# Macroporous hydroxyapatite bioceramics by solid freeform fabrication: towards custom implants

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**Solid freeform fabrication is a recent technology by which prototype devices can be manufactured layer by layer under computer control. This allows the production not only of individual devices of complex shape, but also objects with an internal structure that would be impossible to make by conventional manufacturing methods. Application of this technology to the manufacture of macroporous hydroxyapatite bioceramics for bone substitute applications is discussed. A new design is described with features of conventional ceramics that are known to induce bone growth *in vivo*.**

Macroporous bioceramics based on hydroxyapatite [$Ca_{10}(PO_4)_6(OH)_2$, or HA] are of considerable interest for use as bone substitutes in skeletal repair. The pores in these materials are several hundred microns in size, and are well connected, so as to allow the penetration of bone and tissue at the surface of the implants.[1,2] Such devices are osteoinductive (induce new bone growth) under certain conditions.[3-5] While maximum porosity of the implant structure is sought for biological reasons, this must be balanced by a conflicting requirement for mechanical strength. The manufacture of highly porous ceramics is difficult, however, and the strength and reliability of such devices are of concern.[6] Some of the best materials available have been produced by chemical conversion of structures formed by nature, such as coral exoskeleton (Pro Osteon®, Interpore International) or bovine cancellous bone (Endobon®, E. Merck). Demands are emerging for materials with very specific properties, particularly for the loading of biomolecules in bone tissue engineering.[7] The ability to manufacture entirely synthetic, highly porous materials with engineered properties is becoming increasingly important.

In a companion paper,[5] an improved strategy is described for the production of synthetic porous bioceramics by modification of a conventional method. In this article we report on a new approach based on solid freeform fabrication (SFF).

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## Solid freeform fabrication

This refers to a number of recent technologies by which complex devices are manufactured on an individual basis directly from computer-aided design (CAD) models. Associated techniques involve forming structures through deposition of successive thin, patterned layers ('slices') of material that incorporates ceramic or metal powder, and subsequent processing of these 'green' structures to metal or ceramic products. The SFF approach permits not only the capability literally to build idealized structures pore by pore, but also the flexibility to manufacture implants of complex shape with great accuracy. This raises the possibility of custom implants, manufactured using a so-called CAT-CAD-CAM approach. This involves imaging a bone-defect site using a method such as computer axial tomography (CAT), designing an implant to fit the defect accurately using CAD and direct production of a custom implant for the site by computer-aided manufacture (CAM) or, more specifically in this case, solid freeform fabrication. An accompanying article[9] describes the CAT-CAD-CAM approach in the manufacture of polymer models of bone structure, which are typically used for surgery planning and evaluation of implants in difficult procedures.

Several laboratories are currently producing ceramic substitute materials by SFF.[9] Although little has been published to date, much of this activity seems to be aimed at producing structures resembling natural cancellous bone. The design proposed here is somewhat different, consisting of thin, extruded strands of HA deposited crosswise in layers and sintered to an integral structure.[10] The composite has the appearance of a three-dimensional grid, with clear open channels in two dimensions and enlarged channels in the third direction that is the primary direction of bone growth.[11] Internal spaces bounded by the strands function as macropores. The effective pore shape of the basic device is unsatisfactory, however, since the ceramic strand surfaces adjacent to the internal pores are of convex, cylindrical shape, whereas new bone grows preferentially in concavities.[3] The effective pore shape is therefore modified by placement of large hemispherical indentations around and along the length of the strands. The resulting structure comprises a macroporous ceramic with channels to direct bone growth, large macropore size, concavities of appropriate radius facing the internal pores, adjustable porosity, extremely high connectivity and variable high strength. The structure is rapidly manufactured and meets the known requirements for osteoinductivity.[3,5]

## Experimental

*Routine analysis.* Phase purity of powders and ceramics was confirmed by X-ray diffraction. Chemical composition was determined by wet chemical methods and examined for conformity to ASTM F1185-88 specification. Ca/P ratio was determined using Inductively Coupled Plasma – Atomic Emission Spectroscopy (ICP–AES). Chemical surface was examined by infrared absorption. Density and porosity were measured by Archimedes' principle. Powder and particle morphology and micro- and macrostructures were studied by scanning electron microscopy. Particle size of powders was determined by SEM/image analysis and laser scattering.

*Mechanical properties.* Mechanical testing was based on ultimate compressive strength and modulus as criteria. Specimen dimensions were nominally $10 \times 10 \times 10$ mm cubes. Measurements were conducted using a crosshead speed of 0.5 mm $min^{-1}$. The modulus was calculated between 25 and 75 % strain.

*Solid freeform fabrication method.* A proprietary powder-polymer mixture with solids loading near 55 v/o was produced by high shear compounding at 110 °C. This feedstock was extruded at 60 °C, under computer control, onto a table with three-dimensional motion to produce sequential layers of an open grid-like structure. Strands were indented during extrusion by actuator-driven pins, located at 90° intervals around the extrusion nozzle, and this structure was fired to produce an integral open, three-dimensional ceramic grid. Strand spacing and diameter of 800 $\mu$m and 400 $\mu$m, respectively, with strand indentations of 200-$\mu$m radius, were used in the present study.

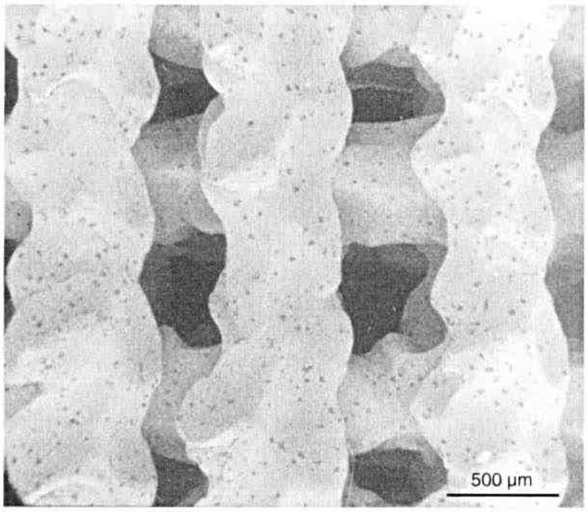


**Fig. 1**. Macrostructure of specimens produced by SFF.

*Sintering*. Specimens were sintered under conditions ranging from 1150 °C for one hour to 1260 °C for four hours. Sintering was completed within a cold-to-cold cycle of 12 hours.

Microporosity is considered beneficial to induce bone growth, although its role in bone formation is not clear.[4] For our purposes, surface roughness was further introduced by etching implants in dilute orthophosphoric acid.[5]

### Results

A typical macrostructure is shown in Fig. 1. The specimens have a distinctive regular, open appearance. Connectivity is high to the point where light can be transmitted through the channels in the structure in three dimensions. Typical defects encountered for specimens produced by this method include delamination of successive layers, hollow strands due to inadequate removal of air during extrusion, and strand cracks, particularly at junctions. These can be largely eliminated through processing.

Specimens manufactured by this method with an apparent density of 1.8 g $cm^{-3}$ exhibited an ultimate crushing strength of $19 \pm 1.7$ MPa. Crushing behaviour tended towards brittle failure at high load, with little evidence of a collapse plateau often observed for porous materials.

### Conclusion

The structure manufactured by solid freeform fabrication is simple and quick to produce with minimal processing difficulty. Required properties are achieved, particularly with regard to strength, pore size and connectivity. The strength achieved using the selected strand diameter and spacing is considered excessive for bone substitute applications without load bearing. Since the structures are adjustable, however, devices of lower strength but higher porosity are possible simply by varying strand spacing, diameter and surface cavities.

The production of a custom implant, where external dimensions have been tailored for a specific defect using a CAT-CAD-CAM approach, therefore appears to be feasible. The osteoinductive potential of the reported device has been tested *in vivo*, by implanting in heterotopic sites in baboon as described previously.[3]

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# Agony Column

## Dear Prue

**Your last column praised the benefits to South Africa when foreigners invest world-class expertise and funding to work on research projects here with local academics. But the lure of 'international recognition' among 'global players' disguises our exploitation by subtle first-world 'colonizers' — a variation on the theme of 'beads in exchange for land'. For paltry forex we're bribed to store THEIR first-world waste in OUR third-world backyards. For gratefully accepted research assistance, OUR labs and agricultural lands are requisitioned for THEIR experiments on genetically modified food plants, because THEIR public considers the work too dangerous to do back home.**

**They find — then steal — our best academics, offering glamorous research opportunities in America and Europe. Their national journals attract our best results, then publish US under THEIR imprints, promising kudos while taking away the 'Made in South Africa' brand name of research we pay for.**

**These foreign 'investors' — in effect — extract then process OUR natural and research resources for THEIR needs, sell the applications back to us for high prices — and keep us forever impoverished, begging for aid. Shame on them!**

OUTRAGED SOUTH AFRICAN

## Dear Outraged

What do you expect — free lunches? We can return to the laager and ignore the world, as we did under *apartheid*. Or go international and be exploited. Or we can get wise and start trading as equals!

Volatile economies mean foreigners look after their own interests — if they don't, nobody else will. We *can* avoid exploitation once we design smarter contracts and conditions that give each side a fair deal.

Offer third-rate journals and fifth-rate facilities to first-rate (and potentially first-rate) researchers, and they'll never do here the work that best benefits the public at home and abroad.

If SA negotiators put *low* value on our own human, natural, and research resources — and *no* value on the social, infrastructural, and risk-taking costs we carry, we're lost. If then, to solve our problems, we put *high* value on imported consultants (who don't live with the consequences of their recommendations) we can blame only ourselves if we're exploited. Proper value, support and networking at home and elsewhere is the winning formula!

**Any problems?** Write to Auntie Prue c/o *South African Journal of Science* (e-mail: sajs@nrf.ac.za)