Surface modification of bioceramics by grafting of tailored allyl phosphonic acid

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A new route to interfacial bonding between ceramic and matrix in biocomposites is identified. A tailored allyl phosphonic acid is used as a coupling agent bound to the surface of a bioceramic to form a 'grafted' calcium phosphate (CAP). The allyl phosphonic acid coupling agent is synthesised by reaction of allyl halide and trialkyl phosphite. Successful synthesis was confirmed by nuclear magnetic resonance and Fourier transform infrared spectroscopy (FTIR). The allyl phosphonic acid was incorporated onto calcium phosphate using a wet chemical coprecipitation synthesis route. The resulting 'grafted' CAP was characterised using FTIR coupled with photoacoustic sampling, and Fourier transform Raman spectroscopy (FTR). The spectroscopic data suggest an interaction between the allyl phosphonic acid and calcium phosphate resulting from observed reductions in intensity of the hydroxyl (3570 cm^{-1}) and phosphate ν_3 (1030 cm^{-1}) peaks. The continued presence of C=C functionality on the surface of the grafted CAP was indicated by FTIR and FTR spectra (peaks at 1650 and 1635 cm^{-1} respectively) and confirmed by X-ray photoelectron spectroscopy (XPS). On the basis of these results, it is concluded that grafted CAP may be used to produce a chemically bonded composite with superior mechanical properties.

Keywords: Calcium phosphate, Composite, Coupling agent, FTIR, Surface grafting, Surface modification

Introduction

Cortical bone is made up of a nanoparticulate crystalline calcium phosphate phase and an organic phase largely consisting of type I collagen fibres. The mineral calcium phosphate phase in bone can be characterised as a non-stoichiometric substituted apatite.[1] In the field of bone replacement, calcium phosphate (CAP) can be produced in the form of hydroxyapatite (HA) $Ca_{10}(PO_4)_6(OH)_2$, a synthetic and bioactive material similar to human bone mineral. Calcium phosphates can be manufactured synthetically using a number of different methods.[2–5]

Bioactive composites that attempt to mimic the mechanical and biological properties of bone have been developed utilising calcium phosphates.[6] Failure of many such composites often occurs at the interface between filler and polymer. The bonding mechanism in commercial biocomposites such as HAPEX (a composite of polyethylene and HA) involves mechanical interlocking between ceramic filler and polymer phase, which occurs when the composite is cooled during manufacture. Consequently, these composites tend to be stronger in compression than in tension, and as a result they tend to fail owing to debonding (during prolonged cyclic extension and compression) under conditions that normal cortical bone (a natural composite) can withstand.[7] If bonding between the ceramic filler and the polymer could be improved, the mechanical properties could potentially also be improved to make a credible composite replacement for cortical bone. A number of methods have been employed to improve bonding between the ceramic filler and polymer matrix in composites, for example coupling techniques. These include zirconyl salt $ZrO(CH_3)_2$ absorption,[8] polyacid RCOOH adsorption[9] and isocyanate NCO grafting.[10] Silane coupling is one of the most common treatments cited for coupling glass and clay. The method has also been used for coupling hydroxyapatite in bone cements.[11,12] Deb *et al.*[13] have reported the use of silane coupling agents to bind polyethylene to hydroxyapatite to improve mechanical properties. However, the stability of such a linkage is debatable in an aqueous environment and as a consequence the choice of silane coupling agents in this application is not ideal.

When considering grafting materials for use with hydroxyapatite, phosphates RPO_4 and phosphonates $RP(O)(OH)_2$ appear to be a promising choice, but have received relatively little attention to date as grafting/coupling agents. However, in the form of bisphosphonates,

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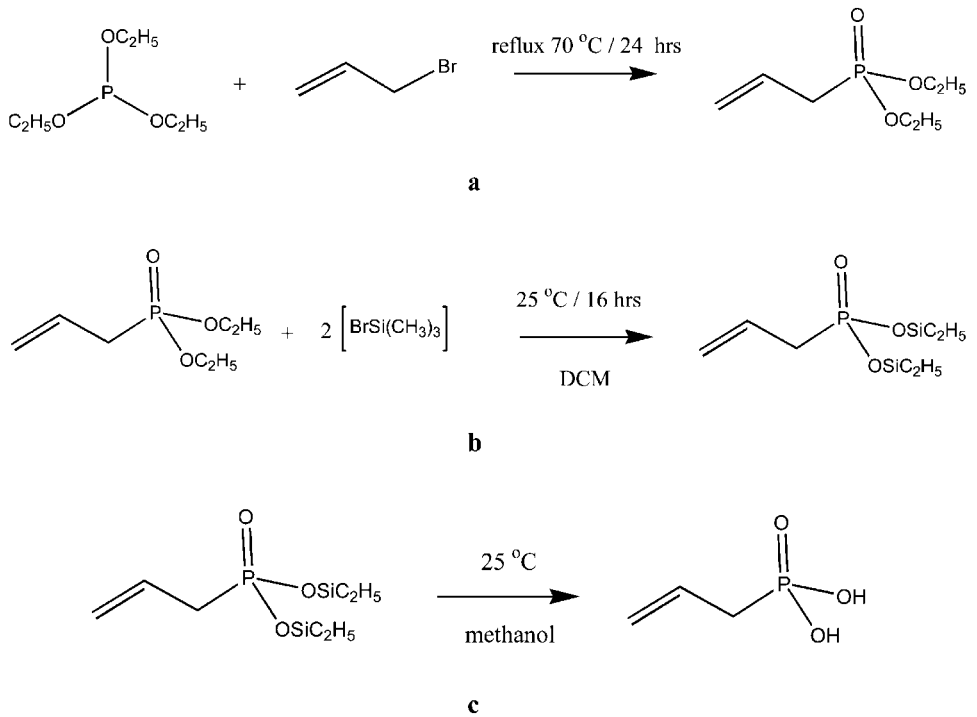


1 ***a*** **reaction of triethyl phosphite and allyl bromide to produce diethyl propen-2-ylphosphonate,** ***b*** **reaction of diethyl propen-2-ylphosphonate and bromotrimethylsilane to produce bis(triethylsilyl) propen-2-ylphosphonate,** ***c*** **reaction of bis(triethylsilyl) propen-2-ylphosphonate with methanol to form allyl phosphonic acid (ally phosphonic acid).**

phosphonates have been used as compounds that have the ability to inhibit bone resorption.[14] The chemical properties of bisphosphonates are very similar to those of pyrophosphates, and inorganic pyrophosphate was found to inhibit precipitation[15] and dissolution[16] of hydroxyapatite crystals in vitro. As a result, bisphosphonates were utilised by Hilding *et al.*[17] to reduce prosthetic migration. This study indicated that early prosthetic migration was related to bone resorption and that preemptive use of bisphosphonates might reduce prosthetic loosening. However, there have been few studies on the use of phosphonates as grafting or composite materials with hydroxyapatite. Poly(vinylphosphonic acid) (PVPA) contains functional groups similar to phosphoric acid and has also been used with aluminosilicate glasses in the development of a new class of polyphosphonate dental cement analogues to glass polyalkenoate cements.[18,19] The manufacture of chemical composites of PVPA and tetracalcium phosphate (TTCP) has been reported by Greish and Brown.[20] The elastic modulus of the composites formed was found to be higher than human bone but tensile strengths were lower.[21]

The success of phosphonic materials such as PVPA and bisphosphonates in binding to bone and various calcium phosphates suggests that they have potential for use in preparing grafted biomedical composites. The present study reports work aimed at increasing interfacial bonding between a bioceramic and polymer matrix through the use of a tailored phosphonic acid coupling agent. Synthesis and characterisation of the novel phosphonic acid through to the grafted biocomposite is described.

Materials and methods

Chemicals

For the allyl phosphonic acid preparation, triethyl phosphite $(C_2H_5O)_3P$ (98%), allyl bromide CH_2CHCH_2Br (99%), bromotrimethylsilane $(CH_3)_3SiBr$ (97%) and dichloromethane CH_2Cl_2 (ACS grade, 99·6%) were used as supplied by Sigma-Aldrich (UK). Methanol CH_3OH (GPR grade, 99·5%) was used as supplied by VWR International (UK). For the preparation of the grafted CAP, analysis grade (AnalaR) calcium nitrate tetrahydrate $Ca(NO_3)_2.4H_2O$ and diammonium hydrogen orthophosphate $(NH_4)_2HPO_4$ were used as supplied by VWR International (UK). AnalaR grade ammonium hydroxide (NH_4OH) solution (specific gravity 0·88) was used for pH adjustment as supplied by VWR International (UK). Bromine Br (GPR grade, 99·5%) and carbon tetrachloride CCl_4 (GPR grade, 99·9%) were used as supplied by Sigma-Aldrich (UK) and VWR International (UK) respectively. Deionised water (10 MΩ) from an USF Elga Option 3 water purifier was used in all reactions.

Preparation of tailored coupling agent

Stage 1: diethyl propen-2-ylphosphonate

Triethyl phosphite (0·29 mol, 33·65 g) was added dropwise to allyl bromide (0·2 mol, 24·3 g) without the use of solvent (Fig. 1*a*). The reaction mixture was then refluxed at 70°C for 24 h while being stirred. Excess reagents were removed before purification by fractional distillation in a Vigreux column under vacuum, with hydroquinone dissolved in the sample.

Stage 2: bis(triethylsilyl) propen-2-ylphosphonate

Pure diethyl propen-2-ylphosphonate (0·13 mol, 24 g) was dissolved in 100 mL dichloromethane (DCM) and added to 0·29 mol (45 g) bromotrimethylsilane in 150 mL DCM (Fig. 1*b*). The reaction mixture was stirred for 16 h under N_2 at 25°C to give bis(triethylsilyl) propen-2-ylphosphonate.

Stage 3: propen-2-ylphosphonic acid (allyl phosphonic acid)

Methanol (25 mL) was added to the bis(triethylsilyl) propen-2-ylphosphonate and excess solvent removed to give allyl phosphonic acid (Fig. 1*c*). This material was then used in the work described below.

Grafted CAP preparation

The allyl phosphonic acid was incorporated onto calcium phosphate using a wet chemical method, adapted from hydroxyapatite synthesis.[22] First, 0·05 mol (11·81 g) of $Ca(NO_3)_2.4H_2O$, 0·02 mol (2·64 g) of $(NH_4)_2HPO_4$ and 0·01 mol (1·21 g) of allyl phosphonic acid were measured before mixing. The $Ca(NO_3)_2.4H_2O$ suspension was prepared in 45 mL H_2O and stirred for 10 min. The pH of the suspension was adjusted to 11 using NH_4OH, added dropwise. Another 45 mL H_2O was added and stirring continued for a further 10 min. The $(NH_4)_2HPO_4$ solution was prepared in 75 mL H_2O and stirred for 10 min. The pH of the solution was adjusted to 11 using NH_4OH, added dropwise. The allyl phosphonic acid was mixed with 85 mL H_2O and stirred for 2 min. The allyl phosphonic acid mixture was then added directly to the $(NH_4)_2HPO_4$ solution and stirred for 10 min. While stirring of the $Ca(NO_3)_2.4H_2O$ suspension was maintained, the $(NH_4)_2HPO_4$/allyl phosphonic acid mixture was added dropwise using a glass dropping funnel. The pH was monitored throughout the dropwise addition and maintained at pH 11 using NH_4OH, again added drop wise. When the dropwise addition was finished, the suspension was stirred for another 2 h before being left to age for 18 h. The resulting precipitate was filtered using a Buchner filter and washed in 50 mL H_2O, before being freeze dried using an Edwards 4K Modulyo freeze dryer. The wet filter cake was rapidly frozen using liquid nitrogen and then dried at around 10^{-1} mbar for 18 h.

Hydroxyapatite reference preparation

Before mixing, 0·05 mol (11·81 g) of $Ca(NO_3)_2.4H_2O$ and 0·03 mol (3·96 g) of $(NH_4)_2HPO_4$ were measured. The $Ca(NO_3)_2.4H_2O$ suspension was prepared in 45 mL H_2O and stirred for 10 min. The pH of the suspension was adjusted to 11 using NH_4OH, added dropwise. Another 45 mL H_2O was added and stirring continued for a further 10 min. The $(NH_4)_2HPO_4$ solution was prepared in 75 mL H_2O and stirred for 10 min. The pH of the solution was adjusted to 11 using NH_4OH, added dropwise. Another 85 mL H_2O was added and stirring continued for 10 min. While stirring of the $Ca(NO_3)_2.4H_2O$ suspension was maintained, the $(NH_4)_2HPO_4$ mixture was added dropwise using a glass dropping funnel. The pH was monitored throughout the dropwise addition and maintained at pH 11 using NH_4OH, added dropwise. When the dropwise addition was finished, the suspension was stirred for a further 2 h before being left to age for 18 h. The resulting precipitate was filtered using a Buchner filter and washed in 50 mL H_2O, before being freeze dried using an Edwards 4K Modulyo freeze dryer. The wet filter cake was rapidly frozen using liquid nitrogen and then dried at around 1×10^{-1} mbar for 18 h.

Bromination for XPS

Direct bromination of the grafted CAP was performed as follows: 1 g of grafted CAP and 10 mL carbon tetrachloride CCl_4 were placed in a 50 mL round bottomed flask and stirred at room temperature. Separately, 0·021 mol (3·4 g) of bromine Br_2 was added to 10 mL CCl_4 in a 50 mL round bottomed flask and stirred. Then the Br/CCl_4 solution was added dropwise to the grafted CAP and CCl_4 mixture. Each dropwise addition was made only when the grafted CAP/CCl_4 mixture had turned colourless (indicating bromination). Addition of Br/CCl_4 was stopped when the grafted CAP/CCl_4 mixture stopped returning to a colourless state. Bromination of the hydroxyapatite was performed in the same way.

Characterisation

Fourier transform infrared spectroscopy (FTIR)

FTIR spectra were obtained at each stage of allyl phosphonic acid synthesis using a Nicolet 800 FTIR spectrometer in conjunction with a thin film attachment. Spectra were obtained over an average of 128 scans. The liquid samples were tested in the as prepared state with an appropriate solvent used for the background scan. FTIR spectra of the calcium phosphate/allyl phosphonic acid powdered samples were obtained using a Nicolet 800 FTIR spectrometer in conjunction with an Mtech photoacoustic spectrum (PAS) cell. Spectra were obtained in the wavenumber range 400–4000 cm^{-1} at 4 cm^{-1} resolution, averaging 128 scans. The sample chamber of the PAS cell was purged with dry helium gas (predried over a column of magnesium perchlorate).

Fourier transform Raman spectroscopy (FTR)

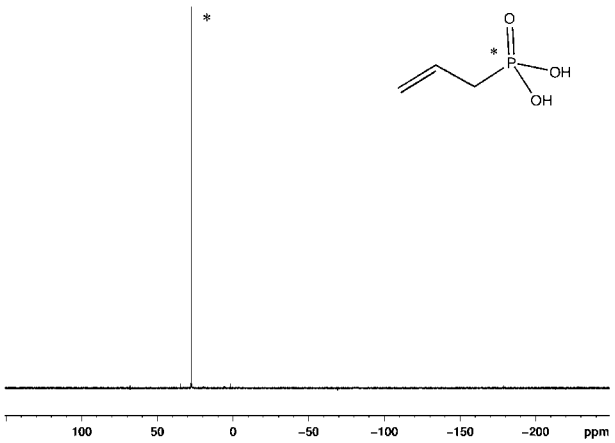
FTR spectra were recorded using a Nicolet 910 spectrophotometer equipped with an $Nd:YVO_4$ near infrared laser. All spectra were obtained in the range 400–3500 cm^{-1} over an average of 256 or 512 scans and with 4 cm^{-1} resolution. At each stage of allyl phosphonic acid synthesis, the liquid samples were tested in the as prepared state in 5 mm outside diameter glass tubes. Grafted CAP powdered samples were tested in the as prepared state in 20 mm outside diameter glass bottles.

Nuclear magnetic resonance (NMR)

Solution state NMR spectra were recorded in $CDCl_3$ using Jeol GSX 270 and Bruker Avance 600 spectrometers. All solid state spectra were recorded on a Bruker Avance 600 spectrometer in a 4 mm MAS probe at 12 kHz. ^{31}P spectra were acquired using a single pulse. Conditions for the ^{31}P MAS were: 64 scans acquired with a 125 kHz sweep width (~500 ppm), 20 s relaxation delay, 2 μs excitation pulse width corresponding to 45°. ^{13}C spectra were acquired with ^{1}H cross-polarisation (CP) and high power decoupling during acquisition. Conditions for the ^{13}C CP MAS were: 14 000 scans collected with a 45 kHz sweep width (~300 ppm), ^{1}H 90° pulse for 3·5 μs, 1 ms contact time, 5 s relaxation delay.

X-ray photoelectron spectroscopy (XPS)

XPS measurements were performed using a Kratos Axis HSi instrument equipped with a charge neutraliser and



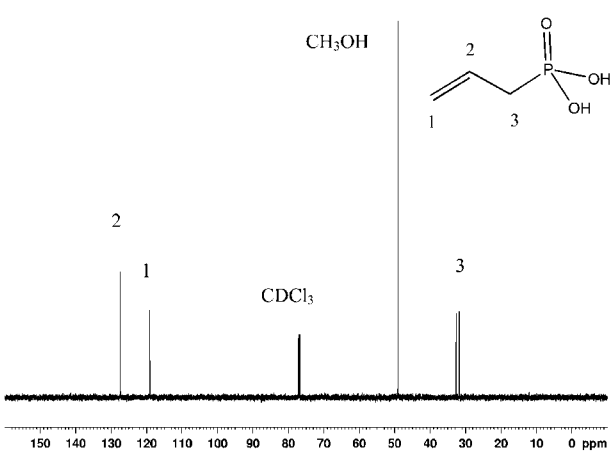
2 ^{31}P NMR spectrum for allyl phosphonic acid (ally phosphonic acid)

Mg K_α X-ray source. Spectra were recorded at normal emission using an analyser pass energy of 20 eV and X-ray power of 144 W. Quantification of spectra was performed following correction of peak areas for the atomic relative sensitivity factors of O 1s (0·736), Ca 2p (1·95), C 1s (0·318), P 2p (0·53) and Br 3d (1·155). All spectra were energy referenced with respect to Ca $2p_{3/2}$ at 347·4 eV.

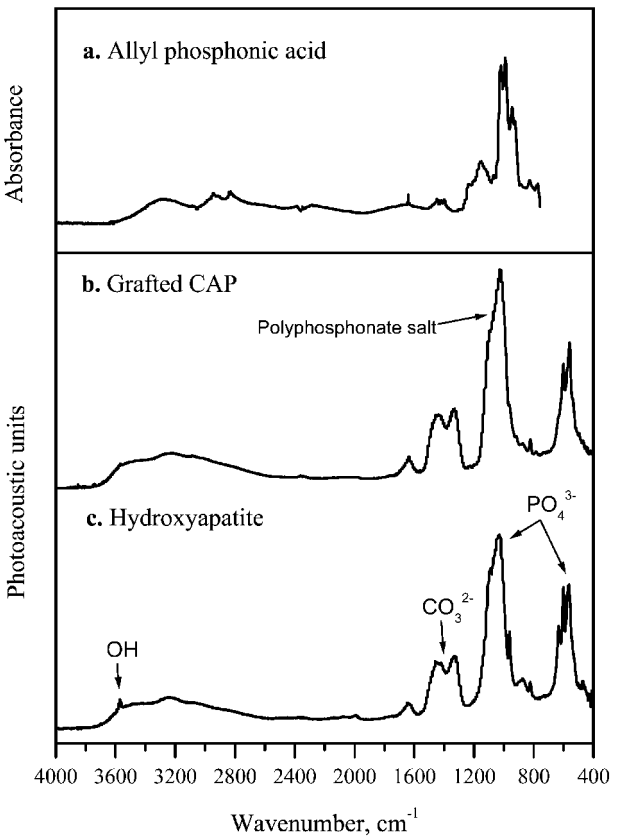
Results and discussion

The synthesis of allyl phosphonic acid by a Michaelis–Arbuzov method, where excess allyl bromide was used to minimise the formation of ethyl phosphonate, was confirmed using ^{31}P and ^{13}C NMR. The three stage synthesis resulted in the successful preparation of allyl phosphonic acid (ally phosphonic acid). The ^{31}P NMR spectra obtained are shown in Fig. 2 ($CDCl_3$, 27·6 ppm). One major peak is observed, confirming the presence of a unique phosphorus environment, that of the allyl phosphonic acid.[23] ^{13}C NMR further confirms the backbone structure of the allyl phosphonic acid (Fig. 3). The peaks associated with $-CH_2$, $=CH_2$ and $=CH$ are identified at 31·8 and 32·7, 119·1 and 119·2, and 127·4 and 127·5 ppm respectively.

The grafted CAP was prepared as follows: allyl phosphonic acid was used in a modified hydroxyapatite precipitation, where a proportion of the phosphate

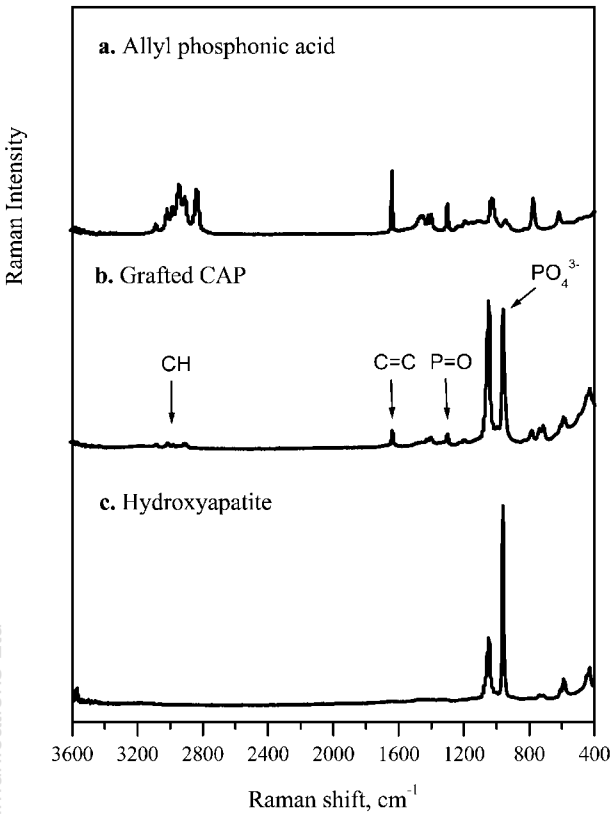


3 ^{13}C NMR spectrum for allyl phosphonic acid (ally phosphonic acid)



4 FTIR spectra for *a* allyl phosphonic acid, *b* grafted CAP, *c* hydroxyapatite

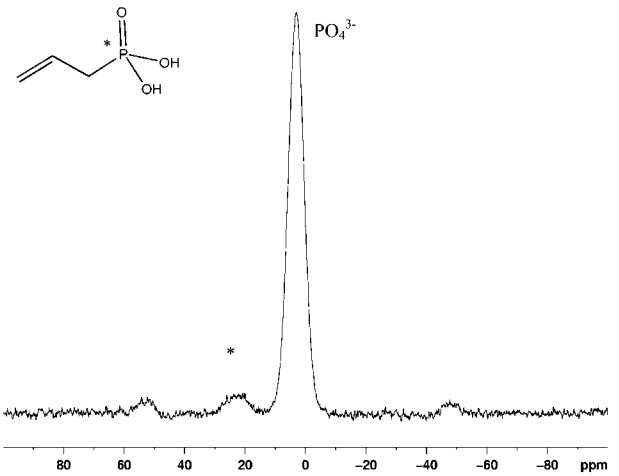
reagent was replaced with an equimolar amount of allyl phosphonic acid. This mixture was then filtered and freeze dried prior to analysis. The calcium phosphate peaks in the FTIR spectra for the grafted CAP (Fig. 4) matched well those found for hydroxyapatite.[24] The hydroxyl OH peak (3570 cm^{-1}) and the phosphate ν_3 stretching vibration (1030 cm^{-1}) for the acid were reduced in intensity compared with hydroxyapatite, indicating an interaction between the allyl phosphonic acid and calcium phosphate. The phosphate ν_4 peaks of the composite were reduced to two peaks at 562 and 602 cm^{-1}, compared with the hydroxyapatite peaks at 563, 602 and 634 cm^{-1}. D'Andrea and Fadeev[25] proposed that the reduction in the OH stretch at 3570 cm^{-1} is due to changes in the crystalline structure and bulk modification of the hydroxyapatite matrix when the phosphonic acid–hydroxyapatite reaction takes place during grafting. An additional peak is observed in the FTIR spectra for grafted CAP K-4 at 1070 cm^{-1}, which is likely due to the ν_{as} P–OH stretch, as described by D'Andrea and Fadeev,[25] however it may be due to the formation of a polyphosphonate salt as proposed by Ellis and Wilson.[19] The ν_{as} and ν_s P–OH stretches of phosphonic acid, at 991 and 945 cm^{-1} respectively, disappear in the grafted CAP K-4. When considered in combination with the appearance of the polyphosphonate band at 1070 cm^{-1}, it is proposed that this indicates bonding of the phosphonic acid functional groups to the calcium phosphate. The continued presence of C=C is confirmed by the band (although weak) at 1650 cm^{-1} in the FTIR spectra of the grafted CAP K-4. This indicates that grafted CAP remains viable for use in coupling to a polymer and forming a chemically bonded composite.



5 FTR spectra for *a* allyl phosphonic acid, *b* grafted CAP, *c* hydroxyapatite

FTR spectra provided complementary information to that obtained from FTIR, confirming the presence of allyl phosphonic acid (Fig. 5). The ν C=C band of the allyl phosphonic acid was evident at 1635 cm^{-1}, along with the ν P=O peak at 1300 cm^{-1}. Peaks associated with =CH, $=CH_2$ and $–CH_2–$ were observed in both the allyl phosphonic acid and grafted CAP material between 2800 and 3100 cm^{-1}. Combined with the reduction in intensity of the phosphate symmetric stretch at 962 cm^{-1}, this verifies the FTIR data suggesting an interaction between allyl phosphonic acid and calcium phosphate.

Solid state NMR was carried out on the powdered grafted CAP sample, supporting the results obtained by FTIR and FTR. The ^{31}P solid state NMR trace is shown in Fig. 6. This trace indicates two phosphorus peaks, a weak, broad peak at 20·8, and a more intense one at 2·9 ppm. The peak at 2·9 ppm is that expected for the phosphate (PO_4^{3-}) of a hydroxyapatite like calcium phosphate as compared to the hydroxyapatite data.[27,28] The weak, broad peak seen at 20·8 ppm is believed to be that of allyl phosphonic acid.[23] A small upfield peak shift is seen compared to the pure phosphonic acid peak in Fig. 2, indicating some interaction between the phosphonic acid moiety and hydroxyapatite which may be due to bonding to the calcium in the calcium phosphate. The two weak peaks at 47·8 and 52·2 ppm are believed to be weak spinning side bands (ssb) as seen for PVPA–hydroxyapatite composites[20] and calcium methylphosphonate.[29] Spinning side bands such as these arise due to rotation of the NMR sample through field gradients in the *XZ* plane.[30] They are identifiable by their symmetrical spacing on each side of the parent centre band (in this case the PO_4^{3-} band at 2·92 ppm).

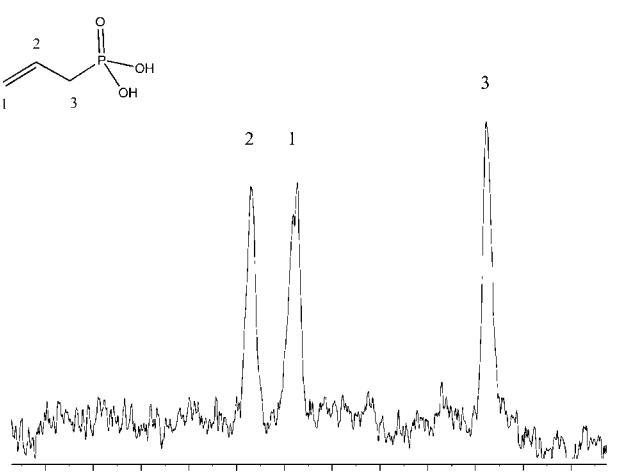


6 Solid state NMR: ^{31}P MAS spectrum at 12 kHz of grafted CAP

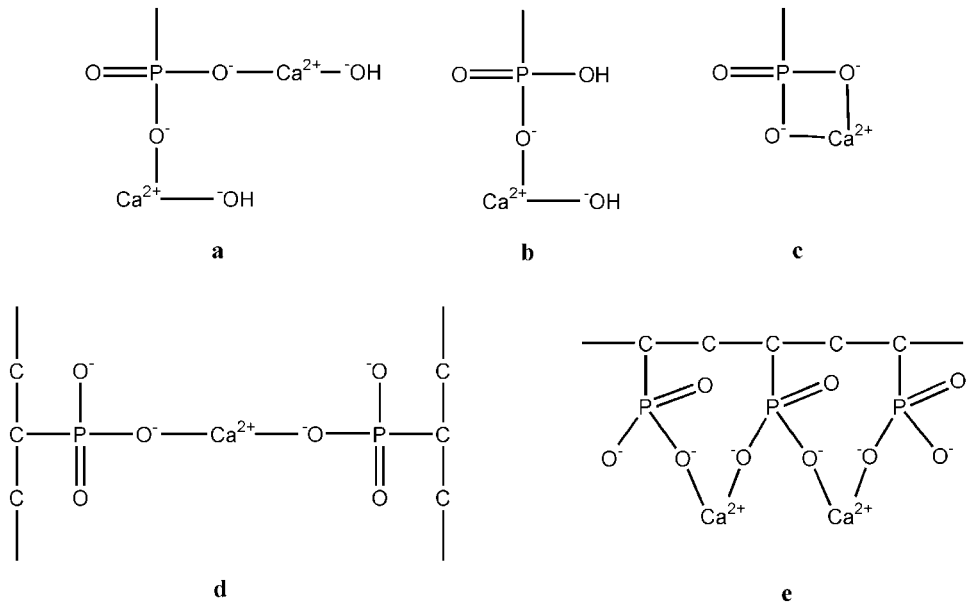
Figure 7 shows the ^{13}C solid state NMR trace for the grafted CAP material (12 kHz, DMSO). The peaks at 35·5 and 133·9 ppm are assigned to CH_2 and =CH respectively. These peaks are usually seen as doublets, as in Fig. 3. However, the peaks seen here are broad and the doublets could be masked by this broadening. The peaks at 114·5 and 116·3 ppm represent the presence of the alkene $=CH_2$, indicating the continued presence of the double bond in the grafted CAP. Again, there is some shifting of peaks compared to phosphonic acid. Peaks 2 and 3 have moved to higher chemical shift values of 133·9 and 35·5 ppm compared to 127·5/127·4 and 32·7/31·8 ppm in the allyl phosphonic acid. This suggests the phosphorus atom is experiencing increased shielding, possibly as a result of bonding calcium in the calcium phosphate. Thus, the solid state NMR data appear to support the FTIR and FTR data, suggesting bonding of the phosphonic functional group to the calcium phosphate and the continued availability of the double bond.

Coupling mechanism

The bonding modes of the allyl phosphonic acid in the grafted CAP could be a number of types. When discussing the grafting of phosphonic acids onto hydroxyapatite, D'Andrea and Fadeev[25] suggested that



7 Solid state NMR: ^{13}C CP MAS spectrum at 12 kHz of grafted CAP



8 Possible Ca^{2+}–PVPA structures (adapted from Greish and Brown[21] and Ellis and Wilson[19])

the P–O of the phosphonic groups would react with the hydroxyapatite surface hydroxyl groups P–OH during grafting. In addition, they indicated that interaction between P=O and these surface hydroxyl groups would result in a shift or reduction in intensity of the *v* P=O band. However, Ellis and Wilson[19] suggest that a shift in the *v* P=O band in the FTIR spectra could be due to an interaction between the phosphonic group P=O and metal ion M^{n+}. FTIR spectra from the present study for grafted CAP do not support such an interaction owing to little change in the *v* P=O stretch, although changes in the *v* P–O stretches are observed. Therefore, bonding is thought unlikely to occur solely via the surface hydroxyl groups or through a phosphonic–metal ion interaction.

Mechanisms for salt formation or bonding between PVPA and calcium ions Ca^{2+} have been proposed by Greish and Brown[20] and Ellis and Wilson,[19] as seen in Fig. 8. It is believed that it is not possible to predict the exact structure owing to a lack of available evidence, although Greish and Brown stated that the bifunctionality of the phosphonate group means that it can form strong associations with cations, resulting in structures d and e. Another study, by Lima and Airoldi,[29] investigated the synthesis of calcium methyl phosphonate. They proposed a mechanism whereby methyl phosphonic acid reacted with calcium chloride as follows:

$$2[H_3CPO(OH)_2] + CaCl_2 \cdot 2H_2O \rightarrow$$

$$Ca[(HO)O_2PCH_3]_2 \cdot H_2O + 2HCl + H_2O$$

This again indicates that the reaction is most likely to occur between the phosphonic acid functional group and the calcium ion of the calcium phosphate.

Comparing peak shifts observed in the NMR spectra for grafted CAP (Figs. 2 and 3) to phosphonic acid (Figs. 6 and 7) suggests that there is increased shielding of the phosphonic functional group. It is proposed that this is due to coupling of the phosphonic group with the calcium ion in calcium phosphate.

The results in the present study therefore indicate that the hydroxyl groups on the phosphonic end of the acid could be binding with the calcium in the hydroxyapatite. As such, the phosphonic acid end group replaces the hydroxyl groups in the hydroxyapatite. It is also possible that the phosphonic acid end groups are occupying sites that would normally have been occupied by the phosphate. This type of interaction has been suggested by Räsänen *et al.*[31] in a theoretical study of binding of bisphosphonates to hydroxyapatite. The *ab initio* molecular orbital models suggested that the oxygen of the methylenebisphosphonic acid may take the place of the oxygen in the hydroxyapatite crystal, suggesting that this would be the preferred bridging mode since other calcium bonding sites in the bisphosphonate backbone are higher energy and therefore less likely.

Grafted CAP reactivity

The presence of the double bond C=C from the allyl phosphonic acid has been maintained throughout the coprecipitation process, as confirmed by solid state NMR (Figs. 6 & 7). Quantification of XPS spectra (Table 1) also confirms that there is a significant increase in surface carbon and phosphorus content of CAP materials. The Ca/P ratio of 1·55 for untreated hydroxyapatite, which is consistent with the value of 1·67 (5Ca/3P ratio) expected for $Ca_{10}(PO_4)_6(OH)_2$, decreases to 1·38 on grafting of allyl phosphonic acid. This indicates that there is a higher proportion of phosphorus in the grafted material than in the untreated hydroxyapatite. This coupled with a threefold increase in the surface carbon/calcium ratio in the grafted CAP over the hydroxyapatite control powder is attributable to the

Table 1 XPS results for grafted CAP compared to hydroxyapatite

	Content, at.-%					
Sample	O 1s	N 1s	Ca 2p	C 1s	P 2p	Ca/P ratio
Hydroxyapatite	65·93	1·00	17·81	3·74	11·52	1·55
Grafted CAP	60·91	1·20	15·71	10·80	11·38	1·38

Table 2 XPS results for brominated grafted CAP compared to hydroxyapatite

	Content, at.-%					Ratios		
Sample	O 1s	Ca 2p	C 1s	P 2p	Br 3d	Ca/P	C/Ca	C/Br
Hydroxyapatite	67·89	18·60	1·65	11·52	0·34	1·61	0·09	4·85
Grafted CAP	63·63	16·44	7·76	11·21	0·96	1·47	0·47	8·08

successful incorporation of allyl phosphonic acid in the surface.

For effective application of these materials it is essential that the presence of reactive C=C functionality at the surface is demonstrated, which can be achieved by subsequent Br derivatisation.[32] XPS quantification of a brominated grafted CAP sample suggests that about 1 at.-% bromine was present on the surface (Table 2). Assuming that two bromine atoms react with each double bond, and the total carbon signal arises from the propene function of the grafted allyl phosphonic acid, it is estimated that 19% of the surface alkenyl groups are accessible for post-modification. The functionalisation of such calcium phosphate ceramic by chemical addition of an allyl phosphonic acid in this way confirms that there are active sites (double bonds) available for bonding through the grafted acid (ultimately to, for example, a polymer). This may be exploited to produce a chemically bound biocomposite in which the grafted CAP is covalently bonded to a polymer matrix, thus resulting in a material with potentially increased strength and toughness. Further studies are currently under way to produce a composite material using reaction of monomers, including hydroxyl ethyl methacrylate, in the presence of grafted CAP.

Conclusion

An improved method of synthesis of allyl phosphonic acid has been developed and successfully applied. The allyl phosphonic acid was utilised in a coprecipitation reaction with calcium phosphate to form grafted CAP. The allyl phosphonic acid was found to be incorporated into the calcium phosphate via bonding between the phosphonic acid group and calcium ion. The C=C functional group was found to be present on the surface of the grafted CAP after coprecipitation. XPS indicated a threefold increase in the surface carbon/calcium ratio in the grafted CAP compared to the hydroxyapatite control powder. This is attributable to successful incorporation of allyl phosphonic acid in the surface. The continued presence of this reactive C=C functionality on the surface of the grafted CAP suggests that these potentially active sites may be filled during in situ polymerisation of poly(HEMA), resulting in a biocomposite that is chemically bound via interfacial bonding and potentially has improved strength and toughness.

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