Hydroxylapatite Coatings for Fixation of Orthopaedic Implants to Bone

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Hydroxylapatite (HA), a form of calcium phosphate, is the mineral phase of bone and contributes about 40% to bone volume and 70% to bone weight. In the 1970s, in vivo studies of synthesized dense and porous forms of HA showed that it ‘becomes chemically bonded to bone via naturally-appearing bone cementing mechanisms‘1. Subsequently, application of HA as a fixation coating for orthopaedic implants was developed in 1985 by Ronald Furlong in Britain2 and in 1986 separately by Rudolf Geesink in the Netherlands3.

Today, many thousands of HA coated total hip and knee components have been implanted worldwide. Clinical follow-up studies show rapid adaptation of bone to HA coated implant surfaces with impressive implant survivorship.

Basic Science

Calcium phosphate ceramics have been used to fill dental defects since 19814. However, the materials are brittle, with low tensile strength and poor impact resistance. For weight bearing implants the mechanical solution was to apply an HA coating to a metal substrate; the metal providing the mechanical strength and the HA coating the biological interface for bone attachment. Most often, HA is applied to metal using a high temperature plasma spray with an arc temperature of 30,000 degrees Kelvin. The HA powder is fed into the arc using argon as the carrier gas and is projected at high velocity onto the metal substrate5. For a hip stem, a coating of about 100 micrometers in thickness is built up in two minutes. Careful controls ensure that the final coating is primarily HA, rather than the more soluble beta-tricalcium phosphate.

Studies of HA coated cortical plugs6, intra-medullary rods4 and hip implants5 in animals confirm that when implanted in bone, new bone forms directly on the HA surface and the bone adapts to the implant contours6.

Examination of the bone/implant interface at high magnification shows bone bridges between bone and the HA surface (Figure 1). Implantation of uncoated control implants shows development of a seam of fibrous tissue between the implant and bone. Comparison of the mechanical strength of HA coated and uncoated implant-bone interfaces confirms the superior mechanical properties of the coated devices5. Defects and gaps of up to 1mm at the fixation interface fill with bone in the presence of an HA coating5,6 with gap filling confirmed even in the presence of interface micromotion5,6.7.8

Figure 1: Bone bridge between HA coated titanium alloy implant (left) and surrounding bone in a canine intramedullary implant (polarized light)
Experimental evidence suggests that the longevity of HA coatings in vivo depends on coating density, crystallinity and purity\(^1\). Bone formation begins with dissolution of calcium and phosphate ions from the coating, followed by precipitation of carbonated apatite on the implant surface and new bone formation on both the coating and the bone surfaces\(^11,12\). For a plasma sprayed coating, high crystallinity of the HA is required for coating persistence in vivo, while a small quantity of tricalcium phosphate (<5%) in the coating allows dissolution to start bone formation. For implants with an ingrowth (porous) metal coating, animal studies show that a hydroxylapatite-tricalcium phosphate (HA-TCP) mixture applied to the porous metal by plasma spray accelerates bone ingrowth into the implant pores\(^13\). Solution deposition of HA on porous implants, with the coating nucleated and grown on the implant in solution, shows similar enhancement of bone ingrowth into porosities\(^14\). Plasma-sprayed HA and ingrowth HA-TCP coatings have been used with success in clinical studies. However, most long-term clinical studies are with on-growth coatings.

HA Coatings and Joint Replacement

The first comprehensive articles documenting clinical findings with HA coated implants were published in 1993\(^1\). Later reviews\(^15,14,16\) documented excellent survivorship of HA coated femoral stems at five, ten and fifteen-years. Long-term survival of on-growth HA stems at more than fifteen-year follow-up are available now in the literature\(^17,18\), with anecdotal reports of excellent survivorship at 25 year post-surgery. Radiographic studies of HA coated femoral hip stems show positive remodeling of bone and a "quiet" bone implant interface. Early bone remodeling stabilises until ten years post surgery\(^17\). Longer radiographic follow-up studies suggest that bone remodeling can begin again after ten years\(^20\) (Figure 2), perhaps because of reduced patient activity with age or because of age related mineral changes in the supporting bone.

In the acetabulum, initial five-year results with HA coated acetabular components were disappointing. In comparison to HA coated threaded (screw) cups and to porous cups, smooth HA cups showed an unacceptable loosening rate\(^21\). Analysis of the cup interface suggested the smooth metal/HA/bone inferior to the acetabulum failed to withstand tensile stresses as the pelvis flexes during activity. The solution was to apply a roughened titanium "bond coat" to the implant. This allowed mechanical interlock between the HA and the metal and interlock between the bone and the coating. Rough surface HA coated cups now show similar survivorship to that of HA coated hip stems\(^22,23\).

In the knee, HA coated total knee arthroplasties have been compared to controls that were fixed by cemented or porous fixation. Results suggest that HA coated tibial implants are more stable than their porous coated counterparts\(^24\). In a comparison study of HA coated versus uncoated grit-blasted tibial components, there were fewer radiolucentencies with the coated implants (suggesting superior stability) but little difference in short term survivorship of the two designs\(^25\). An experimental fixation strategy to limit stress shielding by partially coating knee implants showed lucent radiographic lines in the uncoated areas, but excellent survivorship\(^26\). When used in unicompartmental knees, an HA coating was shown to speed patient rehabilitation, improve bone adaptation to the implant and provide exceptional clinical survivorship\(^27,28\).

Discussion

An early finding that an HA coating may be digested by osteoclastic activity caused concern for long-term implant survivorship\(^29\). The concern was resolved by findings in autopsy specimens of new bone formation in intimate contact to implant contours\(^29,30\) and by radiographic reports of a continued stable implant/bone interface in the hip at more than fifteen years post implantation\(^17,18\). In the knee, HA coated tricompartmental knee replacements are successful but do not show any clear advantage over cement fixation. For HA coated unicompartmental knee replacements results are superior to cemented designs. In general, patients with HA coated implants report more rapid recovery than recovery with other cementless fixation strategies. At least in the hip, this rapid patient rehabilitation, positive bone remodeling and superb very long-term survivorship suggests that HA coated implants are the gold standard that others must reach.

Michael Manley FRSA, PhD was, until recently, the Chief Scientific Advisor to Stryker Orthopaedics in Mahwah, New Jersey, USA. He retired from that position in December 2016 and now is the President of his own company (Michael T. Manley FRSA, PhD, LLC) specialising in providing consulting services in Biomechanics, Biomaterials and Clinical Research. Since 2007, he has been a Visiting Professor at the University of Bath, UK. He continues to publish the results of clinical studies as well as manuscripts that describe the impact of Federal health policy on the outcomes of hip and knee replacement in the US.

References

References can be found online at www.boa.ac.uk/publications/JTO or by scanning the QR Code.