Effect of Surface Chemistry on the Rate of Osseointegration of Sintered Porous-Surfaced Ti-6Al-4V Implants

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Purpose: *The effect of adding a thin sol-gel–formed calcium phosphate (CaP) coating to sintered porous-surfaced titanium alloy (Ti-6Al-4V) implants on rates of initial bone ingrowth was investigated.* ***Materials and Methods:*** *Control implants (as manufactured) and similar implants with sol-gel CaP coatings were randomly placed in distal femoral rabbit condyles (1 implant/leg). After healing for 6, 9, 12, and 16 days, 8 of 10 rabbits in each time group were assessed for maximum implant pullout force (N) and interface stiffness (N/mm). Selected extracted implants also were examined by secondary electron imaging to characterize affected surfaces. The implants of the remaining 2 rabbits in each group were examined by backscattered scanning electron microscopy (BSEM).* ***Results:*** *Significantly greater pullout forces and interface stiffness were found for CaP-coated implants at 6 and 9 days. At 6 days, BSEM revealed bone ingrowth on CaP-coated implants but not on control implants. Secondary electron imaging and BSEM observations also suggested greater bone ingrowth with CaP-coated porous implants at 9, 12, and 16 days.* ***Discussion:*** *Sol-gel–formed CaP surface films significantly enhance rates of bone ingrowth into sintered porous-surfaced implants.* ***Conclusion:*** *This surface treatment may have a number of clinical benefits, including shortening the period prior to functional loading of such implants and improving treatment outcomes in situations of poor bone quality and/or quantity.* (More than 50 references) INT J ORAL MAXILLOFAC IMPLANTS 2004;19:19–29

Key words: *calcium phosphate, dental implants, surface properties*

The use of endosseous dental implants to restore missing teeth has become routine clinical treatment. A key prerequisite to ensure direct bone apposition at the bone-implant interface (ie, osseointegration) is adequate primary stabilization of the implant during early healing.[1,2] In dense bone of adequate volume, this condition is often easily achieved by using long, threaded implants, either in the as-machined condition or with various surface modifications. However, implants placed in bone of low density and/or inadequate quantity are at greater risk of not satisfying this necessary condition. Indeed, the resulting relative micromovements are recognized as one of the main causes of failure to establish osseointegration.[3–5] Therefore, ongoing research continues to be directed toward strategies to improve initial implant stabilization, reduce the susceptibility of implants to small micromovements, and accelerate the rate of osseointegration around implants, especially in these more challenging sites.

Modifications to implant surface geometry and/or chemistry have been shown to be effective in accelerating bone formation and achieving reliable implant fixation in difficult situations.[6] For example, machined threaded implants can be modified by additive surface treatments (eg, plasma spraying with titanium [Ti] or calcium phosphate [CaP]) or subtractive treatments (eg, grit blasting or acid etching). The resulting surface textures, ranging in dimension from 1 μm (eg, "pit" depths and cross

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Fig 1 Nine-mm-long, sintered, porous-surface implants with a 1-mm machined collar segment. *(Left)* CaP-coated implant; *(right)* control implant.

sections of acid-etched surfaces) to 50 μm or more (eg, protrusions and depressions on plasma-sprayed surfaces), appear to promote faster osseointegration, possibly through a mechanism involving the retention of fibrin clot at the interface zone and its role as an osteoconductive scaffold for osteoprogenitor cell migration toward the implant surface.[7] As well as influencing the osseointegration rate, these surface features will, to varying degrees, influence the ultimate degree of mechanical interlocking at the bone-implant interface.[6,8,9]

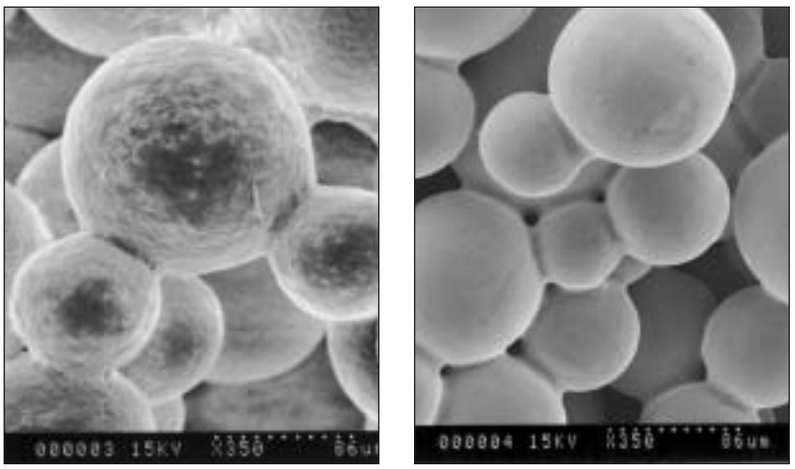
Dental implants with a sintered porous surface zone also provide such benefits.[6] The unique 3-dimensional interconnected porosity of this design has been shown to be more osteoconductive than smooth (polished) surfaces.[10] Such porous-surfaced implants have also been shown to promote faster osseointegration compared with Ti plasma-sprayed implants in rabbit femoral condyle sites.[11] Further, human clinical data have shown that such implants can be used in significantly shorter lengths than threaded implants and that they perform well in sites such as the posterior maxilla, where low-density bone is commonly encountered.[12–16]

Alteration of the chemical composition of an implant surface by application of CaP coating is another avenue that has been used to improve the osseointegration of dental implants in low-density bone.[17] There is a consensus in the literature that CaP coatings are osteoconductive and accelerate implant site healing.[18–28] However, the long-term outcomes of dental implants prepared with plasma-sprayed CaP coatings have not been that favorable. Abnormal numbers of late implant failures (after 5 or more years of clinical function) have been reported with this type of implant.[29–31] In those studies the CaP coating was applied mainly by plasma spraying. Such coatings have generally been relatively thick (30 to 50 μm), weakly adherent to the underlying substrate,[32] and subject to delamination.[20,32–34] As well, the composition of the plasma-sprayed CaP coatings has been shown to be heterogeneous, consisting of a number of different phases of CaP, including calcium hydroxyapatite (HA), tetracalcium phosphate, tricalcium phosphate, and amorphous CaP. Some of these phases are readily soluble in vivo,[35] resulting in concern over the structural integrity and stability of such coatings.[33,34]

More recent developments in dental implant design have made use of very thin (1 μm or less) CaP surface films coated onto metal implants.[36–38] One method for forming such thin film coatings is using wet chemical sol-gel processing. This uses a dip-coating procedure followed by annealing, resulting in the formation of a thin (0.1 to 0.5 μm) CaP film over a metal substrate.[37] The resulting CaP film is coherent and strongly adherent to the metal substrate.[37,39] Given that CaP coatings appear to favor osteoconduction, the objective of the present study was to investigate whether the deposition of a sol-gel–formed CaP coating onto sintered porous-surfaced implants would result in more rapid osseointegration. The study focused on a comparison of titanium-aluminum-vanadium (Ti-6Al-4V) sintered porous-surfaced implants with or without the addition of a sol-gel–formed CaP film over the sintered porous structure. The response after 6- to 16-day healing periods with the 2 types of implants was assessed by mechanical pullout testing, scanning electron microscopy (SEM), and qualitative histologic assessment of the interface zone tissues using light microscopy and backscattered scanning electron microscopy (BSEM).

MATERIALS AND METHODS

The implants used in this study were based on commercially available endosseous dental implants (Endopore; Innova, Toronto, Ontario, Canada). They were made of Ti-6Al-4V and had a tapered (about 5 degrees) truncated conical shape, a length of 9 mm, and a maximum coronal diameter of 4.1 mm. Each implant had a 1-mm-long machined collar segment; the remainder of its length was prepared with a sintered, porous surface region of defined porosity as previously described[6] (Fig 1). This porous surface region was approximately 300 μm thick, consisting of 2 to 3 layers of sintered spherical particles of Ti-6Al-4V, and had a 3-dimensional interconnected porosity with pore sizes ranging from approximately 50 to 200 μm.



Figs 2a and 2b SEM of sintered region (original magnification ×350). *(Left)* CaP-coated implant; *(right)* as-sintered control implant.

The control implants were used as provided by the manufacturer. Experimental implants were prepared in the laboratory by modifying as-received implants through the addition of an ultrathin layer of CaP to the sintered porous surface by sol-gel coating using the solution described elsewhere[37,39] (Figs 2a and 2b). Briefly, calcium nitrate and ammonium dihydrogen phosphate–containing solutions, formulated to give a Ca:P molar ratio equal to 1.67, were prepared for film deposition. Following careful cleaning of the implant surface, the sol-gel film was applied using a multiple-dip coating procedure to progressively build up a film of desired thickness. Final annealing involved a 500°C, 10-minute treatment in air.

For characterization of the CaP coatings, thick, flat disks of Ti-6Al-4V (10 mm diameter by 2 mm thick) were subjected to a simulated sinter anneal heat treatment (to develop surface characteristics resembling those of the surface of the sintered particles that formed the porous-surfaced implants) and were CaP coated using the same procedure used for coating the porous-surfaced implants. The resulting CaP film was examined by thin-film x-ray diffraction (TFXRD) and reflective mode–Fourier transform infrared spectroscopy (RM-FTIR). The chemical composition of the film surface was assessed by x-ray photoelectron spectroscopy (XPS), and the film morphology and thickness were assessed by direct examination using SEM of ground and polished CaP-coated porous-surfaced implants.

Surgical Procedure

The surgical technique and procedures followed those described by Simmons and coworkers.[11] All implants were placed transversely in the femoral condyle of mature (3.6 to 3.8 kg), pathogen-free New Zealand White rabbits. All rabbits were housed for a 1-week conditioning period prior to the surgical procedure. They were anesthetized by induction with 0.5 mL ketamine (100 mg/mL) and 0.5 mL acepromazine (10 mg/mL) and maintained with isoflurane (1.5% to 2.5%).

Implants were placed in the flattest area of the medial surface of the femoral condyle, midway between the anterior and posterior surfaces of the condyle and distal to the growth plate. Osteotomy sites were prepared as recommended by the manufacturer, with dental burs and generous saline irrigation during the drilling procedure. To ensure a tight press-fit of each implant, the diameter of the final tapered implant bur was slightly undersized, and the implants were seated using a driver and surgical mallet with gentle tapping. Intraoperatively, 0.5 mL of enrofloxacine (Bayer, 30 mg/mL, Toronto, Ontario, Canada) was administered and then continued for 6 days to minimize the risk of wound infection. To manage postoperative discomfort, transdermal patches containing 2.5 mg of fentanyl were applied to the neck of the rabbits for the first 3 days postoperatively.

Based on the results of previous work,[11] 40 rabbits were selected for the present study. Implants were placed in a randomized fashion. Every rabbit received a control implant in one condyle and a CaP sol-gel–coated implant in the contralateral condyle. Four groups of 10 rabbits each were used to allow assessment of interface healing at 6, 9, 12, and 16 days postimplantation. Animals were terminated by lethal injection of T-61 euthanasia solution (Hoechst Canada, Regina, Saskatchewan, Canada).

Mechanical Tests and SEM Examination

Eight of the 10 rabbits in each group were used for mechanical pullout testing. This was done within 2 hours of specimen collection using standardized

methodology as described by Simmons and coworkers.[11] A customized loading device was used to attach the implants to a universal testing machine (Dynamic Testing Machine, Model 8500; Instron, Canton, MA). Mechanical testing was accomplished under displacement-controlled loading, with crosshead displacement rates of 1 mm/min. The loading device was attached to each implant via the implant's internal threaded region. The tapered shape of the implant and its axial alignment parallel to the direction of force application ensured that the force-deflection curves reflected the properties of the bone-implant interface zone (a region approximately 100 to 200 μm wide), since any frictional forces related to bone-implant contact would be lost as the tapered implant was withdrawn. The force-deflection curves were used to determine force for pullout and stiffness of the interface zone tissues (using the linear portion of the force-deflection curve) for each set of 8 implants. Appropriate statistical tests (see below) were used to compare the differences between the mean pullout forces and maximum stiffness for control and experimental implants at the 4 healing times. Following pullout testing, the extracted implants were temporarily stored in 10% formalin, and then dehydrated, critical point dried, and coated with a thin platinum layer. Selected samples were examined in the SEM by secondary electron imaging.

Histologic Examination

Implants from 2 of the 10 rabbits in each group (6, 9, 12, and 16 days) were assigned for qualitative histologic assessment. Nondemineralized sections of implants and surrounding bone were prepared by methods routinely used in the laboratory.[40] These sections were about 30 μm thick and were stained with a 1:1 mixture of 0.3% toluidine blue and 2% sodium borate. The sections were rinsed with 70% and 100% ethanol before staining using light green (0.3% Light Green SF in 2% acetic acid) (Fisher Scientific, Nepean, Ontario, Canada). To observe the bone-implant interface, the sections were examined by transmitted light microscopy and then platinum sputter-coated and examined using BSEM.

Statistical Analysis

Descriptive statistics (means and standard deviations) were computed for the dependent variables pullout force (N) and maximum stiffness (N/mm) for each implant type and healing time. To account for the paired nature of this study, differences in pullout force and maximum stiffness between the 2 implant types were analyzed with the Wilcoxon matched-pairs signed rank test. Statistical tests were 2-tailed at $P < .05$.

RESULTS

A complete characterization of the sol-gel–formed CaP film is presented elsewhere.[39] In summary, TFXRD spectra from the flat disk samples indicated that the CaP film was a poorly crystallized HA. RM-FTIR identified the presence of phosphate, carbonate, and hydroxyl groups. XPS analysis of the heat-treated samples showed that the Ca/P ratio in at least the outermost region of the film was equal to 1.46. The 500°C annealing treatment, therefore, resulted in the formation of a carbonate Ca-deficient HA film. SEM examination of the CaP-coated implants showed a crack-free, uniform film over the entire surface of the sintered Ti-6Al-4V particles. Features resulting from the sintering process, such as thermal etch lines on the particles,[6] were still distinguishable. Only a slight masking of these features and a slight roughening of the particle surface resembling an orange peel texture resulted (Fig 2a). Examination of polished cross sections of the CaP film indicated that the film was about 1 μm thick.[39] The CaP film did not occlude the 3-dimensional porous structure of the as-received implants.

Day 6 Samples

During osteotomy site preparation, in 2 of the 10 rabbits, extremely dense and nonbleeding bone was observed, an outcome that was noticeably different from the other 8 animals. Highly vascular bone is considered to be a prerequisite for optimal implant fixation through bone ingrowth with sintered porous-surface implants,[41] and therefore, although the measured pullout forces and stiffness values for the 2 "nonbleeders" were not unreasonable, the samples from these 2 animals were excluded from the analysis of the mechanical pullout testing.

Considering the remaining 6 animals tested, significantly ($P < .05$) greater pullout forces and interfacial stiffness values were found for the CaP-coated implants versus the control implants (Table 1, Figs 3a and 3b). These results concurred with qualitative SEM observations (Figs 4a and 4b), in which more extensive interdigitation of fibrin and collagen matrix with the 3-dimensional porous structure of the CaP-coated implants was suggested. As well at 6 days, the integrity of the CaP films appeared unchanged. BSEM also suggested close apposition of new mineralized bone to the CaP-coated implant and more complete penetration of the sintered porous region by the mineralized tissue, in contrast to the structures observed with the control implants (Figs 5a and 5b). The presence of newly formed bone within the CaP-coated sintered porous region was confirmed by transmitted light microscopy of

Table 1 Maximal Interfacial Tissue Stiffness and Maximal Load

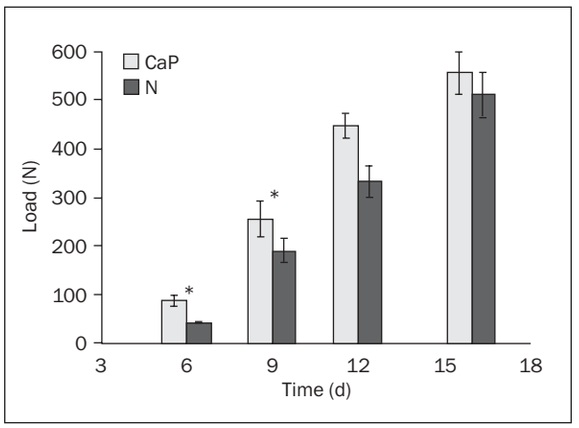
Time/ rabbit no.	Stiffness (N/mm)		Load (N)	
	CaP	Control	CaP	Control
Six days				
1	500	113	117	37
2	311	257	56	41
3	366	236	119	32
4	276*	421*	61*	75*
5	249*	197*	41*	86*
6	447	178	82	41
7	165	159	83	44
8	132	101	60	39
Mean ± SD	320 ± 148	174 ± 63	86 ± 27	39 ± 4
Nine days				
1	641	441	275	242
2	782	542	320	259
3	858	575	417	263
4	519	363	174	116
5	344*	380*	81*	171*
6	687	627	177	202
7	393	89	141	52
8	596	532	273	171
Mean ± SD	639 ± 157	453 ± 183	254 ± 97	186 ± 79
Twelve days				
1	653	606	409	426
2	734	435	485	257
3	595	459	333	339
4	762	349	473	250
5	902	347	501	286
6	**	**	**	**
7	242*	776*	310	397
8	708	855	466	421
Mean ± SD	725 ± 105	508 ± 194	444 ± 62	329 ± 78
Sixteen days				
1	588	695	329	401
2	603	527	489	565
3	757	359	434	302
4	715	722	558	718
5	1031	916	639	551
6	1066	867	623	586
7	943	595	676	518
8	1095	605	668	410
Mean ± SD	859 ± 209	661 ± 181	552 ± 125	506 ± 130

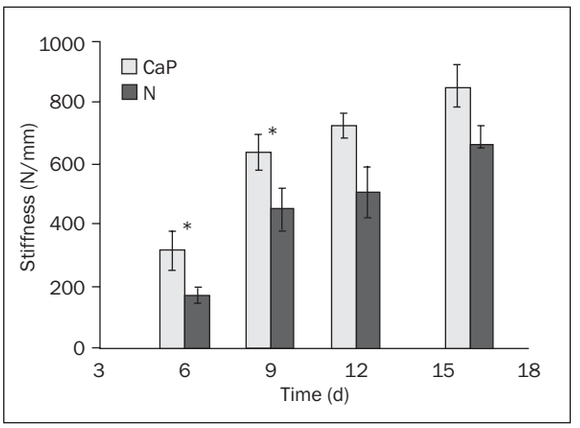
*Nonbleeding osteotomy site; results excluded.
**Fracture of the loading rod.

the samples prepared for histology, while osteoid only was observed within the porous region of the control implants.

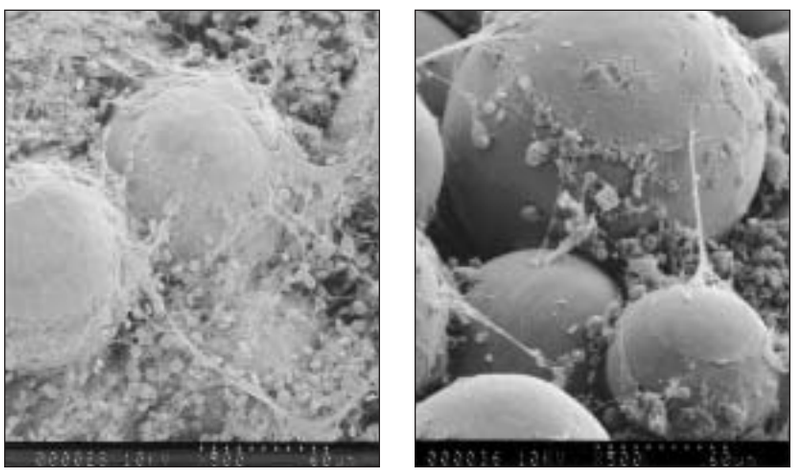
Day 9 Samples

In this group, 1 rabbit femur in which a CaP-coated implant was placed had very dense, nonbleeding bone, and for the reasons discussed above, it was not included in the statistical analysis of the mechanical test results. Testing of the remaining 7 animals demonstrated that the interface zone stiffness and strength of attachment of the CaP-coated implants was significantly greater ($P < .05$) than for the control implants (Table 1, Figs 3a and 3b). SEM examination of the surface of pulled out implants suggested more extensive interdigitation of newly formed tissue within the porous region of the CaP-coated implants compared with the control implants (Figs 6a and 6b). Examination of the sections prepared for histology indicated both bone and osteoid

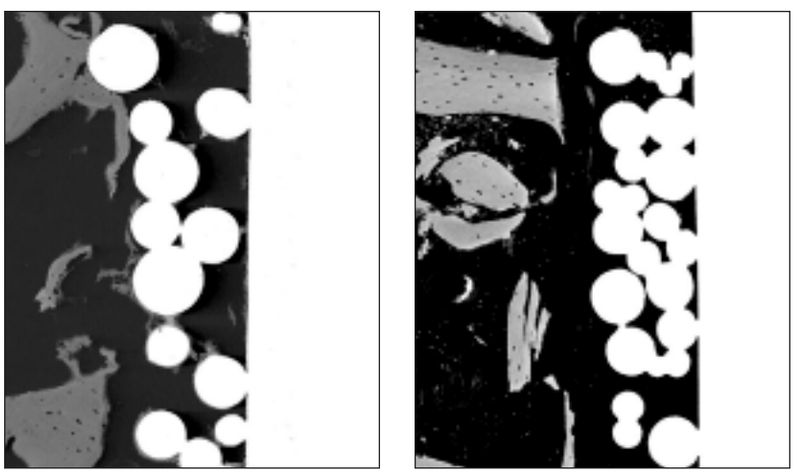




Figs 3a and 3b *(Left)* Pullout forces and *(right)* interface zone stiffness at different times postimplantation (means ± SE). The CaP-coated implants showed significantly ($P < .05$) greater pullout force and interfacial tissue stiffness at 6 and 9 days. *$P < .05$.

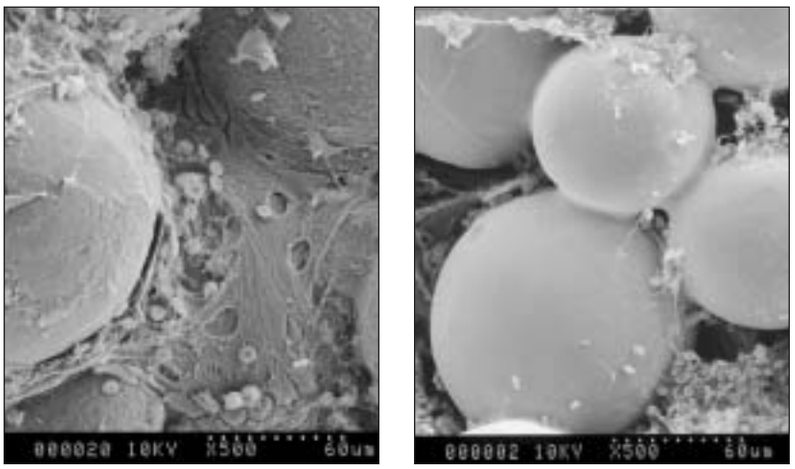


Figs 4a and 4b SEM of 6-day pulled out implants indicating more extensive fibrin-collagen matrix formation with the porous region of *(left)* the CaP-coated implants compared with *(right)* the control implants. Note the presence of red blood cells within the tissue matrix (original magnification ×500).

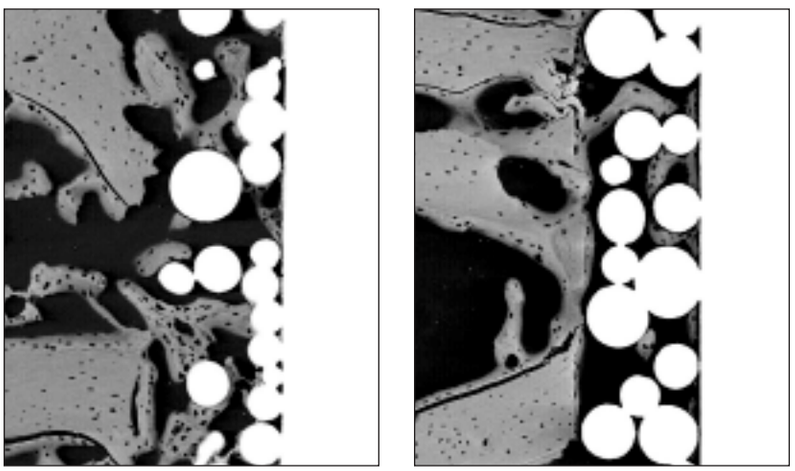


Figs 5a and 5b BSEM of 6-day implants (×100). *(Left)* CaP-coated implants showing mineralized tissue in close apposition to and within some regions of the CaP-coated porous region; *(right)* absence of mineralized tissue apposed to or within the porous region of the control implant.

within the porous region, but with more mineralized tissue associated with the CaP-coated samples. There was evidence of loss of CaP coating from the most exposed regions of the sintered particles (ie, the outer surface of the top particle layer). BSEM of ground and polished sections confirmed the presence of newly formed bone throughout the thickness of the porous region of both implant types but suggested more extensive bone interdigitation and contact with the CaP-coated implants (Figs 7a and



Figs 6a and 6b SEM of 9-day pulled out implants (original magnification ×500). More extracellular matrix material appears within the porous surface region of *(left)* the CaP-coated implants versus *(right)* the control implants.



Figs 7a and 7b BSEM of 9-day implants (×100). *(Left)* New mineralized bone ingrowth is seen in close apposition to the CaP-coated implants, in contrast to *(right)* the structure observed with the control implants.

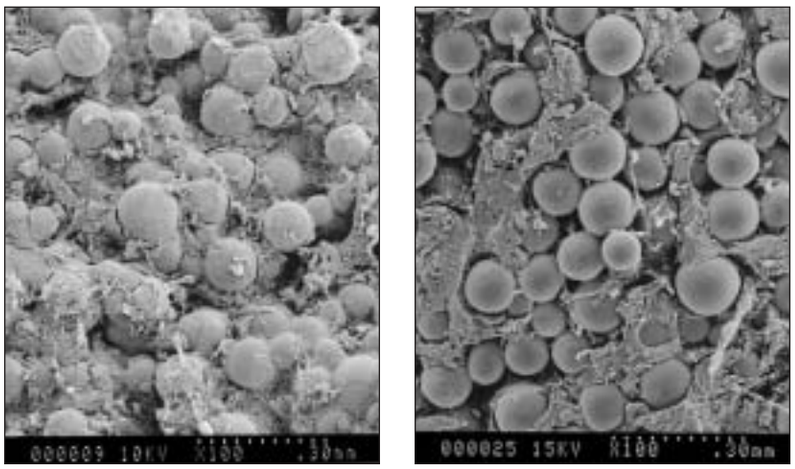
7b). This observation was in agreement with an earlier study that used sol-gel–formed, CaP-coated, porous-surfaced implants placed in rabbit tibial sites for 2-week periods.[42] That earlier study used somewhat different processing to form the CaP film, although a similar CaP structure resulted.

Day 12 Samples

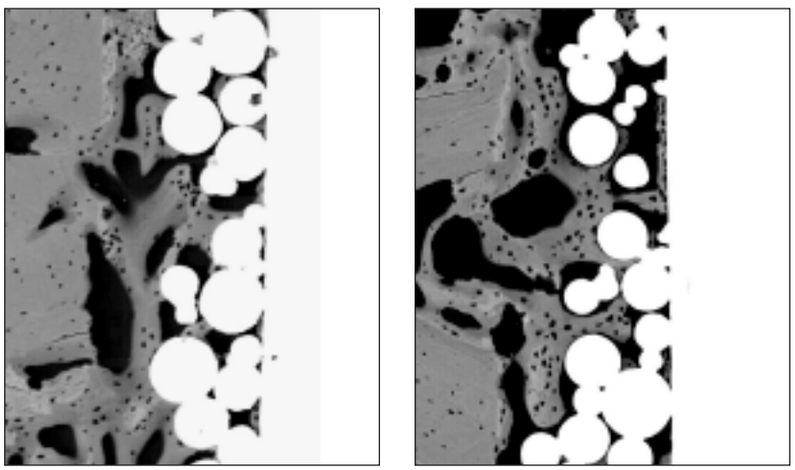
In the 12-day group, 2 animals were excluded from analysis of the mechanical test results; one because it was a nonbleeder and the other because of higher pullout forces, which caused fracture of a part of the loading jig during testing. While no statistically significant differences in pullout strength or interfacial stiffness were observed between the 2 implant types at 12 days, there was a trend toward greater pullout forces with the CaP-coated implants (Table 1, Figs 3a and 3b). Light microscopy and SEM revealed that extensive mineralized bone matrix had formed and interdigitated with both implant types. Examination of the pulled out CaP-coated implants indicated that by 12 days most of the CaP coating was absent from the outermost surface of the top layer of the sintered particles. Presumably, at the high force levels imposed during testing, fracture through ingrown bone segments occurred, resulting in separation of the bone from the outermost surface of the particles. As well, qualitative observation by BSEM suggested more extensive new bone formation and bone-implant contact with the CaP-coated implants.

Day 16 Samples

After 16 days, no significant differences were detected in mechanical test results between the CaP-coated and the control implants. However, the CaP-coated implants did show a trend toward greater interfacial stiffness (Table 1, Figs 3a and 3b). While SEM examination indicated extensive interdigitation of tissue formation with both implant types, subjective qualitative assessment suggested that there was more mineralized tissue in close (virtually direct) contact with the CaP-coated samples (Figs 8a and 8b). This was particularly evident in the deeper regions of the concavities associated with the sintered



Figs 8a and 8b SEM at 16 days (original magnification ×100). *(Left)* CaP-coated implant, *(right)* control implant. The former appeared to demonstrate closer apposition of newly formed bone within the pores of the CaP-coated Ti-6Al-4V.



Figs 9a and 9b BSEM of 16-day implants (magnification ×100). *(Left)* CaP-coated implants; *(right)* control implants.

necks. The BSEM images (Figs 9a and 9b) gave a clearer indication of this difference, with more extensive filling of the sintered neck regions being evident for the CaP-coated implants. Again, the majority of the outermost surface region of the top layer of particles appeared denuded of the CaP surface film.

DISCUSSION

The aim of this study was to investigate whether sintered porous-surface Ti-6Al-4V implants coated with a thin CaP film using sol-gel deposition would accelerate the early healing events of osseointegration and significantly alter the nature of the interface zone during the early postimplantation period. The mechanical test results suggested that this was the case, as early implant stability, denoted by both increased pullout force and increased interface stiffness, was found for the CaP-coated implants. The significantly greater force needed to break the anchorage of the CaP-coated implants is in agreement with previously reported studies,[18–25] although it should be noted that the tests used in the present investigation were performed much sooner after implant placement.

The reason for the higher pullout forces for the CaP-coated implants was revealed through the SEM and BSEM examinations. After 6 days of healing, newly formed bone was observed in direct contact with the outermost surface as well as within the porous region of the CaP-coated implants, while this was not the case with the control implants (the latter were devoid of mineralized tissue within the porous region at 6 days). In addition, it appeared that there was more extensive bone formation within the porous region of the CaP-coated implants at all time periods studied. This would be expected to result in greater interface stiffness and pullout force, as was observed for the CaP-coated implants at all time periods, although the difference was shown to be statistically significant only at 6 and 9 days. In addition to the reinforcing effect caused by more extensive bone formation within the

porous region, which resulted in higher stiffness and strength (ie, formation of an interpenetrating composite of bone and CaP), the slight texturing that resulted from the CaP coating might have contributed to more effective coupling at the bone-implant interface through additional mechanical interlock. The effect of enhanced chemical bonding, either to bone directly or indirectly through adsorbed protein layers, has also been proposed as an effect associated with CaP surfaces that might have contributed to the observed results.[43] However, the magnitude of the observed differences in measured interface stiffness and pullout force for the CaP-coated versus the control implants (Figs 3a and 3b) would seem to favor the mechanical interlock explanation.

In the present study, the apparent superior osteoconductivity of the CaP-coated implant design was clearly suggested by the mechanical test results at the earlier postimplantation times studied (6 and 9 days). At later times (ie, 12 and 16 days), the pullout force and interface zone stiffness of the experimental and control implants were not significantly different. The similar results for the 2 designs at these later times might have been anticipated, since previous studies have suggested the osteoconductive nature of sintered porous-surfaced implants.[10,44] Nevertheless, the addition of a thin CaP surface coating over the sintered particles forming the porous structure may present a clinical benefit by decreasing overall times for osseointegration or in allowing reliable implantation in bone of low density or marginal quantity (ie, for endosseous dental implants placed in sites with less than 3 mm of bone height below the maxillary sinus floor or in severely atrophied mandibular crestal bone, particularly in the posterior region).

Dental implants placed in areas of poor bone quality and/or inadequate quantity may be more susceptible to displacement because of inadvertent early loading forces. Relative displacements greater than some critical amount may inhibit new bone formation and result in fibrous tissue anchorage or even fibrous tissue encapsulation of implants in extreme cases.[45–48] The magnitude of relative displacement is directly related to the forces acting on the implant and the interface zone stiffness. The stiffer the interface zone, the lower the displacement for a given loading condition. In the present study, CaP-coated implants displayed significantly greater interface stiffness than control implants ($P < .05$) at 6 and 9 days. The clinical significance of these results can be derived from Fig 3b, which shows that the same interface stiffness levels seen at days 6 and 9 with CaP-coated implants were not reached by the control implants until about days 8 and 16, respectively. Given that rabbit bone forms approximately 3 times more rapidly than human bone,[49] the difference in time to achieve a certain interface stiffness would become even more dramatic in humans. For example, at 27 days in the human (ie, the equivalent of 9 days in the rabbit), the CaP-coated implants might be expected to have an interface stiffness that would be reached only 3 weeks later with uncoated, sintered, porous-surfaced implants.

A previous study[47] suggested a critical level of relative displacement of approximately 50 μm for inhibition of significant bone ingrowth with porous-surfaced implants. Considering the data shown in Fig 3b, at 6 days for the uncoated porous-surfaced implants (ie, controls), this level would be exceeded if a critical displacing force (F_c) of approximately 8.7 N acted axially on the implant (ie, stiffness at 6 days would be about 174 N/mm or 8.7 N/50 μm). For the CaP-coated implants, this critical axially oriented displacing force would be approximately twice that value (ie, stiffness at 6 days would be about 320 N/mm or 16 N/50 μm). With progress in healing, the difference in F_c for the 2 implant designs would become smaller, indicating the great importance of very early loading conditions on success or failure to achieve osseointegration. The potential advantage of a CaP surface modification that benefits very early tissue integration through increased interface zone stiffness is obvious.

The present results appear to demonstrate that chemical modification of sintered porous-surfaced implants can accelerate the osseointegration process. However, it is important to point out that the sol-gel CaP film used did introduce some additional surface texture (orange peel–like topography), and this superimposed surface topography may have contributed to the accelerated healing response. The effect of surface topography in enhancing the osseointegration rate has been proposed by others.[7,50]

Deporter and coworkers[51] had reported the failure to integrate of 3 sintered porous-surfaced dental implants (Endopore) placed in nonbleeding osteotomy sites in a clinical trial patient. Four of the rabbits used in these studies displayed minimal bleeding during implant site preparation, which was noticeably different from the osteotomy sites prepared in the other animals, which bled profusely. For this reason, the authors chose to exclude these from the analysis, since this would introduce a further variable influencing initial implant stability and bone ingrowth rate.

Earlier work with dental implants coated with relatively thick (30 to 50 μm or more) CaP surface layers applied by plasma spraying had indicated

improved early performance in bone of low density, as is common in the maxilla. However, late failures were frequent with these implants, and these were linked to bioinstability (dissolution) and delamination of the thick CaP surface layers.[29–31] Since the ultrathin CaP films used in the present study are much thinner than plasma-sprayed CaP coatings (1 μm versus 50 μm), they are expected to have few (if any) effects on host inflammation, even if delamination does occur. Further, by virtue of their structure and chemistry (carbonate Ca-deficient HA), they are expected to slowly resorb without a negative impact on long-term implant success.

CONCLUSION

This study showed that a sol-gel–formed CaP surface film can significantly enhance the rate of bone ingrowth and interface zone stiffness of sintered porous-surface Ti alloy implants. Because of its greater interfacial stiffness at earlier times in the healing process, this implant design is likely to be better able to resist the negative effects of inadvertent forces (or intentional forces, in the case of immediately loaded implants) acting on the implant that might result in significant relative micromovements greater than some critical level during the early days of implant site healing. This may present a number of clinical benefits, including shortening overall integration healing times and increasing the probability of implant success in regions of poor bone quality or quantity (eg, implants placed into 3 mm or less of bone beneath the sinus floor using indirect sinus floor elevation with osteotomes[13]). Whether the differences reported here are the result of the effects of altered surface chemistry and/or topography of the sol-gel–formed thin surface film remains uncertain and requires further study.

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