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CERAMICS IN SURGERY

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ABSTRACT

Ceramics have entered medical practice initially by reason of their inertness and good friction and wear properties. A further interest has been in those which are progressively broken down in the body and are replaced by living tissue. These two groups are now referred as bioinert(alumina, carbon) and bioactive ceramics (calcium phosphate) respectively. The inert materials show minimal chemical or physical change during prolonged exposure to physiological media. To give some idea of the extent to which ceramics are being used in medicine, it is estimated that for the period 1975-76 to 1981 more than 30,000 alumina ceramic spherical components have been made (on the contineat) for use as the ball portion of the hip prosthesis. In many cases this component is used in combination with a ceramic cup which fits into the pelvis as the opposite part of the new joint. Dense alumina ceramics has also been investigated for dental and middle ear applications. In this article, the preparation of medical uses of calcium phosphates are considered.

1. Introduction

What are Technical Ceramics?

There are many terms used to describe the new developments in ceramics technology. "Technical ceramics", "special ceramics", "engineering ceramics", and "new ceramics" are labels used interchangeably causing a certain amount of confusion in any onloker.

The new developments tend to concentrate on different properties of the ceramic material.

Electronic Ceramics predominantly exploit electrical. properties of ceramic materials-but thermal properties such as conductivity, and physical properties such as strength and toughness must also be considered. Applications include dielectric capacitors, substrates etc.

Bioceramics are concerned with both the physical properties of the material i.e. is it strong enough to replace the natural component, and the chemical and biological properties i.e. is it nontoxic, will it bond to bone and encourage bone growth. Applications include joint and tooth replacement.

Engineering ceramics utilise primarily the physical properties of certain ceramics-strength, toughness, hardness, wear resistance and heat resistance. Chemical and electrical properties are also important in certain

aggressive environments. There exists a wide range of applications, both in the replacement of existing, metal and ceramic components and also in the development of new application areas where metallic or conventional ceramic materials fail. The applications range from weld shrouds to turbine blades from ball bearings to extrusion dies.

BACKGROUND

For centuries man has attempted to use foreign materials to repair or replace parts of the human body. Wood, ivory, glass and of course metals have all been investigated but the major developments in implant surgery have all occurred in the postwar period. One reason for this was the demands placed on surgeons during the war period and the resultant advance in techniques. The advent of antibiotics reduced the problems of infection following surgery and injury. The way was prepared for new advances and the appearance of new man-made materials catalysed the process. Metals had already reached a stage of development such that several were suitable for surgical use. Stainless steel and cobalt-chromium based alloys were available in the 1950s and the aircraft industry produced titanium and its alloys, in particular the aluminium-vanadium type. These materials in various compositions are all in regular use as implants and provide the foundation of all presently employed metal-containing devices.

It was the non-metallics, however, which made possible the major step forward. Plastics and rubbers in a variety of

forms and fibres (nylons, polyesters and acrylic) have each gained an established place. Hip joint replacement surgery using the combination of stainless steel, polyethylene and an acrylic grouting agent as a prosthesis system has given pain relief and mobility to tens of thousands of people. Knitted polyster fibre tubes have replaced numberiess arteries. Silicone rubbers have given new confidence to many by use in plastic surgery, for example in breast prostheses.

This exciting progress has not been without problems, included among them being corrosion, wear and breakage. The early aim was to produce so-called inert materials with the hope that they would have a purely passive role in the body, until it was realised that there is no such thing as total inertness in the sense in which a chemist understands the term. In fact some degree of interaction between tissue and material can be used with advantage to secure a firmer fixation by actual ingrowth of tissue into pores or surface irregularities. Positive surface interaction can improve blood compatibility for arterial replacement. Gradually the concept developed until interactive materials are now deliberately sought, and these include controlled drug release systems having a drug carried in or on a polymer. These can be targetted to specific sites and will retain activity for weeks or months.

CERAMICS AS SURGICAL MATERIALS

Ceramics have entered medical practice initially by reason

of their inertness and good friction and wear properties. A further interest has been in those which are progressively broken down in the body and are replaced by living tissue. These two groups are now referred to as "bioinert" and "bioactive" ceramics respectively, although subdivisions are also applied (Table 1).

Table 1

Bioinert-Alumina, Cerabon
Bioactive Resorbable-Calcium Phosphate
Bioactive Surface Reactive-Sillicate and ?hosphate Glasses, Synthetic Apatite

The inert materials show minimal chemical or physical change during prolonged exposure to physiological media. This excluded wear, although recent reasearch shows that this may result from environmental as well as mechanical factors. An important characteristic is that tissue will actually grow onto the surface and if a "textured" surface is provided, interlocking of tissue will stabilise the device in position in the body. In contact with blood there is no interaction and hence no clot formation. This has led to successful cardiovascular uses as components of replacement heart valves and in fact both classes of

ceramics have been used.

The resorbable bioceramics are in general materials to which the body is accustmed and normal metabolic activity removes them. Their ease of replacement makes them ideal for temporary filling of defects in bone in the mouth region. In contrast, the surface reactive group are intended to provide a scaffold for integration and bonding with living tissue. Surface coating of other materials is being investigated as a means for providing long-term stable fixation of orthopaedic implants, e.g. joint prostheses. The process involves an interchange of ions between the ceramic and the environment and the avoidance of heavy metal ions is essential. The ionic interchange offers possibilities in controlled drug release systems and these are under investigation.

To give some idea of the extent to which ceramics are being used in medicine it is estimated that for the period 1975/6 to 1981 more than 30,000 alumina ceramic spherical components, have been made (on the continent) for use as the ball portion of the hip prosthesis. In many cases this component is used in combination with a ceramic cup which

fits into the pelvis as the opposite part of the new joint.

The production level indicated is a surprising number for a fairly recent development and shows the consequence of applying a high level of research to improve an existing technology. The close collaboration between manufactures, scientists and surgeons has resulted in this being one of the best researched and docoumented areas of biomaterials development.

The bioceramic area began in 1963 when Smith reported a bone substitute comprising a 48 % porous alumina ceramic filled with epoxy resin 'Cersium' .

Early experimental success was followed by use in repairing human skull defects and less successfully in mandible replacement. There was consequent interest in developing porous ceramics since they appeared to give better healing patterns. Calcium aluminate, titanate and zirconate have all been studied. It became apparent that composition was as important as physical form and a zone of separation seen between calcium aluminate implants and bone tissue was attibuted to progressive hydration of the material inhibiting bone mineralisation. Pure alumina did not show

this feature. The improved tissue acceptance and the mechanical properties of pure dense alumina made it inevitable that this would become the main material for use in the major load-bearing

BIOINERT CERAMICS

The most important material under this heading is Alumina ceramic. The porous forms originally introduced have now mainly been replaced by the fully dense material for the reasons given in the first article. Surgical use has expanded throughout the countries of Europe from their original introduction in France and Germany, although the use in the U.K. is negligible at present. The reasons for this are the present high cost as far as the Health Service is concerned and the uncertainty as to satisfactory performance since there was no first hand experience in development of surgical grade alumina.

In Germany in particular there has been close collaboration between industry and the medical profession helped by a considerable input of Federal Government funds. A very exacting programme was initiated to develop the material. As

with all surgical devices, it is not sufficient to test one of the components of a system in isolation from the rest. Finite element stress analysis and the concepts of fracture mechanics coupled with proof testing of the final design have been extensively employed to test the products. The method of attachment of the ceramic ball to the metal stem is of particular importance and cone-cone (Morse) tapers are the most common at present though problems arising from incomplete matching of the two tapers, leading to a hoop stress in the ceramic, has led to other designs.

Table 2

Typical properties of alumina implant materials according to current standards

Chemical composition	> 99.5 % purity
Density	> 3.90 g/cm^3
Grain size	< 7 μ m
Microchardness	23000 N/mm^2
Comp. strength	> 4000 N/mm^2
Flexural strength	> 400 N/mm^2
Young's modulus	38000 N/mm^2
Impact strength	> 40 cm N/cm
Corrosion by organic acids	< 0.1 mg/m^2 per day

Some products now available or in development have superior properties to these, e.g. density approaching theoretical maximum, and lower grain size.

Table 3

Typical requirements

Long-term stability
Complete bicocompatibility
Low friction and wear
Wear debris biocompatible
High strength

BIOINERT CERAMICS

SURGICAL USES

Hip replacement surgery is one of the most outstanding innovations in joint replacement operations, and offers improvement in quality of life at a reasonably low cost. Since the early 1960's 200,000 people in Britain have had a hip replaced and approximately 15,000 replacement are carried out each year in England and Wales at a cost of around £ 18,000,000.

Basic requirements are durability i.e., the replacement joint must not fail by breakage, loosening or excessive wear. Material from which the joint is made should be 'inert' to avoid adverse reactions with the host and must be sterilisable. The process must be clinically effective in giving relief of pain and good mobility and should permit early discharge from hospital.

Detal as well as orthopaedic implants have been developed in alumina tc utilise the compression load transmission concepts. These will support a crown or more complex bridgework. Middle ear implants to replace the complex chain of bony units which transmit the sound have been found to offer a potentially useful role for aluminia as have replacements of portions of the skull. These are quite different from the load-bearing applications of joint replacement surgery but the biotolerance of the alumina is still the chief factor and the early expectations seem to have been fulfilled.

BIO ACTIVE CERAMICS

In this article, the preparation and medical uses of calcium phosphate are considered. The interest in this material for a bioceramic stems from the fact that the mineral phase of both bone and teeth is calcium hydroxy-apatite $Ca_{10}(PO_4)_6(OH)_2$. Polycrystalline calcium phosphates can be readily obtained in powdered form by precipitation from aqueous solutions and contain variable amounts of H^+, OH^- and foreign ions depending on preparative methods. In order to obtain dense material suitable for implantation, ceramic techniques have been used and for this purpose it is necessary to know in detail the factors determining stability.

There has been considerable discussion in the literature as to the formulae of products obtained under varying

conditions. Transformations, Which are pH sensitive, from one product to another are possible. It is likely that the first precipiated form is $CaHPO_4 . 2H_2O$ analogous to brushite and this hydrolyses to octacalcium phosphate above pH 6.3. The eventual end product is hydroyapatite and its formation at pH> 4 is enhanced by elevated temperatures. Hence a common method of preparation is precipitation from boiling solutions. A certain amount of F-ions in the solution accelerates the process and it is possible to prepare solid solutions of hydroxyapatite and fluorapatite.

From the ceramic viewpoint solid state reactions are of most interest. Reactions above $700^{\circ}C$ yield one calcium phosphate or a mixture. For Ca/P ratios between 1.5 and 1.7 there are two stable high temperature modifications, apatite and B-whitlockite. For a Ca/P ratio around 1.67 and a wet atmosphere, apatite is expected whereas Ca/P=1.5 and a dry atmosphere leads to B-whitlockite formation.

The biological properties of the calcium phosphates are less easy to assess and the relationships between crystal microstructure and in vivo behaviour are not clear. For their acceptability in bonetissue they appear to be the most compatible materials available. Bone is deposited directly on the ceramic and it seems that the bone becomes bonded directly to the surface in contrast to the situation with bioinert implant materials. The nature of the actual interface is not known but in the early stages of bone formation collagen fibers appear in the intermediate layer which forms at first.

APPLICATIONS OF PHOSPHATE CERAMICS

It is known to wearers of dentures that the fit will gradually worsen in the weeks following extraction of the teeth. Remodelling processes are taking place in the bone which normally holds the teeth and resorption of this bone reaches its maximum extent within six months. Since a very large proportiona of the population (about 25 %) is edentulous i.e. without teeth, this is a major problem, although to some extent a diminishing one as the standards of oral hygiene and care improve. In the long term changes in dietary habits (less sugar) and basic hygiene ought to be more significant than repair methods although injury will still present the need for action. Whereas some oral surgeons consider there is no need for dental implants, there are those who see this as an important aspect of their work in the future and especially since an increasingly longer-living population will contribute to the edentulous numbers.

Already in 1826 an American dental surgeon, Fay, settled in London, was advocating leaving tooth roots in place to prevent resorption. Reimplanted teeth have been unsuccessfully tried and also acrylic implants, which appear to be more useful for reducing bone loss. In the longer term, though, most implants are rejected and the generally unsatisfactory experiences with dental implants has led to British dental surgeons not being very enthusiastic towards the idea. Most research and development plus actual practice

has been on the Continent. Since prevention of bone resorption is important, this was one of the first areas studied with tooth root substitutes of dense apatite ceramic applied immediately following extraction.

EAR SURGERY

At present the indicated uses are for prevention of bone loss and also for reconstruction following actual loss for whatever reason. The ability of calcium phosphates to provide a means for achieving this has led to the other uses in ENT surgery. A complete middle ear implant has been made in gold alloy with apatite for the portion where bone fixation is needed. Dense implants have been tried for replacement of the chain of little bones which make up the mechanical conduction system and for ventilation tubes for drainage purposes. Numbers are still small for complete evaluation. Most of the work has been done in the Netherlands and a recent report records results in 35 patients followed up for 2 ½ years. Hydroxyapatite appears to offer a sound conduction system near to normal and retains the necessary mobility. In the device used the canal wall and conduction system were replaced in one complete unit.

Dense alumine ceramic has also been investigated for dental and middle ear applications and, in the latter, successful 6 year follow-up has been reported. At a recent symposium speakers stressed that ear surgery has not taken advantage of new developments in materials and we should expect to see

further investigations into the uses of bioactive and other ceramics.[2].

GLASSES

Having considered poly crystalline ceramics in the previous articles of the series and then the various forms of carbon, final group of materials for consideration is the glass. This represents a different direction from the development of the inert ceramics (alumina) and concentrates on controlled surface reactivity. We have already indicated that the interface between a biomaterial and living tissue is the key region in determining biological acceptance. The search for supposedly inert implantable materials so dominated research that this is a fairly recent concept. As the imperfections in methods for fixation of devices into the body became more apparent and attempts were made to improve this; so the role of interface reactions was realised. The problems of blood on foreign materials served to highlight the situation.

The beginnings of controlled reaction glasses are due to the work of Hench and colleagues (Bioglass) through other groups have now produced their own systems. In general terms, a bioglass is designed to produce specific physiological responses and these are generated by the availability of groups on the surface, silica, calcium and phosphate, and the provision of a basic pH.

Most of the work has been centred around glasses of

approximate composition 45% SiO_2, 24.5% CaO, 24.5% Na_2O, 6% P_2O_5. The glass is formed by fusing the oxides in the correct proportions and then a randomly oriented polycrystalline material is produced using a two phase thermal process. Various levels of crystallinity have been investigated. The interest stemmed from an observation that direct bonding had occurred between implants and living bone after six weeks. Compositional boundaries have been established for bonding or non-bonding compositions based on the amounts of the glass continues.

Direct bonding is attractive for dental prosthesis use since ingress of bacteria would be prevented. The reduction in Young's modulus would also improve the mechanical compatibility across the implant-bone interface. Even more so than for bone, this is of use where soft-tissue bonding is considered and in fact such soft tissue bonding has now been demonstrated. In consequence a range of clinical applications is being investigated including dental, ENT, and maxillofacial examples.

All the bioglasses which produce bonding develop a significant increase in surface area when exposed to physiological type solutions. The surface develops an active silica-rich gel and the ultra-pores of 3-30 nm size that form seem to nucleate bone mineral crystal formation. These hydroxyapatite crystals appear to provide an environment into which the natural macromolecules, collagen, polysaccharides and glycoproteins can grow. The result is a complex active surface layer which is an inorganic-organic

composite with a gradual gradient of composition across it from glass to tissue. It is this layer which accounts for the bonding properties of the material.

The biological acceptability of these glasses seems to be established and various materials have been produced, Bioglass (the original), Macor, and Cervital (a glass ceramic).

These glasses are brittle as expected and in thermselves of limited value as implant materials. It is as coatings for other mechanically acceptable materials that they have had most study. In particular with the growing interest, especially on the Continent, for the fixation of joint prostheses without the use of cold-setting acrylic cement between prostheses and bone, the bone anchoring properties of the glasses are attractive. Various porous surfaces had been and still are being studies for this purpose as has been described in earlier articles. The glasses gave the chance of a direct bond. Coatings on stainless steel have had clinical trials which confirm the bone attachment although some reports have indicated an eventual loosening as the leaching.

CaO, SiO_2 are and Na_2O present. Some of course do not form glasses; for others the reactivity is either too high or too low. The criterion for bone bonding was resistance to a push out load of Newtons. Control samples of stainless steel or alumina could be pushed out of the bone at loads below 10 Nowtons.

The glasses described above all contained silica as the network former. Another group has been reported which contains no silica but utilises P_2O_5 for the similar purpose with the tetrahedral phosphate ion providing a three dimensional structure. The oxides, as previously are fused together at 110°C and by adjustment of composition the rate of dissolution at the interface can be controlled. The Na_2O is added to the mix as NaH_2PO_4.

Annealing is important for satisfactory performance and after a suitable period, the glass can then be formed mechanically and surface treated chemically if required. Glasses studied contain between 35-60 mol % P_2O_5 and rate of dissolution can be varied from days to several years with the advantage that no residue is left behind. Many of the controlled release systems rely for their action on outer coatings or capsules, but this glass system provides for a matrix itself having a controlled and controllable rate of solution. The sodium ion, occupying the interstitial positions in the structure weakens the network and reduces glass durability. However, the calcuim oxide is an integral part of the netwcrk and inhibits alkali metal ion mobility. Thus the balance between these two provides the means for control of dissolution rate. For example, a change in mol % of CaO from 20.5 to 27 changes the dissolution rate from 1.0 to 0.5 mg/cm^2/hour in water at 38°C[1].

Rods, powders, foam, fiber and woven cloth are among the forms that can be made and capillary tubes are also

possible.

Tests for biological acceptability have been satisfactory with no toxic effects observed; in fact there was a limited reaction at soft tissue sites. Experience in bone shows that as the material dissolved is replaced by new bone filling the gab left by the dissolving glass. There are no adverse effects to data.[3]

THE CHANGING SCENE

Medical uses of materials pose a problem for the materials supplier. There are two groups of products, high volume low unit cost items typified by disposables and low volume items with a potentially high mark up. At first the amount of material required seems unattractively small but the premium charged, not unreasonable due to the requirements of the DHSS Code of Good Manufacturing Practice, should make this a worthwhile area for diversilication. Utmost attention must be given to raw materials preparation and purity as small quantities of impurities may grossly affect biological performance.

Attention has moved away from what might be termed 'engineering only' uses of materials to a deeper consideration of the complex interactions between synthetic material and living tissue. Knowledge of a spectrum of mechanical/physical properties for a material is inadequate. We also need to know mechanical interactions with the tissues and the nature of the reactions at the interface.

There is a greater appreciation of interfacial reactions and their highly specific nature. The factors which determine cell attachment to a foreign surface and subsequent growth thereon are known to involve not just the biomaterial but the tissue macromolecules which are laid down upon it as the first step occurring after implantation. The way in which these are absorbed determines the way in which cells 'see' the surface and hence their reaction to it. The subsequent 'process engineering' follows from initial sequence. Out of these studies should come a unifying principle which will permit predictive assessments to be made. This should extend not just to medical applications but may well lead to a general principle for material environment surface reactions and hence long-term action.

The Future Ceramics

Lack of chemical reactivity is a characteristic of one group of bioceramics, whereas another group is bioreactive. Wherever a highly biologically acceptable material is needed with an application for which the mechanical properties of a ceramic are appropriate, its use should increase. This will include orthopaedic and dental uses primarily. The problem areas are how to obtain a satisfactory attachment to components made from other materials especially metal and how to design the particular device to optimise in vivo requirements, generally of tissue bonding. Ceramic-metal bonding has long been of importance and many engineering applications have emerged for ceramic coatings on other substrates. Engine components and aerospace uses immediately come to mind, but medical practice should see increased uses

for coatings. Carbon coatings are already widespread in blood-contact uses. It is expected that this will develop further since the experience already exists for fairly ciritical uses in the aircraft engine industry. Coatings protect the underlying substrate material and also provide a more acceptable surface towards the external system. Metallic ions taken up into solution in body fluids from metal prostheses are likely to have longer term effects and if the body can be protected this is an advantage. The advantages of a substrate can thus be retained whilst protecting it and the environment. Apatite coated metals have been used in dental prosthesis work and appear to confirm the advantages.

The degradable/leachable glasses offer a considerable potential as temporary implants of variable duration in vivo. Allowing for tissue regeneration and also for therapeutic purposes their use needs to be further explored in both human and veterinary areas. Process control may be another potential application.

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