Orthopaedic Applications of Carbon Fibers

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OF the myriad materials known to man, only a few are tolerated by the body following implantation. Incompatibility is the much more common outcome; either the body attacks the implant directly, or the implant causes a toxic reaction by the tissues. Some materials that are tolerated by the body, such as carbon, have no recognized clinical use because they lack suitable mechanical properties. Lampblack has been implanted subcutaneously for many years in tatoos, apparently without adverse effects, but neither lampblack nor other naturally occurring forms of carbon, such as graphite and diamond, are used in the treatment of injuries.

The development of various forms of synthetic carbon in the 1 950s fostered interest in potential medical applications [1]. In 1977**,** Jenkins [21 suggested that carbon in the form of thin fibers might be useful in the repair of tendons and ligaments, and a worldwide effort ensued to evaluate the possibility. Our aim here is briefly to describe carbon fibers and to outline our view of the mechanism underlying their clinical significance.

MANUFACTURING METHOD

Carbon fibers are made by pyrolyzing organic fibers [3]; a manufacturing process involving polyacrylonitrile (PAN) shown schematically in Fig. 1. The 15-micron PAN fiber is heated in air to permit it to absorb about 12 percent oxygen, which is required to burn off its non-carbon constituents. The pyrolysis is performed in an inert atmosphere with the fibers under load to prevent them from contracting. The resulting carbon fibers (also called high-strength graphite fibers) are about eight microns in diameter and consist of 98 percent carbon with 2 percent adsorbed gases and other impurities. Graphite fibers (also called high-modulus graphite fibers) are produced from carbon fibers by further heating in an inert atmosphere. Graphite fibers are purer and more crystalline than carbon fibers, but they are also stiffer and not in general clinical use.

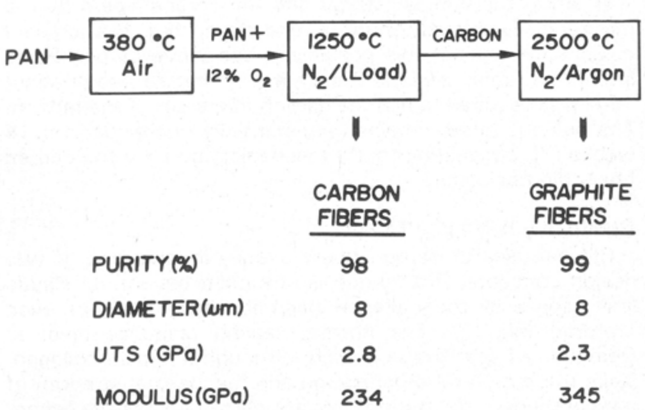

Figure 1. Typical manufacturing method and some physical properties of carbon and graphite fibers. UTS, ultimate tensile strength.

BIOLOGICAL RESPONSE

How does the body react to carbon fibers? We implanted bundles of 5000 8-micron carbon fibers in muscle, fat, and adjacent to nerve in mice. After five weeks, the appearance of oriented tissue adjacent to the fibers in the periphery of the bundle was the characteristic reaction at all three sites (Fig. 2) [4]. The peripheral carbon fibers were covered by fibroblast cells, whose spindle-shaped nuclei were generally oriented along the fiber axis. The structural protein collagen secreted by the fibroblasts was also generally aligned along the same axis. When carbon-fiber debris was implanted (fibers less than 300 microns in length), no identifiable pattern occurred in either cell location or collagen growth. Thus, the organizational influence of carbon fibers was related to their macroscopic length.

No histopathological changes occurred in the muscle, fat, or nerve, and few inflammatory cells (neutrophils, lymphocytes, giant cells) were seen. Such biocompatibility of carbon fibers has been consistently observed in animals [5, 6].

The tissue appeared only around the fibers in the periphery of the bundle, but further penetration of the tissue into the fiber bundle occurred at five weeks after implantation than at one week. In similar studies in rats, we found that the tissue response penetrated still deeper into the bundle at nine weeks after implantation. After cutting the carbon-fiber bundle in a plane normal to its axis, three relatively distinct regions could be seen. The outermost fibers were surrounded by two or three layers of cells and collagen whose organization reflected the cylindrical symmetry of the carbon fibers (Fig. 3). The next deeper zone in the bundle contained tissue, but without apparent structural organization or symmetry. The core of the carbon-fiber bundle contained no tissue.

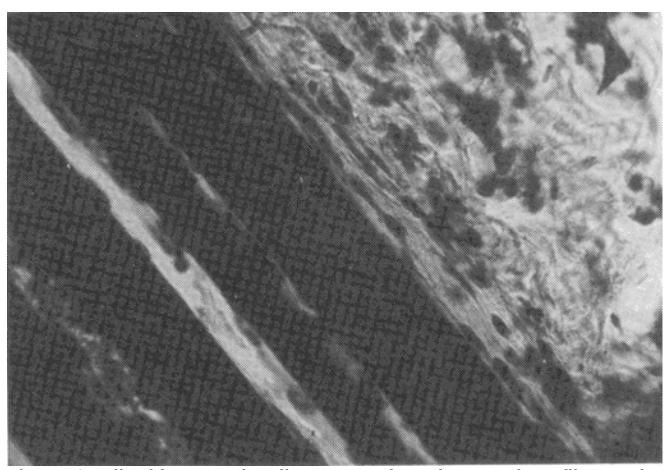

Figure 2. Fibroblasts and collagen growing along carbon fibers. The carbon fibers were implanted in muscle in mice and recovered after five weeks. The tissue in the immediate vicinity of the carbon fiber is oriented along the fiber axis, but the tissue more lateral than 2-3 cell diameters is unorganized. (Embedded in wax, sectioned at six microns, stained with hematoxylin and eosin.)

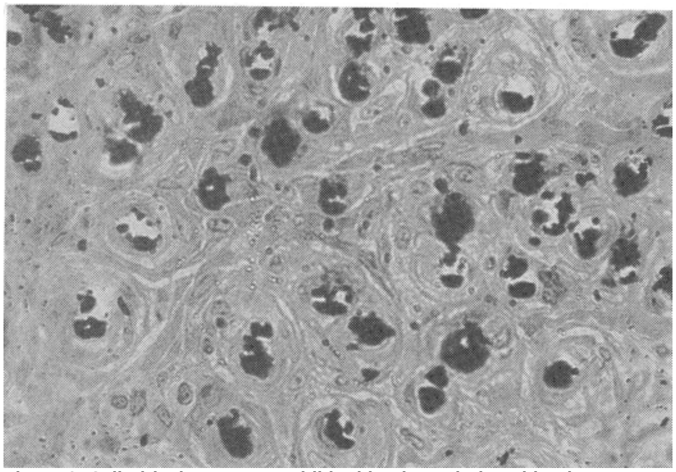

Figure 3. Cylindrical geometry exhibited by tissue induced by the presence of carbon fibers. The carbon fibers were implanted in muscle in rats and recovered after nine weeks. The reaction to each carbon fiber appears to be the formation of concentric tubes of collagen separated from one another and from the fiber itself by intervening layers of fibroblasts. (Embedded in epoxy, sectioned at 0.2 microns, stained with toluidine blue.)

In studies in rabbits, a bundle of 10,000 carbon fibers was used to bridge a 1-cm surgically created gap in the Achilles tendon [7]. By 40 weeks postimplantation, tissue penetration into the carbon-fiber bundle still continued (Fig. 4) [8]. The fibers on the periphery of the bundle stabilized at an average fiber-to-fiber distance of *20* to 30 microns, but the fibers in the core of the bundle still exhibited little surrounding tissue. By about 80 weeks after the surgery, the reaction to the carbon fibers seemed complete [9]. Viable cells and connective tissue were found throughout the cross-section of the carbon-fiber bundle, and the average fiber-to-fiber distance was 20 to 30 microns. Macroscopically, the diameter of the carbon-fiber bundle was three to four times greater than its initial diameter. The ratio, R, of the bundle diameter after implantation to its initial diameter is $R = 1 + 2d/D$, where D is the diameter of each fiber and d is the thickness of the surrounding tissue layer. If the 8-micron fibers are assumed separated by an average of 25 microns, then R is approximately equal to 4, as observed.

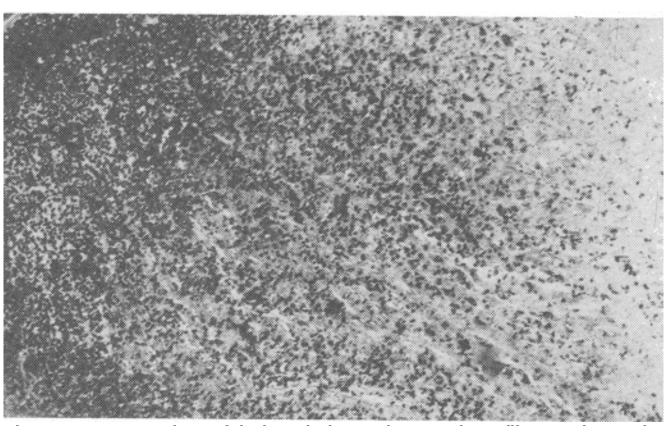

Figure 4. Penetration of induced tissue into carbon fibers. The carbon fibers were placed in rabbit Achilles tendons and recovered after 40 weeks. Maximum separation of the fibers by new tissue occurred among the fibers in the periphery, but only scanty tissue was present around the core fibers. There was an intermediate amount of tissue growth between the two limits. (Embedded in epoxy, sectioned at 1.5 microns, stained with toluidine blue.)

THE BASIC STRUCTURAL UNIT

Figure 5 depicts our conception of the basic reaction of the body to the presence of carbon fibers. It consists of a lamellar structure built from concentric layers of cells, separated by intervening tubes of collagen. The greatest spatial regularity occurs around the fibers in the periphery of the implant, particularly when the implant is mechanically non-functional (Fig. 4). When the implant carries a load which tends to make the carbon fibers slip past the tissue, or when the carbon fibers are tightly bunched, such as in the center of the implant, less structural organization occurs.

The reaction to carbon fibers does not appear to depend significantly on its anatomical location. The interior of the knee joint is a relatively hostile environment for tissue growth, but the response in goats to carbon fibers implanted in the anterior cruciate ligament (80 weeks) was similar to that found in rabbit Achilles tendons after a comparable time (Fig. 6).

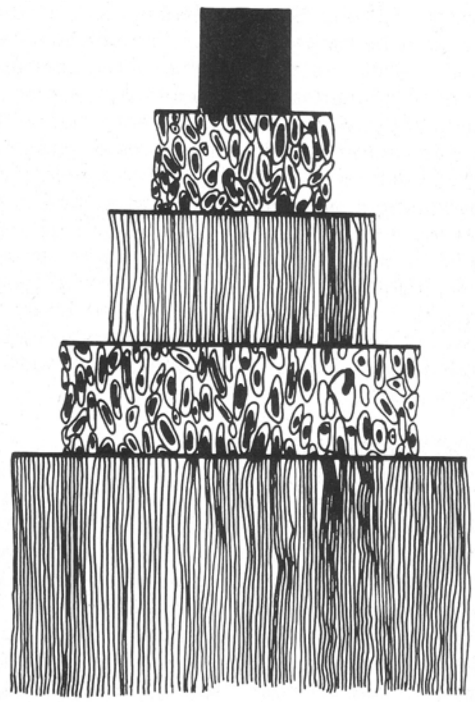

Figure 5. Representation of reaction of the body to carbon fibers. The carbon fibers are surrounded by concentric layers of fibroblasts and collagen. The tissue has an overall axial organization.

Whether the induced tissue and the carbon fibers form a mechanically sound bond is uncertain, but the present evidence is against this possibility. We wove carbon fibers into intact rabbit tendons in such a way that a force of about 10 N was required to pull the carbon fibers out of the tendon. The pull-out force remained substantially unchanged for 18 weeks [7], suggesting that a mechanical bond to the carbon fibers did not occur.

CLINICAL APPLICATIONS

Clinical uses of carbon fibers usually involve one of two design concepts. If a tendon is stretched beyond its elastic limit, some of the collagen becomes attenuated or even ruptured (Fig. 7). The normal healing response involves formation of scar tissue, which, although it is also collagen, lacks the structural organization and mechanical strength of normal tendon. If carbon fibers are placed across the lesion, they may add structural organization (and hence strength) to the healing site. If the injury is chronic rather than acute, the

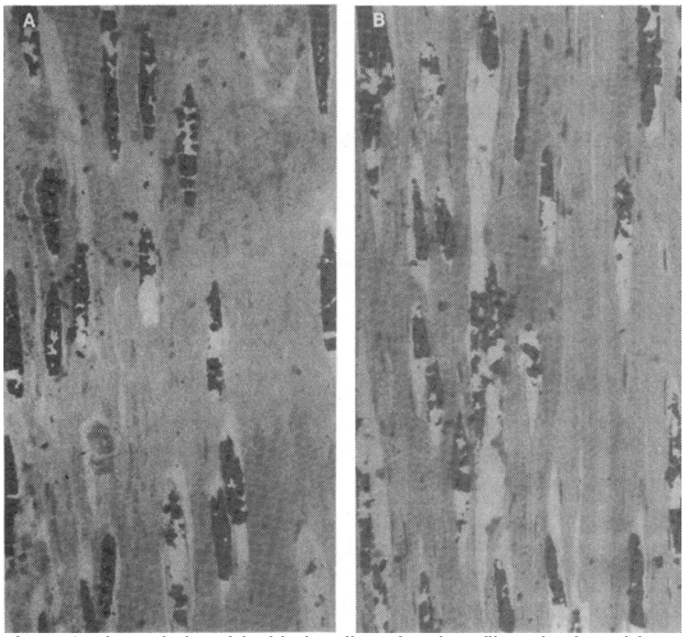

Figure 6. Tissue induced inside bundles of carbon fibers implanted in rabbit achilles tendon (A) and goat anterior cruciate ligament (B) and recovered approximately 80 weeks after surgery. The plane of the sections is along the carbon-fiber axes. The relatively brittle carbon fibers were shattered during cutting, but much of the resulting debris remained in place, permitting visualization of the relationship between the carbon fibers and the induced tissue. (Embedded in epoxy, sectioned at 0.2 microns, stained with toluidine blue.)

tissue response to the carbon fibers may add mechanical strength to the repair site. Histological studies have shown the presence of organized tissue around carbon fibers implanted at a variety of anatomical locations, but no animal studies have convincingly shown that the presence of the induced tissue actually adds mechanical strength to the repair site. A serious problem with tendon studies has been an inability to grip the tendon adequately, so that the strength of the repair site itself, and not the grip point, is actually being tested. A less precise but ultimately more important method of assessing the role of carbon fibers involves clinical evaluation of the results obtained following repair of damaged tendons. Bow tendon is a common injury in horses, involving a tendon between the fetlock and the carpal joint in the distal portion of the leg. Using specially designed instruments, carbon fibers can be placed in the injured tendon through a small incision above the fetlock. If the collagen induced by the carbon fibers adds strength to the tendon, the horse should be able to return to a higher functional level than would otherwise have been possible. Such studies are presently underway.

A second application of carbon fibers involves its use for both collagen induction and mechanical support. A skeletal ligament connects two bones, and a mid-substance rupture (Fig. 8) is a typical injury in such a ligament. If carbon fibers are placed in the ligament across the rupture and anchored to the bones, they will provide mechanical support by acting as a check-rein on the maximum relative displacement of the two bones (thereby relieving collateral soft-tissue structures of the load). The carbon fibers can also act as a scaffold for the induction of new collagen that will add strength to the ligament, particularly at the site of the lesion.

The use of carbon fibers for both induction and stabilization requires a means by which they can be anchored to the bone. The optimum attachment technique would allow the mechanical load to be distributed among all the fibers. The ultimate tensile strength of 40,000 fibers (a typical human ligament implant) would then be far greater than that of any natural ligament. Although many different fixation techniques have been studied, none have even approached the theoretical limit. The present inability to load effectively all fibers simultaneously may not, however, be a serious disadvantage,

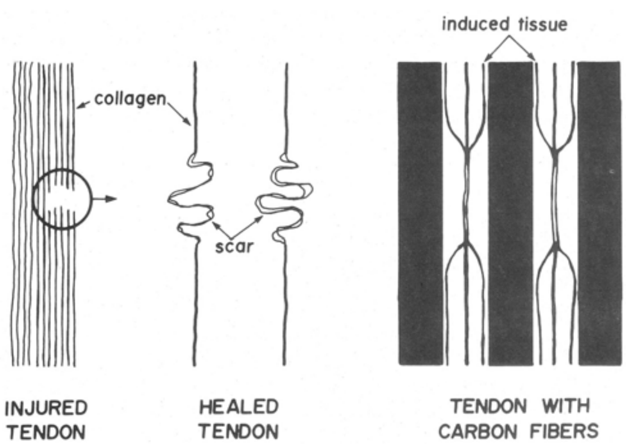

Figure 7. Theorized mechanism by which carbon fibers add strength to partially ruptured tendons. The carbon fibers are placed across the lesion using a cannula. They are not attached at either end and consequently do not produce an immediate increase in strength. The tissue induced by the carbon fibers reinforces the normal healing and thus adds strength to the tendon.

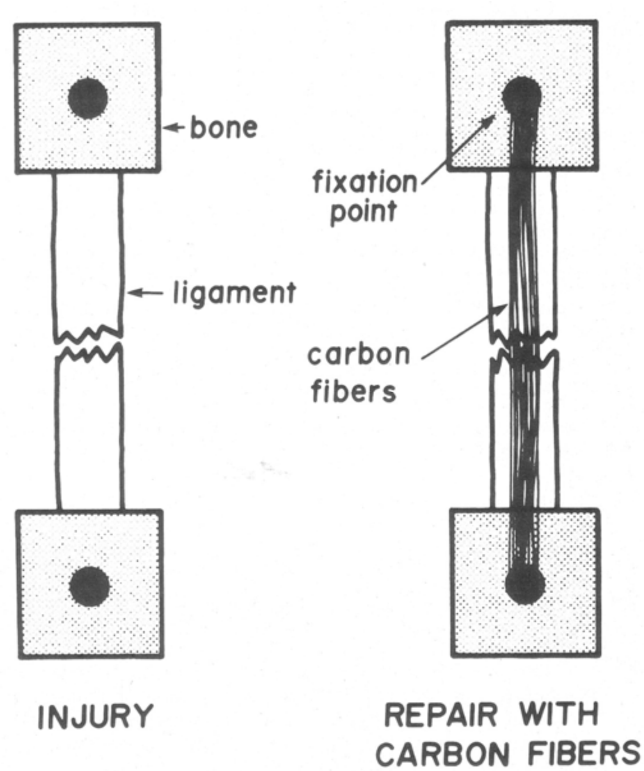

Figure 8. Use of carbon fibers for both induction and stabilization. A mid-substance rupture of the ligament removes a limit on the relative motion of the two bones. If the carbon fiber bundle is passed through both ends of the ligament and anchored to both bones, it serves as a scaffold for induced collagen and also adds immediate stability to the injury site.

because such great strength is not needed, and by allowing the fibers to break — this occurs when the load on a particular fiber exceeds about 0.1 N — the load is eventually transferred to the new tissue, a desirable clinical consequence.

Carbon fibers have been used clinically for tendon and ligament repair since the 1970s [10-12]. Both design concepts have been employed in many different kinds of repairs, but the anterior cruciate ligament (which connects the femur to the tibia) is perhaps the most frequently treated structure. Because of the variety of surgical techniques and fixation methods used, no clear picture regarding clinical efficacy has yet emerged, but controlled clinical studies are in progress, and the question should be resolved shortly.

CONCLUSION

Carbon fiber is a modern material having several characteristics which make it potentially useful as an implant. It is strong and biocompatible and can be used to repair tendons and ligaments. The body's reaction to carbon fibers is the formation of an oriented, highly cellular tissue that may strengthen the tendon or ligament in which it is implanted. Clinical studies of this possibility are nearing completion. A typical human implant consists of 40,000 8-micron fibers with an overall diameter of about 2 mm. The animal studies indicate that, at equilibrium, the implant will induce an amount of tissue resulting in a combined structure of carbon fibers and new tissue of about eight mm in diameter.

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