Review

The menisci of the knee joint. Anatomical and functional characteristics, and a rationale for clinical treatment

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ABSTRACT

The menisci and their insertions into bone (entheses) represent a functional unit. Thanks to their firm entheses, the menisci are able to distribute loads and therefore reduce the stresses on the tibia, a function which is regarded essential for cartilage protection and prevention of osteoarthrosis. The tissue of the hypocellular meniscal body consists mainly of water and a dense elaborate type I collagen network with a predominantly circumferential alignment. The content of different collagens, proteoglycans and nonproteoglycan proteins shows significant regional variations probably reflecting functional adaptation. The meniscal horns are attached via meniscal insertional ligaments mainly to tibial bone. At the enthesis, the fibres of the insertional ligaments attach to bone via uncalcified and calcified fibrocartilages. This anatomical configuration of gradual transition from soft to hard tissue, which is identical to other ligament entheses, is certainly essential for normal mechanical function and probably protects this vulnerable transition between 2 biomechanically different tissues from failure. Clinical treatment of meniscal tears needs to be based on these special anatomical and functional characteristics. Partial meniscectomy will preserve some of the load distribution function of the meniscus only when the meniscal body enthesis entity is preserved. Repair of peripheral longitudinal tears will heal and probably preserve the load distribution function of the meniscus, whereas radial tears through the whole meniscal periphery or more central and complex tears may be induced to heal, but probably do not preserve the load distribution function. There is no proof that replacement of the meniscus with an allograft can reestablish some of the important meniscal functions, and thereby prevent or reduce the development of osteoarthrosis which is common after meniscectomy. After implantation, major problems are the remodelling of the graft to inferior structural, biochemical and mechanical properties and its insufficient fixation to bone which fails to duplicate a normal anatomical configuration and therefore a functional meniscal enthesis.

Key words: Cartilage; bone; entheses; meniscus repair.

INTRODUCTION

The discovery 50 y ago that removal of a meniscus in the knee joint led in the long term to development of cartilage degeneration and bone remodelling (Fairbank, 1948) changed substantially the therapeutic approach to this common work or sports injury. Hence, today a ruptured meniscus is repaired rather than removed, but this treatment is only feasible when the meniscus tissue is otherwise of good quality. In the more frequent cases with irreversible damage of meniscal tissue, partial instead of total meniscectomy is the treatment of choice to minimise loss of this important anatomical structure. The growing knowledge during recent decades about the physiological functions of the knee joint menisci such as load transmission, joint stabilisation, lubrication and sensory function even led to the concept of replacing the meniscus when it was irreversibly damaged (Milachowski et al. 1989). Fifteen years have now passed since partial meniscectomy and repair were introduced as a treatment alternative to...
total meniscectomy (Gillquist et al. 1982; Hamberg et al. 1983) and it is 9 y since the first clinical report on meniscal transplantation was published (Milachowski et al. 1989). In the meantime knowledge as to the physiological characteristics of knee joint menisci has advanced, but these advances have not been reflected in further adjustment of clinical therapy. On the contrary, we still have little evidence that the previous ‘advances’ in therapy are genuinely superior to the earlier methods with complete removal of the meniscus (Rockborn & Gillquist, 1996). In this review, we will summarise what is currently known about the gross morphology of the meniscus, its functional anatomy and joint biomechanics, the cellular and matrix composition of meniscal tissue including blood supply and innervation, and finally its mechanical properties. The relevance of these basic characteristics to clinical treatment of meniscal lesions will be discussed.

**Gross Anatomy**

The knee joint menisci are a pair of wedge shaped semilunar cartilages which are interposed between the femoral condyles and tibial plateaux (Fig. 1a). They measure approximately 35 mm in diameter (Warren et al. 1986), and are attached to the joint capsule by their thick convex-shaped peripheral rim, which has a length of ~110 mm including the length of the insertional ligaments (Kohn & Moreno, 1995). The anterior and posterior meniscal horns are firmly attached to bone via insertional ligaments. In the rabbit, the insertional ligaments are easy to differentiate from the tissue of the meniscal horn by a distinct change in tissue stiffness on palpation (Gao et al. 1994) (Fig. 1b). We will distinguish between the meniscal body including the horns, the anterior and posterior insertional ligaments, and finally their attachment to bone, which we term meniscal entheses (Fig. 1a, b). The firm attachment to bone at their anterior and posterior entheses is regarded decisive for the load distributing function of the menisci (Gao et al. 1994; Gao & Messner, 1996a). In man, the anterior insertional ligament of the medial meniscus is a flat fan-shaped structure which inserts to the tibial plateau at the anterior intercondylar fossa (area intercondylaris anterior), ~6–7 mm anterior to the enthesis of the anterior cruciate ligament (Johnson et al. 1995; Kohn & Moreno, 1995) (Fig. 1a). Its posterior or upper fibres were found to blend in 64% of the cases with the fibres of the transverse ligament (Kohn & Moreno, 1995), which connects the anterior horns of the medial and lateral menisci. The posterior insertional ligament of the medial meniscus attaches to the posterior intercondylar fossa (area intercondylaris posterior) of the tibia between the posterior enthesis of the lateral meniscus and the tibial enthesis of the posterior cruciate ligament. The anterior insertional ligament of the lateral meniscus attaches to the anterior intercondylar fossa of the tibia, anterior to the lateral intercondylar eminence (tuberculum intercondylare laterale) just behind the tibial enthesis of the anterior cruciate ligament. Part of its fibres blend with them of the anterior cruciate ligament. The posterior insertional ligament of the lateral meniscus attaches to the tibia posterior to the lateral intercondylar eminence anterior to the posterior enthesis of the medial meniscus. In 50% of the cases, the anterior fibres of the posterior insertional ligament of the lateral meniscus were found to insert to the intercondylar fossa (area intercondylaris) of the medial femoral condyle anterior to the origin of posterior cruciate ligament forming the anterior meniscofemoral ligament (Humphrey, 1858; Kohn & Moreno, 1995; Wan & Felle, 1995). A posterior meniscofemoral ligament (Wrisberg ligament) was found in around 76% of cadaveric material (Last, 1948; Kohn & Moreno 1995; Poynton et al. 1997). It is formed by the posterior fibres of the posterior insertional ligament of the lateral meniscus which attach to the intercondylar fossa of the medial femoral condyle, posterior to the origin of the posterior cruciate ligament. Lateral discoid menisci with complete absence of a tibial enthesis of the posterior insertional ligament have been described in man. In these cases the posterior insertional ligament attached solely to the femur via the Wrisberg ligament (Watanabe, 1974). The area of enthesis of the anterior insertional ligament of the medial meniscus was found to be consistently larger (1.3–1.7 times) than that of the posterior ligament (Johnson et al. 1995; Kohn & Moreno, 1995). Reports on the proportions of the insertional areas of the lateral meniscus are more controversial. Kohn & Moreno (1995) found the area of the anterior enthesis of the lateral meniscus to be 1.2 times smaller than the posterior, which was in contrast to Johnson et al. (1995) who found it 1.5 times larger than the posterior one. A larger insertional area may reflect a more oblique angle of attachment to bone (Benjamin et al. 1986), but it may also be indicative for a stronger attachment. In the rabbit we found the anterior insertional ligament of the medial meniscus to be ~1.5 times stronger than the posterior one during tensile testing to failure, but we did not measure the insertional area (Gao et al. 1996b; Goertzen et al. 1996). However, the size of the
insertional area alone without knowledge as to
insertional angle and collagen density does not give
any conclusive information about the size and strength
of the attached structure.

Knee joint menisci are found in all mammals and
also in other types of animals, but their shape and
insertional anatomy vary considerably. In the rabbit
knee, the medial and lateral menisci have long anterior
insertional ligaments which pass each other and attach
to the anterior aspect of the lateral and medial tibial
plateau, respectively (Fig. 1b). A transverse ligament
was lacking in the rabbit knee (Gao et al. 1994). The
posterior insertional ligament of the lateral meniscus
in the rabbit attaches solely to the medial femoral
condyle, posterior to the origin of the posterior
cruciate ligament. Any connecting fibres to the tibia
are missing. Both rabbit menisci have prominent
anterior horns and a narrower central meniscal body.
In man, the anterior horns of both menisci are narrower and the meniscus becomes wider posteriorly (Fig. 1a). In the rat, over and above differences in shape, proportions and anatomical location compared with man, menisci develop central ossicles. These differences in anatomical characteristics between different animals and man reflect certain major differences in limb use and joint biomechanics, and therefore limit the validity of animals models. In addition to rabbit menisci (Ghadially et al. 1978; Moon et al. 1982; Webber et al. 1985; Gao et al. 1994; and others), canine (O’Connor, 1976, 1984; Adams & Muir 1981; and others), ovine (Ghadially et al. 1986; Swiontkowski et al. 1988; and others) and bovine menisci (Cheung 1987; Proctor et al. 1989; Skaggs et al. 1994; and others) have frequently been investigated. Most experiments concern the medial meniscus (Sommerlath & Gillquist, 1992, 1993a, b; Roeddecker et al. 1993; Jitsuiki et al. 1994; Messner, 1994; Gao & Messner, 1996a, b; Gao et al. 1998), probably because degenerative tears of the medial meniscus are common in clinical practice, and the rate of osteoarthrosis is high after medial meniscectomy (Appel, 1970).

Clark & Ogden (1983) showed that both menisci in man already assumed their characteristic shapes within the first 4 mo of gestation. They also found that the lateral meniscus covered ~80% of the corresponding tibial plateau and the medial one ~60%, the proportions of which remained constant throughout growth. The most common congenital abnormality of the meniscus in man is a discoid meniscus with a frequency of 1.5–4.6% for the lateral (Smillie, 1948), and 0.3% for the medial one (Nathan & Cole, 1969).

**FUNCTIONAL ANATOMY AND JOINT BIOMECHANICS**

The incongruency between the semicircular shaped femoral condyles and comparably flat tibial plateau are adapted by the concave upper meniscal surface facing the former, and the lower, flat meniscal surface facing the latter. The contact area in the femorotibial joint thereby increases significantly, and the stresses on tibial cartilage are reduced (Kettelkamp & Jacobs, 1972; Walker & Erkman, 1975). In a loaded, in vitro situation, 70% and 50% of the loads in the lateral and medial compartments, respectively were transmitted though the corresponding menisci (Fukubayashi & Kurosawa, 1980; Kurosawa et al. 1980; Ahmed & Burke, 1983; Chen et al. 1996), reflecting their proportion of coverage of the respective compartment (Clark & Ogden, 1983). After removal of the menisci, contact areas in the femorotibial joint were largely reduced and the peak stresses on tibial cartilage considerably increased (Kettelkamp & Jakobs, 1972; Fukubayashi & Kurosawa, 1980; Kurosawa et al. 1980; Paletta et al. 1997). The above described load distributing function of the menisci is made possible by their strong anterior and posterior entheses to bone which prevent the wedge shaped menisci from extruding from the joint during axial loading. Joint loading will tension the insertional ligaments and also the circumferential fibres of the meniscus. Thus part of the axial load will be transformed into hoop stresses at the meniscal periphery. Theoretically, a radial transection through the entire meniscal body or insertional ligaments will completely disable the load distribution function of the meniscus (Seedhom & Hargreaves, 1979) (Fig. 2). In accordance, transection of the anterior and posterior insertional ligaments in vitro results in a similar stress increase on the tibial plateau as does complete meniscectomy (Paletta et al. 1997). We noted 6–12 wk after transection of either the anterior or posterior medial meniscal insertional ligaments similar osteochondral changes as are commonly found after complete resection of the menisci in a rabbit model.
fusiform cells are found in the superficial layer of human meniscal tissue, which are aligned parallel to the surface. The cells in deeper layers have an ovoid or polygonal shape (Ghadially et al. 1978). The cells in the superficial layers resemble fibroblasts, but also have similarity to chondrocytes from the superficial layers of articular cartilage. In man, cell morphology does not differ between peripheral and central locations in the meniscal body (Ghadially et al. 1978). In contrast, in the rabbit meniscus, the cells in the central region resemble chondrocytes more closely and those in the periphery, fibrocytes (Moon et al. 1982; Bland & Ashhurst, 1996).

The meniscal body consists predominantly of a dense framework of coarse type I collagen fibres, the main orientation of which is circumferential. Radial fibres are found throughout but are less numerous. These latter may act as a ‘tie’ holding the circumferential fibres together, thereby resisting longitudinal splitting of the menisci (Bullough et al. 1970; Merkel, 1980; Beaupré et al. 1986; Ghosh et al. 1987). The collagens are heavily crosslinked by hydroxylpyridinium aldehydes (Eyre & Wu, 1983). Type I collagen accounts for over 90%, and types II, III and V collagens for the remaining meniscal tissue collagens (Eyre & Wu, 1983; McDevitt & Webber, 1990). The distribution of the different collagens shows significant regional variations. Except for trace amounts (< 1%) of types III and V collagens, the peripheral two-thirds of bovine menisci consist solely of collagen type I, whereas type II collagen (60%) predominated over type I collagen (40%) in the inner third (Cheung, 1987). Throughout development and adulthood, types III and V collagens are predominantly found pericellularly and in meniscal surface layers (Eyre & Wu, 1983; Bland & Ashhurst, 1996). A matrix containing types I, III and V collagens is found as early as at 25 d in the rabbit fetus, but only at 3 wk postnatally the menisci also contain collagen type II, the content of which increases with further maturation (Bland & Ashhurst, 1996). Apparently, appearance of collagen type II is associated with the increase in joint loading during postnatal development. The amount of collagens and noncollagen proteins is less at sites of meniscal tissue degeneration which may account for the inferior mechanical quality of this tissue (Ingman et al. 1974; Herwig et al. 1984).

Normal human meniscal proteoglycans contain ~ 40% chondroitin 6 sulphate, 10–20% chondroitin 4 sulphate, 20–30% dermatan sulphate, and 15% keratan sulphate (Herwig et al. 1984), the proportions of which are maintained under tissue culture conditions by a corresponding glycosaminoglycan pro-
duction (Verbruggen et al. 1996). Nakano et al. (1997) recently reported significant regional variations in the distribution of different glycosaminoglycans in bovine menisci. In dry weight, the inner third of the meniscal body contains ~76% collagen and 8% glycosaminoglycans, and its peripheral third 93% collagen and only 2% glycosaminoglycans. Chondroitin sulphate is the most abundant, and accounts for ~80% of total glycosaminoglycans in the inner third, and 50–56% in the peripheral third. Dermatan sulphate is the second most abundant glycosaminoglycan. The ratio dermatan/chondroitin sulphate was found to be 1:5–1:6 in the inner third of the meniscal body and 1:1.5 in the peripheral third. Hyaluronic acid accounted for 4–5% of the total glycosaminoglycan content in the inner third, and for 10% in the peripheral third. Aggrecan has been found to be a major proteoglycan in adult bovine menisci. Its biosynthesis and accumulation begins in meniscal tissue and insertional ligaments during fetal development (Koob et al. 1995). Meniscal tissue explants from inner and middle zones produce predominantly aggrecan like proteoglycans under culture condition, but also smaller proteoglycans. Explants from peripheral zones produce in general less proteoglycan and, preferentially, smaller ones (Collier & Gosh, 1995). Biglycan and fibromodulin were found in higher amounts in the inner and middle than in the peripheral zones of pig menisci, whereas decorin showed the reverse order (Nakano et al. 1997; Scott et al. 1997). The amount of uronic acid, hexosamine and hydroxyproline (Nakano et al. 1986) is 2–4 times higher in the inner third than in the peripheral third of the porcine meniscus. The apparent regional distribution of proteoglycans certainly reflects the tissue adaption to local loads, which is even maintained under tissue culture conditions. Specific proteoglycans (aggrecan, biglycan, fibromodulin) seem to accumulate in the inner compressed region of the meniscus.

**FINE MORPHOLOGY OF MENISCAL ENTHESES AND INSERTIONAL LIGAMENTS**

The circumferential collagen fibres of the meniscal body continue into the anterior and posterior insertional ligaments and finally attach to subchondral bone via uncalcified and calcified fibrocartilages (Aspden et al. 1985; Benjamin et al. 1991; Gao et al. 1994) (Fig. 3a, b). The continuity of fibres between the meniscal body and its entheses to bone certainly guarantees an effective fixation to bone, and enables transformation of axial loads into hoop stresses during joint loading (Fairbank, 1948; Shrive et al. 1978). The tensile strength of the meniscal insertional ligaments may be indicative of the physiological loads to which they are subjected. In the rabbit we found their tensile strength in the range of 3–4 times body weight (Goertzen et al. 1996; Gao et al. 1996b). We also found significant differences in ultimate strength between the different insertional ligaments. The anterior insertional ligament of the lateral meniscus was stronger than that of the medial (Goertzen et al. 1996). The latter was stronger than its posterior counterpart (Gao et al. 1996b). This could indicate that the insertional ligaments of the lateral meniscus are subjected to higher tensile forces than the medial ones, and the anterior to higher loads than the posterior. Comparable mechanical data are lacking for man. However, morphological features may to some degree reflect the amount of physiological loading. It has been suggested that the thickness of calcified tissue under articular cartilage surfaces or under an enthesis may be positively related the loads to which the structure is subjected (Evans et al. 1991; Milz & Putz, 1994). Benjamin et al. (1991) showed in man a thicker layer of cortical calcified tissue in the anterior enthesis of the lateral than that of the medial meniscus. They explained these differences by the fact that the anterior insertional ligament of the former blend with the fibres of the anterior cruciate ligament and that higher forces are probably transmitted through this site than the latter. However, the larger amounts of calcified tissue in the enthesis of the anterior insertional ligament of the lateral meniscus may also mean that it is physiologically subjected to higher loads than the medial one, and therefore that it is stronger, similar to the findings in the rabbit (Goertzen et al. 1996). The lateral meniscus in man also covers more of the tibial plateau and transmits a higher percentage of load than the medial one (Walker & Erkman, 1975; Clark & Odgen 1983). In the rabbit, the amount of calcified cartilage in the meniscal entheses increases with maturation as a possible sign of increased strength of the insertional ligaments (Gao et al. 1994). The calcified fibrocartilage in the meniscal entheses interdigitates with the bone at different angles and depth similar to other ligament entheses (Gao et al. 1996a) (Fig. 3a, b). This irregular interface increases the contact area between these 2 tissues and probably the resistance to separation at this site (Schneider, 1956). Thus the amount of interface at an enthesis might be related to the strength of the attached structure. However, no differences in inter-digitation frequency and depth were found between anterior and posterior entheses of the rabbit medial meniscus despite the apparent difference in tensile
strength between the insertional ligaments (Gao & Messner, 1996b; Goertzen et al. 1996; Gao, 1997).

We also identified differences in the fine morphology between the anterior and posterior insertional ligaments of the rabbit medial meniscus (Gao et al. 1994). The anterior insertional ligament had a typical ligamentous structure with longitudinally arranged collagen fibres and small fusiform cells aligned in rows similar to the fibrocytes in ligaments. This ligamentous structure inserted to tibial bone via uncalcified and calcified fibrocartilages. In contrast, the posterior insertional ligament resembled meniscal fibrocartilage with a lesser alignment of collagen fibres and the presence of more rounded cells. It also attached via uncalcified and calcified fibrocartilage to bone, but a distinct difference between the insertional ligament and the uncalcified cartilage of its enthesis was not identified (Fig. 3a, b). We interpreted the morphological differences between the 2 insertional ligaments in terms of their different anatomical location and loading conditions. The anterior insertional ligament is located in front of the joint away from compressive forces and probably mainly loaded under tension which readily explains its solely ligamentous character. In contrast, the posterior one is placed more centrally within the area of contact between the femoral condyle and tibial plateau, and is probably loaded both under tension and compression which may explain its fibrocartilaginous character. We also showed later that transection of the posterior insertional ligament resulted in a healing tissue with fibrocartilaginous character whereas transection of the anterior one was followed by a scar resembling ligamentous tissue (Gao & Messner, 1996a). Furthermore, at tensile load to failure testing we demonstrated that the anterior insertional ligament in the rabbit was about 1.5 times stronger than the posterior (Goertzen et al. 1996). These marked differences in tensile strength between 2 insertions at opposite ends of the same structure may be explained by the fact that the anterior one is solely subjected to tension during joint loading whereas the posterior is at the same time subjected to tensile and compressive forces. Simultaneous compression may reduce the amount of tensile load in the tissue.

The insertional fibrocartilage may make the dramatic changes in stiffness between ligament and bone tissue at the enthesis less sudden and therefore reduce the stress concentration in this unit and prevent failure. It may also diminish the risk for fatigue failure.

Fig. 3. Anterior and posterior entheses of the medial meniscus of the rabbit knee joint. (a) Four different tissues are identified in the enthesis of the anterior insertional ligament of the medial meniscus: ligament, uncalcified and calcified fibrocartilage, and bone. (b) In the enthesis of the posterior insertional ligament, ligamentous tissue is lacking. Note the deep interdigitations between calcified cartilage and bone (arrows). LT, ligamentous tissue; UF, uncalcified fibrocartilage; CF, calcified fibrocartilage; B, bone. Alcian blue/periodic acid Schiff. Bar, 0.1 mm.
during motion by making the transition between soft tissue and bone more gradual (Schneider, 1956). Accordingly, the amount of calcified or uncalcified fibrocartilage in an enthesis has been related to the mobility of the attached structure (Benjamin et al. 1991; Gao & Messner, 1996). Benjamin et al. (1991) found larger amounts of uncalcified fibrocartilage in the entheses of the lateral than the medial meniscus in man and explained these differences by the documented higher mobility of the former during joint motion (Thompson et al. 1991).

Meniscal entheses in the rabbit contained mainly types I and II collagen similar to other ligament and tendon entheses (Rufai et al. 1992; Gao et al. 1996a, 1998). Type I collagen was found throughout and type II collagen was restricted to the fibrocartilages of the entheses (Gao et al. 1998) (Fig. 4a, b).

**BLOOD SUPPLY**

Blood vessels could be identified in the peripheral third of the menisci around the wk 22 of gestation in man (Petersen & Tillmann, 1995). At birth, almost the entire meniscus was vascularised. In the second year of life an avascular area developed along the central margins of the menisci. The insertional ligaments were vascularised, but not the fibrocartilages in the enthesis (Petersen & Tillmann, 1995). Vascular supply to the menisci is provided by the lateral and medial geniculate arteries which form a perimeniscal capillary plexus with radial branches directed towards the centre of the joint (Arnoczky & Warren, 1982). In the adult, the degree of vascular penetration from the periphery was 10–30% of the width of the medial meniscus and 10–25% of that of the lateral meniscus. The anterior and posterior horns of the menisci are more vascularised than their bodies (Arnoczky & Warren, 1982; Danzig et al. 1983; Day et al. 1985; Swiontkowski et al. 1988).

**INNERVATION**

Innervation to the menisci arises mainly from the posterior articular nerve, but part of the innervation of the medial meniscus is provided by branches of the medial articular nerve (Freeman & Wyke, 1967). There is general agreement that the nerve supply to
menisci is more extensive in the horns than the body (Day et al. 1985) similar to vascularisation, but reports vary as to whether any nerves at all are present in the latter. O’Connor & McConnaughey (1978) demonstrated a rich neurovascular supply, including types I and II mechanoreceptors, in the meniscal horns in the cat, but could not detect any nerves in the body. In a later paper, O’Connor (1984) described a further 2 different type II receptors, and less commonly type III receptors at the transitional zone between the posterior horn of the canine lateral meniscus and its insertional ligament. Similarly, Kennedy et al. (1982) found abundant axons, large nerve bundles, free nerve endings, and specialised receptors including complex end bulbs and Golgi-type (type III endings) in perimeniscal capsular tissue, but not extending into the meniscal body. In contrast, Wilson et al. (1969) reported both myelinated and unmyelinated nerve fibres in the human medial meniscus that extended from a periarthritic plexus onto the meniscus as far as its intermediate third of the body. These neural elements were not exclusively paravascular. Also Albright et al. (1987) showed nerves penetrating from the perimeniscal tissue into the peripheral and middle third of the meniscal fibrocartilage, especially near to the horns. They comprised all 3 types of encapsulated end organs (types I–III) and free nerve endings (type IV). Assimakopoulos et al. (1989) found the encapsulated mechanoreceptors types I–III restricted to meniscal horns and free nerve endings throughout the meniscal body except for its inner third, but they did not examine the innervation of the meniscal insertional ligaments. More recently, Biedert et al. (1992) described free nerve endings in the meniscofemoral ligaments of Humphry and Wrisberg, and the meniscal transverse ligament, the density of which was similar to that in the patellar tendon. The number of nerve endings was found to be decreased in older age (Assimakopoulos et al. 1989). These somewhat controversial reports regarding distribution of different nerve endings in the meniscal body may be caused by the use of different classifications of anatomical regions. However, it is evident that encapsulated end organs with mechanoreceptor function predominate at the horns and attachment structures, and that free nerve endings are found throughout except for the inner third of the meniscal body. Nerve fibres carrying substance P, calcitonin gene related peptide, protein gene product 9.5 and synaptophysin immunoreactive type IVa and IVb nerve fibres have been identified near meniscal enthesis and their capsular attachment (Grönlad et al. 1985; Hukkanen et al. 1992; Iwasaki et al. 1995). Nerve filaments were further detected in the uncalcified and calcified fibrocartilages and the subchondral bone in both entheses of the rabbit medial meniscus (Gao et al. 1994). The menisci without doubt have a sensory function, and especially their horns and insertional ligaments may provide important proprioceptive information related to joint position.

MECHANICAL PROPERTIES OF MENISCAL TISSUE

Meniscal tissue, similar to other joint soft tissues, has viscoelastic material properties. Meniscal tissue has been tested under compression, uniaxial tension and pure shear forces (Brantigan & Voshell, 1941; Bullough et al. 1970; Fithian et al. 1989; Proctor et al. 1989; Chern et al. 1990; Anderson et al. 1991; Hacker et al. 1992; Newton & Mow, 1992; Skaggs et al. 1994; Zhu et al. 1994; Tissakht & Ahmed 1995). Under all test conditions, meniscal tissue properties have been found anisotropic and inhomogeneous, that is that they vary with different sampling direction and different locations of the samples.

Meniscal tissue is considerably softer and less permeable than articular cartilage (Woo et al. 1987). Several authors reported differences in compressive and tensile stiffness in human and bovine menisci dependent on location and specimen orientation (Fithian et al. 1989; Proctor et al. 1989; Skaggs & Mow, 1990). During confined compression, specimens taken from deep zones of the posterior third of the meniscus were stiffer than corresponding specimens from the anterior third (Proctor et al. 1989). Significant variations in tensile stiffness were found between circumferentially oriented specimens from anterior, central and posterior regions, especially when the deeper tissue zones were investigated (Proctor et al. 1989). Proctor et al. (1989) demonstrated further that circumferential specimens were 3–4 times stiffer in deeper zones than specimens taken near to the surface, but in radial specimens the situation was the reverse. Radial specimens from the posterior regions were stiffer than those from anterior regions, which coincided with a larger number of radially oriented collagen fibres in posterior than anterior regions (Skaggs & Mow, 1990). In general, circumferentially oriented specimens, parallel to the predominant collagen fibre direction, were stronger than radially oriented specimens (Proctor et al. 1989; Skaggs & Mow, 1990). Only specimens from the meniscal surface behaved isotropically in tension without a major variation in stiffness dependent on orientation and location (Proctor et al. 1989). These
considerable, site-specific variations in mechanical properties of meniscal tissue are certainly a mirror-image of the physiological loads to which the structure is subjected, and thus demonstrate that the menisci are not loaded uniformly.

Goertzen et al. (1996) tested the ultimate load to failure of the anterior and posterior insertional ligaments in adolescent rabbits. They found the anterior insertional ligament of the lateral meniscus to break at mean of 158 N, the anterior insertional ligament of the medial meniscus to rupture at 108 N and the posterior one at 75 N. If these loads reflect physiological loads, this would mean that meniscal ligaments are subjected to very high loads. This would also explain why it seemed impossible to fix a meniscal substitute without elongation or rupture of the insertional ligaments (Gao et al. 1998). In adult rabbits, the ultimate load to failure was even found to be somewhat increased for both insertional ligaments of the medial meniscus compared with adolescent animals (Gao et al. 1996b; Goertzen et al. 1996). The anterior insertional ligament failed mostly by a mid-substance rupture, the posterior at its transition into the meniscal horn, but none failed at the enthesis (Gao et al. 1996b). The differences in ultimate load and failure mode of insertional ligaments at the opposite ends of the same structure may be caused by their different morphology as mentioned earlier (Gao et al. 1994).

The meniscal tissue properties under shear loading were frequency dependent, anisotropic, and inhomogeneous (Anderson et al. 1991; Zhu et al. 1994). The magnitude of the shear modulus increased with frequency and was greatest in specimens from the posterior surface region, when the shear test was performed parallel to the main fibre orientation. At low strain rates the shear modulus of circumferential specimens was greater than that of radial and axial specimens (Chern et al. 1990).

RATIONAL FOR PARTIAL MENISCETOMY

According to in vitro studies the increase in peak stresses on the tibial plateau after removal of meniscal tissue was directly correlated with the amount of tissue removed (Burke et al. 1978). This would mean that the less the resection of meniscal tissue (without leaving unstable parts which may give rise to symptoms), the better the mechanical situation of the joint after partial meniscectomy. On the other hand, according to Seedhom & Hargreaves (1979) solely transecting around the whole periphery of the meniscus or one of the insertional ligaments without removal of any tissue would lead to a complete loss of the load distribution function of the meniscus. We also showed in a rabbit experiment that transection of the anterior or posterior insertional ligaments of the meniscus led to osteochondral changes after 6 and 12 wk similar to meniscectomy (Sommerlath & Gillquist, 1992; Gao & Messner, 1996a). Removal of increasing amounts of tissue from the central part of the meniscal body without compromising the meniscal periphery or insertional ligaments resulted in a successive increase of peak stresses on the tibial plateau (Burke et al. 1978). However, the latter situation is solely encountered in a clinical case of central longitudinal rupture. Here, only the loose central part of the meniscal body needs to be removed and the resection does not reach the meniscal periphery, insertional ligaments or entheses. On the contrary, in the more frequent case of extensive tear or damage of the posterior horn, the risk of completely cutting through the whole of the meniscal periphery or insertional ligament in order to resect all damaged tissue, is high. If the meniscus is cut through its periphery, its load distribution function will probably be completely disrupted (Seedhom & Hargreaves, 1979; Paletta et al. 1997), despite the fact that most of the meniscal body (central region and horns) remains intact. Such a partial meniscectomy probably results in a similar increase of peak stresses on the tibial plateau and therefore a potential risk of the joint developing osteoarthritis. Part of the so-called ‘partial meniscectomies’ are thus in reality total ones, and this may also explain why the reduction in radiographic osteoarthritis after partial meniscectomy was not as large as expected (Rockborn & Gillquist, 1996). This potential risk of a partial meniscectomy to result functionally into a total one has been completely disregarded in clinical practice, probably because it is impossible by visual control under arthroscopy to judge the extent of meniscal resection. Any functional tests during operation to control the load distributing function of the remaining meniscus are not available. Therefore, we still do not know in the individual case today if the so called advancement in therapy using partial instead of total meniscectomy really means improvement of the long term prognosis of knee function.

RATIONAL FOR MENISCAL REPAIR

Ideally, meniscal repair should result in healing of the tear and reestablishment of normal meniscal functions. Tears in the vascularised zone in the peripheral third of the meniscus body heal similarly as
for other vascular tissues (King, 1936; Heatley, 1980; Cabaud et al. 1981; Arnoczky & Warren, 1983). The initial formation of a haematoma and fibrin clot in the gap acts as a scaffold for ingrowth of vessels from the perimisical capillary plexus. The vascular ingrowth is accompanied by migration and proliferation of undifferentiated mesenchymal cells. Eventually, the lesion becomes filled with a highly cellular fibrovascular scar tissue. Final remodelling of this scar tissue required several months until it acquired a meniscus tissue like shape. Newman et al. (1989) showed complete repair of a longitudinal incision in the vascularised zone of the rabbit medial meniscus at 13 wk, and the joint surfaces did not show the degenerative changes which are otherwise common in a rabbit joint with a nonfunctional or removed meniscus (Sommerlath & Gillquist, 1992; Gao & Messner, 1996a). Both in in vitro and in vivo investigations, a joint with a sutured (and healed) peripheral, longitudinal meniscal incision had similar stiffness and contact areas as a sham operated joint under loading (Baratz et al. 1986; Newman et al. 1989). The clinical experience with this type of tear is usually good. Repair of peripheral, longitudinal tears show a high frequency of healing and good functional results (Hamberg et al. 1983; DeHaven et al. 1989; DeHaven & Arnoczky, 1994; Perdue et al. 1996). It also seems that a once healed meniscal tear remains as stable as an initially intact meniscus (Sommerlath, 1988; Sommerlath & Hamberg, 1989). In a 7 y perspective this type of operation resulted in a reduced frequency of radiographic knee joint changes indicative of early osteoarthrosis than partial meniscectomy (Sommerlath, 1991). Nevertheless, in a 13 y perspective, even knees with successful repair developed in some cases discrete bone changes in radiographs (Messner & Rockborn, 1998, unpublished data). The initial trauma to the knee joint surfaces may have given rise to these changes. Another reason may be that a repaired meniscus does not function as well as a normal one due to scar tissue formation.

In contrast to tears located in the vascularised zone, the more frequently encountered ruptures in the avascular zone heal poorly (King, 1936; Henning et al. 1990; Tenuta & Arciero, 1994). Because of the obvious advantages of meniscal repair many efforts have been made to improve the healing of tears in these regions. Longitudinal incisions in the nonvascularised portion of the meniscus were successfully induced to heal by connecting the lesion to peripheral vasculature by ‘vascular access channels’, which resulted in a similar healing process as described for tears in the vascular region (Arnoczky & Warren, 1983; Gershuni et al. 1989; Zhang et al. 1995). For this procedure, a major radial split through the peripheral third of the meniscus to create the channel should be avoided to minimise damage of the circumferential collagen framework, which is a prerequisite for normal meniscal function. Another possibility for improving healing in avascular tears is the use of free synovium (Jitsuiki et al. 1994; Shirakura et al. 1997) or a synovial pedicle flap (Veth et al. 1983; Ghadially et al. 1986; Kobuna et al. 1995), which is sutured directly or through a tunnel into the lesion. Use of fibrin clot alone (Arnoczky et al. 1988) or together with endothelial cell growth factor (Hashimoto et al. 1992) or autogenous precultivated stem cells (Port et al. 1996) and even implantation of porous polymers (Klompmaker et al. 1991, 1992, 1996) did improve the healing response of experimentally created lesions in the avascular region of the meniscus. However, the strength of the scar tissue which was measured after use of fibrin clot and stem cells only achieved 40% of normal within 4 mo after implantation (Port et al. 1996). Thus there is no doubt that tears in the avascular lesion can be made to heal with various methods, although the healing frequency for this type of lesion is clinically lower than after repair of more peripherally located tears (Hamberg et al. 1983; Henning et al. 1990). However, it is doubtful whether repair of these tears reestablishes normal meniscal function. The repair enhancing methods described above make it possible to repair tears of all kinds and even suture back loose fragments (Henning et al. 1990). Experimentally, suture of radial tears through the entire meniscal body results in a similar biomechanical situation as after meniscectomy, and such a joint shows degeneration of articular cartilage (Newman et al. 1989). The effect of a healed central tear or more complex tear on joint biomechanics and cartilage has not yet been tested. Thus there is no evidence that repair of a tear in the avascular region is better than partial meniscectomy.

RATIONALE FOR MENISCAL REPLACEMENT

Because of the important functions of intact menisci and the well documented risk for development of osteoarthrosis after meniscal removal (Fairbank, 1948; Appel, 1970), meniscus replacement has been advocated in a case with extensive meniscal damage or after total meniscectomy (Siegel & Roberts, 1993). A large variety of methods including use of autografts (Kohn et al. 1988, 1992, 1997), allografts (Canham & Stanish, 1986; Arnoczky et al. 1989; Milachowski
et al. 1989; Jackson et al. 1992, 1993; Mikic et al. 1993; Cameron & Saha, 1997; Cummins et al. 1997), resorbable scaffolds (Wood et al. 1990; Stone et al. 1992; Stone, 1996; de Groot et al. 1996, 1997), and permanent prostheses (Toyonaga et al. 1983; Sommerlath et al. 1992; Sommerlath & Gillquist, 1992; Messner & Gillquist, 1993; Sommerlath & Gillquist, 1993a, b; Messner, 1994) have been used experimentally and clinically during the last few years. Encouraging results concerning healing of the implant to joint capsule, relief of clinical symptoms, and some protection of joint articular cartilage compared with total meniscectomy were claimed from a number of investigations, but none proved that the procedure reestablished the load distribution function of the meniscus and was able to prevent the cartilage changes which are common after meniscectomy.

The primary goal of such an invasive procedure is reestablishment of a normal joint load distribution. For this purpose a substitute is required with tissue properties as near to normal as possible. This requirement instantly excludes the use of prostheses, because today there is no artificial material available with similar properties to a normal meniscus (Sommerlath et al. 1992). Use of Dacron or Teflon prostheses further results in frequent formation of osteophytes and synovitis (Toyonaga et al. 1983; Sommerlath et al. 1992; Sommerlath & Gillquist, 1992; Messner & Gillquist, 1993; Sommerlath & Gillquist, 1993a, b; Messner, 1994). Resorbable copolymeric collagen scaffolds for meniscal tissue regeneration were introduced some years ago, but there are no reports as to the mechanical properties of such a regenerated meniscus (Stone et al. 1992). Autologous tissue would have the advantage of minimizing adverse reactions and the risk of disease transmission, but there is no autograft with meniscus-like properties. Fat pad or patellar tendon autografts were used experimentally to replace the medial meniscus, but the ability of these transplants to transmit loads was not tested. Although both acquired a resemblance to meniscus tissue some time after implantation, they did not acquire normal tissue properties within 1 y (Kohn et al. 1992, 1997). This leaves the use of meniscal allografts as the most promising method.

Storage of meniscal allografts by cryopreservation, deep freezing or lyophilisation did not result in deterioration of their viscoelastic mechanical properties (Arnoczky et al. 1988, 1992; Zukor et al. 1990), and major graft rejection after use of meniscal allografts was not observed in animal models (Ochi et al. 1993). Meniscal cells with their associated surface histocompatibility antigens appear to be largely protected from the immune system by a dense extracellular matrix (Arnoczky & Milachowski, 1990). However, the general problem with use of freely transplanted auto or allografts is the tissue remodelling which takes place after necrosis and revitalisation of the graft (Amiel et al. 1986). Against previous beliefs that a viable graft at time of implantation remains viable and functions better than an avital substitute (Arnoczky et al. 1992), it has been shown more recently that meniscal fibrochondrocytes do not survive transplantation (Jackson et al. 1993), and that the long term quality of the substitute is independent of initial graft viability (Fabbriciiani et al. 1997). Implantation means initial necrosis of the graft, and then repopulation by extrinsic cells from the host. Thus the meniscal allograft functions as scaffold rather than as a functional tissue after implantation (Jackson et al. 1993). Probably for this reason, the mechanical properties of allografts are found to deteriorate after some time of implantation (Milachowski et al. 1989; Zukor et al. 1990). The substitute becomes more elastic, weaker and more prone to prolonged deformation similar to what has been observed after use of a freely transplanted patellar tendon autograft for cruciate ligament reconstruction (Amiel et al. 1986). Signs of remodelling and even significant changes in shape were observed when the medial meniscus was excised and immediately reimplanted as an autograft (Messner, 1994). The tissue remodelling after healing and revascularisation of the substitute apparently results in a graft with inferior tissue properties. It is doubtful whether such a graft can provide a meniscus-like function and it has not been shown yet if it functions better than meniscectomy.

The other major problem with the concept of meniscal transplantation is the fixation of the graft to bone. As we discussed earlier, firm attachments to bone are a prerequisite for a normal load distribution function of the substitute. In vitro implantation of an allograft meniscus only resulted in an improved (but not normalised) load distribution across the knee when both ends of the graft were firmly attached to bone (Paletta et al. 1997). Lack of fixation of the substitute to bone resulted in a similar in vitro joint load distribution as total meniscectomy (Chen et al. 1996; Paletta et al. 1997). Thus inappropriate fixation alone may be the reason for failure of a meniscal substitute. There is evidence from several in vivo investigations that sufficient fixation of the substitute is usually not provided despite of bone sutures. Using prosthetic material or autografts, the substitutes were
usually found to be partially dislocated at the periphery some time after implantation, and the sutures to bone were either torn or the insertional ligaments elongated (Messner, 1994). Such a meniscus no longer covered the tibial plateau and degenerative changes of the articular cartilage were common (Messner, 1994). However in the latter experiment, a significant remodelling of a meniscal autograft was noted at the same time, and it was impossible to decide whether the inferior properties of the autograft or its insufficient fixation to bone were responsible for the failure. In an in vivo follow-up experiment, we therefore tested the performance of an intact rabbit meniscus either with transected anterior or posterior insertional ligament (Gao & Messner, 1996a). Such a meniscus had dislocated at the periphery and covered the tibial plateau to a lesser extent some time after implantation than a meniscus with intact entheses. Furthermore, although there was no obvious remodelling of the meniscal body itself, similar cartilage changes were noted as after meniscectomy. Apparently, insufficient fixation alone without graft remodelling causes dysfunction of the meniscus. When we later tried to reattache a transected anterior insertional ligament through a bone channel, we still noted elongation of the insertional ligament and significant signs of joint degeneration pointing to dysfunction of such a meniscus (Gao et al. 1998). In most cases the refixed insertional ligament had partially pulled out of the channel; in the remaining cases it had pulled out completely. Apparently, soft tissue fixation with sutures did not withstand the high loads at this site when the animal was allowed full weight bearing. Although the healing tissue between the refixed insertional ligament and bone matured from highly cellular, nonspecific granulation tissue at 1 wk, to bone, fibrocartilaginous and fibrous tissues which at some sites developed an insertion specific fibrocartilage deeply interdigitating with bone which is typical for a normal insertion did not become reestablished (Figs 3a, 5a). Also the distribution and labelling pattern for types I and II collagens in the newly formed insertions were abnormal. The labelling for collagen type II was more diffuse and weaker compared with a normal insertion and did not show indigitations with the unlabelled subchondral bone (Figs 4a, b, 5b, c). The failure load of this newly formed enthesis was less than 20% of normal at tensile testing. A method with the potential of achieving a rigid fixation of the meniscal graft is the use of bone blocks attached to the insertional ligaments of the allograft (Jackson et al. 1993). However, it has not been shown as yet whether normal insertional structure and mechanics can be retained in the long term (Nagano et al. 1997). In addition, such a technique requires exact size matching between donor and recipient, and exact placement, in order to provide a normal load distributing function and mobility of the substitute. This latter requirement limits the use of this technique, and in cases of size mismatch, fixation of ligamentous or meniscal soft tissue to bone is the only treatment alternative, but is probably not satisfactory. Hence other potential problems with the use of allografts are mismatch of size and shape between graft and host joints, and inappropriate placement. The fact that allograft transplantation was not able to normalise joint areas and stresses on the tibia in vitro (Paletta et al. 1997) despite proper fixation may point to an abnormal shape and placement of the substitute. Tissue remodelling after transplantation may improve the fit of the substitute but at the same time deteriorate its material properties.

CONCLUSIONS AND FUTURE DIRECTIONS

The menisci and their entheses to bone are a functional unit and should not be regarded as separate structures. They possess a complex structure, which shows substantial variations in tissue composition and configuration at different locations reflecting different functional demands. Although their anatomical structure and chemical composition is well defined, knowledge about their biomechanical and sensory function tends to be extrapolated from anatomical characteristics and theoretical models rather than measured directly. Speculations by far outweigh the facts. We still lack knowledge as to the loads to which the normal knee is subjected, and therefore the physiological loads in the meniscus at organ and tissue levels are unknown. The amount and magnitude of different loads during development is certainly a key factor for the normal remodelling of the tissue to its specified structure in adulthood as has been shown for other skeletal tissues, and without knowledge of these facts it will be difficult to create a functional meniscus substitute. We also need to know to what extent adult menisci are able to adapt to changes in physiological loading. In order to develop means for a successful meniscal replacement in the future we need to know how to control tissue remodelling after initial necrosis of the substitute. This is necessary so as to retain or reestablish near normal anatomical characteristics, and also the biomechanical and sensory functions of the meniscus body and its insertions.
Fig. 5. The newly formed enthesis 12 wk after refixation of the anterior insertional ligament of the rabbit medial meniscus into a tibial bone channel. (a) Insertional fibrocartilage is identified, but the typical configuration of interdigitations between bone and calcified fibrocartilage has not formed (arrows). (b) Immunohistochemical demonstration of type I collagen. The refixed insertional ligament and healing tissue are strongly labelled for type I collagen. (c) Immunohistochemical demonstration of type II collagen. Labelling for type II collagen is found focally in the fibrocartilaginous tissue of the newly formed enthesis. The labelling is weaker and more diffuse compared with a normal meniscal enthesis as shown in Fig. 4b, and has an even boundary with the unlabelled bone. RIL, refixed insertional ligament; UF, uncalcified fibrocartilaginous tissue; CF, calcified fibrocartilaginous tissue; FT, fibrocartilaginous tissue; B, bone. (a) Alcian blue/periodic acid Schiff; bar, 0.1 mm; (b, c) fluorescence microscopy; bar, 0.05 mm. (Reproduced with permission from Gao et al. 1998.)
to bone. The tissue remodelling after necrosis probably needs to duplicate the process of normal development in order to reach a structure with satisfying structural and biomechanical properties. Thus this answer may also be found by studying normal meniscal development and the identification of key factors for tissue remodelling.

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