaces are not normally smooth has provoked controversy among students of joint lubrication. Any acceptable theory of diarthrodial joint function must take account of a complex relationship between a rough-surfaced cartilage and a lubricant, synovial fluid, with very unusual physical properties.

That articular cartilage surfaces have, until very recently, been assumed to be smooth appears to have been due to too ready an acceptance of authoritarian statements in the 18th and 19th century literature, and to a failure to investigate *en face* rather than in section the structure of the cartilage surface beneath the normal glistening film of synovial fluid.

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This review is intended to supplement the paper by I. C. Clarke, which appears in this issue (see p. 15).

Table *Historical views on the nature of the surfaces of articular cartilage*

HUNTER (1742-3)	Articular cartilage, viewed 'with a glass', has a smooth polished surface covered with a membrane.
BRODIE (1813)	No comment on details of joint surface structure.
HENLE (1838)	No views expressed on smoothness of cartilage surfaces.
LISTON (1840)	Cartilage surface, in drawings, is irregularly undulating. No factual comment.
TOYNBEE (1841)	Cartilage surfaces said to be smooth: drawings show primary contours of femur of human foetus, but not secondary.
PAGET (1842)	No reference to surface of cartilage, the cells of which are described.
ECKER (1843)	Drawings preoccupied with cells, not surfaces.
TODD AND BOWMAN (1845)	A full description of the cells of articular cartilage without reference to the microscopic structure of the surface.
BIRKETT (1848)	Drawings depict secondary undulations, more obvious in diseased than in normal joints.
HASSALL (1849)	Vol. 1: no mention of surface structure. Vol. 2, Fig. 3, Plate XXX: shows gently undulating character of cartilage surface, with tertiary prominences caused by underlying chondrocytes. No comment made on nature of surface.
LEIDY (1849)	Free surface is 'very smooth and shining'. (One of the most perceptive observers: Leidy demonstrated that cartilage, contrary to Hunter's view, is not covered by synovial membrane).
REDFERN (1849)	Secondary surface undulations are (probably) illustrated without comment.
REICHERT (1849)	No reference to cartilage surface except in relation to problem of whether surface is covered with synovial membrane.
TOYNBEE (1849)	Semi-diagrammatic drawings show absolutely smooth articulating surfaces. Perpetuates belief that synovial membrane covers cartilage.
REDFERN (1850)	Approximately 100-200 μm . surface prominences, 30 μm . high, are shown 'at a dimple-like depression', on surface of internal glenoid cavity.
DUNCAN (1855)	No comment on structure of normal cartilage surface.
LUSCHKA (1855)	Fig. 2 depicts beautiful shallow surface undulations.
HOLDEN (1857)	Crude illustrations of probable secondary surface undulations. No comment.
KÖLLIKER (1860)	No detailed description of cartilage surfaces. Drawings uninformative.
HUETER (1866)	Preoccupied with distribution of cartilaginous blood vessels; no comment on surface structure.
BUBNOFF (1868)	No reference to details of surface structure.
GOODSIR (1868)	No comment on smoothness of surfaces which 'perform maximum function with minimum of contact'.
HUETER (1870)	Describes joint surface as 'regelmässig glatt', micro- and macroscopically.
HEITZMANN (1872)	In survey based on thin sections, shows that ramifications of fine cell processes extend out into cartilage matrix. No comment on surface structure.
REYHER (1874)	Cartilage cell processes described in three dimensions without reference to articulating surfaces.
TILLMANS (1874)	Drawings of indifferent quality, devoid of information relevant to cartilage surfaces. Controversy over nature of lining of joint capsule.
OGSTON (1875)	A drawing of a healthy adult astragalus shows a faintly undulating surface. Similar undulations shown on surface of normal cartilage of tibia from boy aged 10 years.
RANVIER (1875)	No comment on nature of joint surface.
BUDGE (1877)	No reference to surface structure.
NYKAMP (1877)	Attempts to demonstrate lymphatic channels.
TILLMANS (1877)	Entirely concerned to show that cartilage has a fibrillary structure, without reference to its surface.
WEICHELBAUM (1877)	Discusses normal structure of articular cartilage and synovium.
ZIEMSEN (1877)	No comment on articular cartilage surfaces.
SCHLEICHER (1878)	Discussion of division of cartilage cells.
BIGELOW (1879)	Speculation on cell division in cartilage.
BRAUN (1895)	Drawings show no surface undulations.
HAMMAR (1894)	Drawings of sections of articular cartilage almost invariably show tertiary surface prominences corresponding to location of superficial chondrocytes. Stated: 'the joint surface is never smooth but is frequently covered with shallow depressions'.
AXHAUSEN (1923)	Shallow, secondary undulations shown in drawings of abnormal surfaces.
BENNINGHOFF (1925)	With aid of polarized light, showed tangential surface arrangement of fibres.
HEINE (1926)	In this classical account of osteoarthritis, no comment made on lack of smoothness of normal surface structure.
POMMER (1927)	In a lengthy account of osteoarthritis, normal cartilage surfaces are not illustrated. Secondary prominences are illustrated on abnormal surfaces.
SCAGLIATTI (1930)	Effects of local pressure on joint surfaces. No description of normal structure.
SCHAEFFER (1930)	Illustrates gently undulating surface of cartilage in the cyclostome <i>Ammocoetes</i> and in <i>Myxine</i> . Cartilage surface undulations are not confined to vertebrates.
COLLINS (1949)	No comment on surface structure.

- BARNETT, DAVIES, AND MACCONAILL (1961) Articular cartilage smooth and glistening.
- CRUICKSHANK, DODDS, AND GARDNER (1968) Tertiary undulations shown photographically, but not described, on surface of articular cartilage sections.
- DAVIES (1969) Cartilage surfaces described as 'strikingly smooth'.
- GARDNER AND WOODWARD (1969) Tertiary surface undulations shown by scanning electron and by incident light microscopy.
- INOUE, KODAMA, AND FUJITA (1969) Tertiary undulations described on human cartilage surfaces by scanning electron microscopy.
- WALKER, SIKORSKI, DOWSON, LONGFIELD, WRIGHT, AND BUCKLEY (1969) Tertiary undulations shown by scanning electron microscopy.

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