THE REPAIR OF CRUCIATE LIGAMENTS WITH FLEXIBLE CARBON FIBRE

A LONGER TERM STUDY OF THE INDUCTION OF NEW LIGAMENTS AND OF THE FATE OF THE IMPLANTED CARBON

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Carbon fibre appears to induce the formation of tendon in both animals and humans. Experiments have been conducted in sheep in which new anterior cruciate ligaments have been induced in response to the implantation of filamentous carbon fibre. Long-term studies indicate that the carbon fibre slowly breaks up at the site of implantation and later begins to appear in the regional lymph nodes.

In an earlier study, the Cardiff group were able to demonstrate the induction of tendons and ligaments in rabbits and sheep after replacement of the calcaneal tendon and the collateral ligaments of the knee with flexible filamentous carbon fibre (Jenkins et al. 1977). Since then, it has been shown that, after replacement of the calcaneal tendon, the volume of fibrous tissue gradually increases and may exceed the original volume of the carbon implant by as much as fifteen times (Forster et al. 1978).

In the development of this material with its property of ligament and tendon induction, it is clearly necessary to determine not only the long-term effects of implantation, but also the volume of carbon to be implanted at any particular site where long-term activity of the new tendon or ligament is required.

This report outlines the long-term results after the implantation of filamentous carbon in the site of the excised calcaneal tendon in sheep. It also examines the use of carbon fibre as a replacement of the cruciate ligament.

METHODS

Experiment 1. In ten adult sheep, the calcaneal tendon was excised and replaced with a double loop of spun carbon fibre tow (80 000 filament units) in the manner described in our earlier publication (Jenkins et al. 1977). In this and in the other experiments described in this paper, carbon fibre of Type A.S. made by Courtaulds U.K., but prepared by ourselves, has been used. After the implantation, no attempt at immobilisation was made, and the animals were left to walk freely as soon as they were able. They were killed after periods ranging from six months to two years. Necropsies were performed on all animals.

Experiment 2. In eight adult sheep, the anterior cruciate ligament was excised and replaced with a spun strand of filamentous carbon containing approximately 40 000 individual strands of filamentous carbon fibre tow (Type A.S.) In eight other adult sheep, the anterior cruciate ligament was similarly excised and replaced with a single strand of carbon fibre containing approximately 10 000 individual units. The strand of 40 000 units was similar in diameter to the excised anterior cruciate ligament.

In four sheep, the anterior cruciate ligament was excised but not replaced. In terms of its reliance on ligaments for stability, the knee of the sheep is sufficiently similar to the human knee for it to be used as an experimental model. After excision of the anterior cruciate ligament, anterior instability with the knee in flexion was clearly demonstrated.

In all sheep an oblique drill hole was made through the femoral cortex at the origin of the anterior cruciate ligament, and a second oblique hole was made through the tibial cortex at the site corresponding with its insertion. The entire anterior cruciate ligament was excised and carbon fibre fed through the holes to lie across the joint in such a manner that the ligament had been totally replaced. Proximally, the carbon was held tightly by a single large knot which was pulled well down into the drill hole and, after achieving correct tension with a negative anterior drawer sign but with the retention of full range of knee flexion and extension, the carbon was turned backwards and forwards upon itself and fixed to the tibial cortex by means of three stout silk sutures. No attempt at immobilisation was made and the animals were killed at varying periods up to eight months.

RESULTS

Experiment 1. All animals were able to bear weight on the affected lower limb within one week, and all walked normally at one month. Naked eye examination at periods of six, twelve and twenty-four months after the implantation showed development of an apparently normal tendon around the carbon prosthesis; the new tendon was more bulky at twelve months than at six months, but by two years it has assumed an appearance not dissimilar in size and shape to that on the opposite side. The cross-sectional area of the carbon implant was approximately one-sixth that of the original tendon. The presence of the implant had therefore induced a new tendon of approximately six times its own bulk.

Histological examination confirmed our earlier findings of well-formed and well-organised fibrous tissue with collagen bundles running parallel to each other in the long axis of the new tendon. Continuous erosion and resorption of the carbon filament were indicated by the finding of carbon debris in mobile macrophages adjacent to the implantation site.

After one year, carbon fragments were found in the

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Para-aortic nodes in a sheep one year after carbon fibre replacement of the calcaneal tendon on the right side. Heavy carbon staining in the node from the right side contrasts with the normal node from the left side.

Proximal lymphatics and within the para-aortic nodes on the implantation side only (Fig. 1). Histological examination of more proximal nodes, and of the spleen, liver, lung and kidney in all sheep, produced no evidence of carbon at any of these sites. These findings were confirmed after two years when no further proximal spread of the carbon fragments was found.

Experiment 2. All animals were able to bear weight within one week and all walked normally with a normal range of movement at the knee one month later. In all, the anterior drawer sign remained negative. Naked eye examination of the implantation site at necropsy, at periods ranging from three to eight months, showed the gradual development of a new cruciate ligament and a gradual envelopment of the carbon matrix. In the animals with the larger bulk of carbon fibre, the new tendon had, by eight months, increased in size to a volume approximately four times the original carbon implant (Fig. 2), but in the animals with the lesser volume of carbon the new tendon had increased in bulk to a size similar to the normal anterior cruciate ligament (Figs. 3 and 4).

Sections taken of the carbon passing through bone showed early development of a fibrous capsule adherent to both bone and carbon, and by eight months there was marked ingrowth of fibrous tissue into the carbon matrix.

Histological examination at the proximal and distal ends of the carbon implant protruding through the cortices of the femur and tibia showed disorganised scar tissue growing within and throughout the matrix of the carbon.

Within the joint itself, there was initial covering of the carbon implant with synovium and, with the progression of time, gradual development of new tendon-like tissue. The rate of development of new tendon was markedly slower than that seen in other experiments in which the calcaneal tendon had been replaced (Fig. 5).

No carbon was found in the regional nodes or at any other site throughout the body.

Non-implantation group. There was no evidence of any redevelopment of an anterior cruciate ligament in the control group.

DISCUSSION

The first series of experiments involving the replacement of the calcaneal tendon confirm our earlier findings of new tendon development at the site of carbon implantation when the carbon is put under stress, and indicate that the newly induced tendon is not only acting anatomically, but has also taken on full physiological function.

It is suggested that the carbon matrix initially acts as a true cord-like prosthesis both in the calcaneal tendon and in the cruciate ligament. As ingrowth of fibroblastic tissue occurs, the carbon matrix acts as a scaffold throughout which the new tendon-like tissue can develop. Finally, it is suggested that the carbon fibre
orientation and partial fragmentation of the carbon encourage new collagen orientation in the line of the original ligament or tendon.

After carbon had fragmented it might be expected that particles would appear in the regional lymph nodes. This was the finding one year after carbon replacement of the calcaneal tendon, but we found no evidence of carbon in regional nodes in the group in which the cruciate ligament had been replaced. It is suggested that this absence of carbon is due to the slower fragmentation of the carbon at this site, but we anticipate that particles will eventually appear at the regional nodes in the manner described in the calcaneal tendon experiments.

While fragmentation of carbon and transfer of stress from carbon to collagen appears to be an advantage, the question of detriment to lymph nodes and other organs, still remains. That the carbon only remains in the first major proximal lymph node group is clearly an advantage and might be expected.

We have found no evidence of tumour formation or other detrimental effects resulting from carbon implantation. Indeed, there is strong evidence to suggest that carbon is relatively harmless and not carcinogenic. It is only in tattoos, where carbon is implanted in its impure form, as Indian ink with other unknown chemicals, that carbon is implicated in the development of malignant change (Kirsch 1972). The development of carcinoma of the bronchus after the ingestion of coal dust is thought to be associated with silica, and not carbon (McLintock 1975) and the Registrar General's Report of 1961 goes so far as to state that prolonged exposure to coal dust does not necessarily increase the risk of carcinoma. Certainly, carbon induces fibrosis in the parenchyma of the lung (Uragoda 1972) and our experiments suggest that fibrosis is a pronounced early feature following carbon implantation at other sites.

The long-term studies of replacement of the calcaneal tendon and the subsequent development of a continuously functioning new tendon provide evidence that the success of this material lies not in its integral strength but in its inductive capacity.

The studies of anterior cruciate replacement indicate that fibrous ingrowth can occur from the remaining original ends of the excised ligament. Once again the volume increase as a result of tendon induction is recorded, and the suggestion is made that should carbon be considered for clinical use this factor must be borne in mind.

REFERENCES


