Fibre-reinforced Materials

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Abstract: This paper considers the role of fibres in the reinforcement of composite materials, and the significance of the form the fibre takes and the material from which it is made. The current dental applications of fibre reinforcement, including dental cements and splints, fibres made into structures for use in composites, denture bases and the contemporary use of fibres in fixed partial dentures, are reviewed. Their role in biomedical implants is surveyed and their future forecast.

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Clinical Relevance: Several manufacturers of contemporary dental materials are extolling the merits of products which contain reinforcing fibres. This paper reviews the science of reinforcement and examines the ways it has been used in a range of dental materials.

In the search for strong materials humans have been trying to imitate nature for many centuries. However, it has only been in the latter half of the twentieth century that the technology has been available to achieve this, and engineering structures and devices produced that need high strength and stiffness coupled with small size. Such are the requirements of many biomedical applications, including those of clinical dentistry.

THE WORLD OF MATERIALS

The world of materials is divisible into three basic categories – ceramics, metals and polymers – and when materials of different categories are brought together they produce *composites* (Figure 1). For the last 30 years the dental profession has been using composite filling materials made from fluid monomers containing ceramic powder. Many different sizes and shapes have been tried, but in general the particulate fillers have had similar dimensions. The presence of up to 60 Vol % of ceramic in these composites has had two main effects: it has reduced the amount of monomer (and thus reduced both the shrinkage due to its polymerization and its coefficient of thermal expansion), and it has made the set materials stiffer and more resistant to wear. This improvement in the mechanical properties is called reinforcement; however, to obtain significant reinforcement it would be necessary to use fibres instead of powdered ceramics.

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WHAT IS A FIBRE?

A fibre is a thin, flexible structure, approximately cylindrical in shape, which has a length at least 100 times greater than its diameter. For filling small cavities in teeth with a paste that contains such fibres, which must be packed and set *in situ*, these dimensions are impracticable. However, for larger restorations and appliances long fibres are quite realistic as a means of reinforcement.

Fibres are used extensively in nature: plants rely on the cellulose fibres that make up their cell walls to give them the flexibility and strength they need to bend in the breeze without breaking; sea urchins employ ceramic fibres in the flexible spines that enable them to move (however, the fracture resistance of these fibres is low, as anyone who has trodden on one will attest).

It is not surprising that humans have learned to use natural polymeric fibres. We have also developed ways of producing fibres from each category of the world of materials, and for dental applications have devised techniques for incorporating fibres within a matrix which is generally, but not always, polymeric.

ROLE OF FIBRES

Fibres in general tend to contain fewer imperfections than bulk materials do, and this increases their resistance to failure and makes them strong. Ceramic or polymeric fibres are akin to metallic

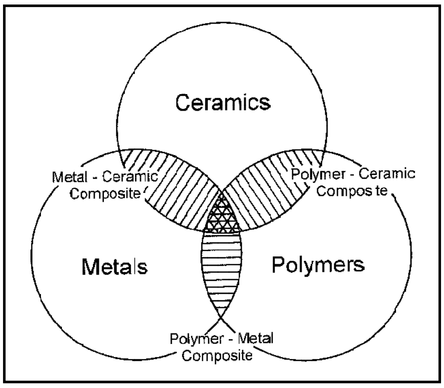

Figure 1. *The basic categories of the materials world and the composites that can be formed from them.*

Figure 2. *Natural and synthetic fibres are used in both the fixed and running rigging of tall-ships such as this.*

wires, and when fibres or wires are wound together they produce ropes which bring together in a unique way strength and flexibility. Ropes made of steel can be used to hold up the masts of sailing ships or to support the decks of suspension bridges; ropes made of natural or synthetic polymers can be used to raise the sails of ships or connect them to the quayside (Figure 2), and mountain climbers rely on ropes in all their endeavours.

As well as having the ability to stiffen and strengthen a weaker matrix material, a composite containing fibres also has the ability to hold together fractured fragments of the composite and to assist in its shaping. Straw was used to good effect to make bricks in ancient Egypt, cotton gauze is still used to control the placing of surgical plaster splints or to hold together a splint that has been damaged and a walk down our streets would probably reveal damaged concrete street furniture held together by its steel reinforcing rods.

EFFECTS OF MORPHOLOGY

Fibres can be introduced into fluid matrices in various forms. These composite materials are then shaped or moulded and the matrix material hardens or sets. The effects of the fibres on the properties of the resultant composites are summarized in Table 1, which also indicates their dependence on the orientation of the fibres.

TYPES OF FIBRES USED IN DENTISTRY

Ceramic, metal or polymeric fibres of diameters between 3 and 300 microns have been used as a means of achieving reinforcement of dental materials (see Table 2).

The latest approach to improving the strength of dental restorative composites based on setting resins has been the use of silicon nitride whiskers. These are much smaller than fibres (mean diameter 0.4 microns; mean length 5 microns), which enables them to bridge micron-sized cracks in the set matrix effectively and thus constrain growth of cracks, reinforcing the composite very strongly.

REQUIREMENTS FOR REINFORCEMENT

If the reinforcing fibre is to be effective in any of these roles, it needs to form a strong bond with the matrix material, and whilst natural fibres have their own inherent surface topography, steel reinforcing rods in concrete, for example, need to have their surfaces textured in some way to aid mechanical attachment to the set cement that surrounds them.

To make ceramic whiskers more retentive to the polymeric matrix, Xu *et al.*[1] have devised a way of coating them with fused silica particles, which are only 0.04 microns in diameter, fusing the particles to the whiskers at high temperatures and then silanizing the roughened whiskers. Silanes form chemical bonds between ceramics and polymers, and these treatments thus raise the strength and fracture resistance of the resin composites that contain such fibres. The presence of such treated whiskers also raises the resistance of the composite to contact damage.

CLINICAL DENTAL APPLICATIONS OF FIBRE REINFORCEMENT

A range of fibres has been used to form composite structures, and the many ways in which they have been used to enhance the properties of dental materials are outlined below. In some cases genuine reinforcement has been achieved, in others composite structures have been formed and in most applications the fibres have been used to hold together fragments of fractured restorations or appliances.

All of the cases demonstrate the expansion of our understanding of the mechanisms of reinforcement along with some of the ways devised by dental clinicians and technicians working with materials scientists for producing restorations and appliances with improved mechanical properties.

Dental Cements

In 1973, Brown and Combe[2] tried to incorporate short lengths of thin,

Format	Morphology	Effects on properties	Orientation dependence
Short staples	- - - - - - - - - - - - - -	Reduce matrix volume May improve wear resistance	None None
Long lengths	_______ _______	Can improve strength and stiffness Act to hold fractured matrix together	Mainly one dimensional
Woven mats	######## ########	Can improve stiffness and strength Assist in forming structures	Mainly two dimensional

Table 1. *The effects on the properties of fibre-reinforced composites of the morphology of the fibres and their orientation.*

stainless steel wire into experimental versions of polycarboxylate cement, which forms a chemical bond with the steel. However, the handling of such a metal–ceramic composite was far from easy, and there was little in the way of actual reinforcement, but the fibres did act to hold together fractured sections of the brittle cement matrix when specimens were tested to destruction.

Xu *et al.*[3] have recently reported that calcium phosphate cement (which is noted for its low strength) can be substantially reinforced by incorporation of aramid or carbon fibres.

Category	Example	Used in:
Metal	Stainless steel	Cements, splints
Ceramic	Alumina, carbon, glass, silicon nitride	Denture bases, fillings, crowns, bridges, root posts
Polymers	Aramid (Kevlar), high-density linear polyethylene (HDLPE)	Denture bases, crowns, bridges

Table 2. *The dental applications of fibres made from the various categories of materials.*

Dental Splints

Although wires are not strictly fibres, their use as frameworks to support resins and resin-based composite restorative materials has been widespread for many years. For example, in 1986 Christensen[4] constructed a fixed partial denture using orthodontic wire to span an edentulous space from small cavities cut into the enamel of the teeth on either side. The enamel was etched using acid and the wire acted as a support for the light-cured, resin-based composite that was bonded to the enamel. As actual fibres became available, they were also used to support resin-based composites, and both Goldberg and Freilich in 1999[5] and Meiers *et al.* in 1998[6] have described their use in creating splints for hypermobile teeth.

As concerns about the use of base metals in the mouth have grown, fibre-reinforced composites are increasingly being suggested as alternatives for the construction of dental appliances. In 1997 Karmaker *et al.*[7] described how long fibres could be introduced into polycarbonate or dimethacrylate copolymers for this purpose. Should such appliances become damaged then, as Rosentritt *et al.*[8] discovered, their surfaces can be air-abraded, silanized and light-cured composite bonded to them to effect a satisfactory repair.

Composite Structures

Several attempts at reinforcing dimethacrylate resins with fibres have been reported. In 1989, Krause *et al.*[9] discovered that the mechanical properties of a Bis–GMA resin improved in relation to the amount of silane-coated glass fibres they managed to incorporate. The fibres they used were 5 microns in diameter and 25 microns long. One manufacturer took up this idea, and in 1992 Willems *et al.*[10] reported that *Restolux SP* (Lee Pharmaceuticals, CA 91733, USA) contained fibres that were 300 microns long. However, although these fibres improved the stiffness and strength of the resin, they were intrinsically rough and likely to produce too much wear on the opposing teeth.

Ehrnford[11] described a composite material that contained a fabricated structure made from glass fibres. The fibres had been heated under pressure to form a dense network of fused fibrils and were impregnated with resin under vacuum. Once the resin had been cured it was suggested that the composite could either be used in large sections or broken up to produce ‘filler particles’. The importance of wetting the fibres thoroughly with the resin was appreciated by Kilfoil *et al.*[12] in 1983, who described how the poor wetting of carbon fibres in the composite structures they were investigating actually reduced the flexural strength of a restorative resin.

It was not until the 1990s that the technology became available for the production of such structures for commercial purposes. In 1996 Leinfelder *et al.*[13] described how PRIMM (a polymer rigid inorganic matrix material) was showing promise as ‘the posterior restoration of the future’. However, Bayne and Thompson found it a challenge to incorporate more than 15% PRIMM into either commercial composites[14] or resin-modified glass-ionomer composites.[15] Although this produced only modest improvements in flexure strength and fracture toughness, they hypothesized that significant enhancement in mechanical properties could be achieved if the mixing problems could be remedied.

Using silicon nitride whiskers, together with precured glass-ionomer particles, Xu *et al.*[16] have managed to improve the properties of composite filling materials and produce materials that will release modest amounts of fluoride.

Root Posts

Resins reinforced with carbon or quartz fibres have been used to produce black or white root posts, with stiffness similar to that of dentine. This is considered by some to be a good thing: in 1998 Dean *et al.*[17] reported no root fractures when carbon-fibre reinforced posts had been employed in ten teeth, whereas five of the ten teeth treated using metal posts had developed root fractures; Mannocci *et al.*[18] observed only one root fracture with posts reinforced with either quartz fibres or a mixture of quartz and carbon fibres under all-ceramic crowns in 13 teeth, compared with 6 of the 13 treated with solid ceramic posts. However, Stockton and Williams.[19] considered that fibre-reinforced polymer posts were too flexible, and that this led to a transfer of stress to both the core and the bonded or luted interfaces, adversely affecting the success of these restorations.

Reinforcement of Denture Bases

The span of the complete denture and the inherent poor performance of poly(methyl methacrylate) under either sudden impacts or cyclic stresses has cried out for reinforcement. Many techniques have been tried, from large internal frameworks (which act as stress raisers within the polymer and thus as sites where cracks can start) to every sort of fibre ever devised.

The use of glass fibres in dentures was first described by Smith in 1957,[20] and in 1971 Schreiber[21] reported on the use of carbon fibres for the same purpose. Both sorts of fibre were unwieldy to handle, and preventing sharp and potentially irritating fibre ends from poking out of the surface proved to be a challenge. In addition, the inherent colour of the carbon fibres did not suit everyone.

In 1990 Berrong *et al.*[22] produced a preliminary study on the use of aramid (*Kevlar*, DuPont, DE 19898, USA) fibres in an acrylic matrix, and in 1992 Ladizesky *et al.*[23] introduced the dental world to highly drawn linear polyethylene (HDLPE) fibres. These were impregnated for several hours in a syrup made from one part of methyl methacrylate and one part of poly(methyl methacrylate). Like many before them, Ladizesky discovered that the greatest reinforcement came from using continuous, parallel fibres. Unlike aramid or carbon fibres, which had poor aesthetics and produce bases that were difficult to polish, the polyethylene fibres were easy to handle and looked good. Chow *et al.*[24] also discovered that the presence of the fibres reduced water absorption, decreasing the dimensional changes usually seen when a denture is stored in water. However, the most significant effect was that, when dentures contained 48% of these fibres, longitudinally orientated, there was a six-fold increase in stiffness and a ten-fold increase in impact strength. Chow *et al.* went on to investigate surface treatments of the HDLPE fibres[25] and found that, whilst plasma treatment increased the efficacy of the bond between the acrylic and the fibres, there was no significant improvement in the mechanical properties. However, if these fibres were woven into mats which were incorporated into the acrylic, then considerable improvements were measurable.

By 1996, it was possible for Vallittu[26] to lay down the ground rules for the fibre reinforcement of denture-based resins. He reiterated those facts well known to the world of materials science – that for maximum reinforcement:

- the length of the fibres must be greater than their diameter;
- the fibre should be stiff; and
- a good bond must form between the fibre and the matrix.

To this end the impregnation of the fibres by the resin during the manipulation stage is essential if stress-raising voids are to be prevented from forming around them. Although proven as a concept, these fibres are not generally available to commercial dental laboratories for the routine incorporation into denture bases.

Fixed Partial Dentures (Crowns and Bridges)

The size of these units makes them good candidates for construction from reinforced resin composites, and over the last decade many materials have been brought together for this purpose. In 1990, Malquarti *et al.*[27] wound carbon fibre filaments within the solvent methyl ethyl acetone before incorporating them into poly(epoxy) resin. The composite structures they produced had a poor resistance to abrasion and were considered suitable only for replacements in patients likely to be sensitive to base metals. Glass fibres in poly(terephthalate glycol) were the choice of Goldberg and Burstone,[28] who described how the fibres were coated with resin before being drawn through a heated die in a process known as *pultrusion*. The heat caused the resin to cure. These coated fibres were easy to handle and were used to reinforce various dental appliances, including prosthodontic frameworks, retainers and splints.

An epoxy/carbon composite was the choice of Viguie *et al.,*[29] who rediscovered the relationship between strength, stiffness and fibre morphology, reminding us in the process that long fibres produce stronger and stiffer structures than woven fibres, but that both are better than using only short fibres and hoping for reinforcement. Altieri *et al.*[30] used long glass fibres to reinforce polycarbonate when they shaped this thermoplastic composite under considerable pressure at high temperature to produce frameworks. These they were able to link via resin-composite to acid-etched enamel, thus retaining a single tooth.

The arrival on the dental market of the composite *Targis* (re-designated for its launch by its manufacturers (Ivoclar/Vivadent) as a 'ceromer' – a ceramic-optimized polymer), together with *Vectris* – a glass fibre-reinforced framework used to produce a fibre-reinforced composite, stimulated the imagination of those called upon to produce new uses for old materials. In 1997 Hornbrook[31] reported that the two materials could be used by following conventional prosthodontic principles for the production of 'Maryland-like' bridges. Also in 1997, Brocklehurst[32] was able to provide full details of how to handle these materials and their limitations as aesthetic alternatives for ceramic veneers in adolescent patients. When used with adhesive luting agents, Krejci *et al.*[33] predicted that these materials might be used for exceptionally conservative crowns and bridges, and Freilich *et al.*[34] compared the virtues of woven and unidirectional fibres before revealing which sorts were used in which of the contemporary commercial materials.

All of the underlying principles of reinforcement were used by Vallittu[35] when successfully reinforcing the interpenetrating polymeric network which formed when poly(ethyl methacrylate) was mixed with *n*-butyl methacrylate and cured using woven and unidirectional glass fibres to produce a provisional fixed partial denture.

After testing the *Targis/Vectris* (Ivoclar AG, Liechtenstein) system *in vitro*, Behr *et al.*[36] were impressed by both its fracture strength and its marginal adaptation, and suggested that it showed promise for the production of fixed, posterior inlay dentures.

Significant reinforcement of dental resin composited was recently reported by Xu,[37] who added 70% of silicon nitride whiskers (surface treated as described above) to composites being used in the laboratory to form large stress-bearing crowns and multiple unit restorations. These restorations were heat cured for 3 hours to produce not only reinforcement but also a substantial resistance to degradation in water.

Biomedical Implants

The exacting requirements of other users of biomaterials should not be forgotten, for they have embraced fibre-reinforced materials with the same enthusiasm as the dental profession. In recent reports, which all appeared in 1998, some fascinating combinations of materials were used. For example, Ambrosio *et al.*[38] used a hydrogel–polymer matrix reinforced with poly(ethylene terephthalate) fibres, which were wound helically in order to mimic the architecture of collagen, as part of their programme to develop artificial connective tissues for orthopaedic applications. Graphite fibre-reinforced polymers have also been studied as possible alternatives to alloys as hip prostheses, and Yildiz *et al.*[39] compared the theoretical properties of various combinations of graphite and the polymer PEEK using the techniques of finite element analysis with the actual properties of cobalt–chromium and titanium alloys.

In order to produce artificial bone, it is necessary to mimic its unique natural structure by laying down a scaffold onto which ceramics can be deposited. To achieve this, Thomson *et al.*[40] made three-dimensional scaffolds from short, hydroxyapatite fibres held within a poly(glycolic acid) foam, and Thompson and Hench[41] deposited both bioactive glass and glass-ceramic onto fibres of polyethylene and polysulphone. They also used fibres such as dextran and collagen, which are gradually resorbed, leaving the bioactivity of the glass uncompromised.

Fibre reinforcement has also found a place in the development of artificial skin, and Young *et al.*[42] have reported on the use of woven and knitted fibres of Spandex and low-lint gauze held within a thin matrix of a radiation-cured mixture of methacrylates for this purpose.

A LOOK TO THE FUTURE

Synthetic fibre reinforcement will never mimic nature completely, but it is getting close. Nature has the great advantage of self-assembling its composite structures on the molecular scale, whereas humans are obliged to blend alien materials together and hope for the best. It is possible that, in the distant future, we will be able to persuade synthetic materials to self-assemble, thus giving us the properties shown by Nature's composites. Until then, efforts to understand and use fibres will continue.

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BOOK REVIEW

Catalogue of Dental Health Resources, 3rd edition. By A. Blinkhorn, F. Blinkhorn, K. Davis and H. Draper. Eden Blanche Press, Waterfront, Rossendal, Lancs BB4 7DE, 2000 (154pp., £5.00). (Available from Professor A. S. Blinkhorn, Turner Dental School, University Dental Hospital of Manchester, Higher Cambridge Street, Manchester M15 6FF.)

The first edition of this book was published in 1995, and this proved successful enough to warrant a second edition in 1997. It is a measure of its popularity, let alone the changes in its subject matter, that the third edition has recently appeared.

The book is, as the title suggests, a catalogue of health education material in the form of pamphlets and leaflets, catalogues, books and manuals, and posters aimed at patients or for use by dental professionals. The groups at which the information is aimed included ante- and post-natal mothers, pre-school and school children, young adults, elderly people, disadvantaged and ill people, and non-English speaking people. Pamphlets and leaflets on fluoride and orthodontics are also described. The posters appear to have the most imaginative titles – for example, 'Pay your mouth the lip service it deserves', 'Tap into H_2O', and 'Don't be sheepish about visiting the dentist'. Each item carries a description, with details of the source, target group and purchase price. Each publication is judged on seven

factors including: how easy is it to understand the material?; are the aims stated?; and does the material address a dental health problem relative to the target group?

This catalogue is of potential value to anyone wishing to purchase illustrative material for a practice or clinic. With almost 400 items described, there should be something in it to fulfil every requirement.

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ABSTRACTS

POST-OPERATIVE ANTIBIOTICS
Antibiotic Therapy in Impacted Third Molar Surgery. G. Monaco, C. Staffolani, M.R. Gatto and L. Checchi. *European Journal of Oral Sciences* 1999; **107:** 437-441.

With the emerging and growing problem of antibiotic resistance, this Italian paper casts doubt on the routine use of post-operative antibiotics for minor oral surgical procedures.

A total of 141 healthy adult patients attending for surgical removal of third molar teeth under local anaesthetic were randomly assigned to one of two groups. The first group received 2 g amoxicillin (amoxycillin) daily for 5 days and the control group received no antibiotic therapy.

Although postoperative complications of fever, pain, swelling and alveolar osteitis (dry socket) were reported in small numbers in both groups, there was no significant difference between those receiving post-operative antibiotics and those not.

Interestingly, the authors reported significant associations of postoperative pain with sex (females experiencing more pain and swelling), habitual alcohol consumption and, not surprisingly, smoking. There was a trend, although not significant, between increased postoperative pain and less surgical experience of the operator.

In otherwise healthy adult patients, there seems little justification for postoperative antibiotics for minor oral surgical procedures. The use of such antibiotics would probably best be reserved for those with reduced healing ability such as diabetics, the immunosuppressed and the elderly. In such circumstances, a pre-operative loading dose with a continued postoperative course is probably more useful.

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