

Organic/Inorganic Interaction between Hydroxyapatite and Derivatives of Poly(Ethylene Glycol)

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In order to investigate an interaction between hydroxyapatite (HAp) and organic functional groups, HAp powders were mixed with two kinds of poly(ethylene glycol) (PEG) which had respective OH and COOH by a thermal kneading method. From the results of Fourier-transformed infrared spectroscopy measurements, it was indicated that the COOH groups could interact with calcium ions on the surfaces of HAp, while the interaction of OH groups with calcium ions was very weak. The chemical interaction reflected to the melting points of the composites, shown by differential scanning calorimetry measurements.

Key words: organic/inorganic interaction, hydroxyapatite, poly(ethylene glycol), FT-IR, DSC

1. INTRODUCTION

Some inorganic materials like phosphates or glasses are able to bond directly to hard tissues when implanted in the human body¹⁻³: in particular hydroxyapatite (HAp) is well known as a bioactive ceramic. However, the HAp ceramic is not sufficient for the substitution of bone since its fracture toughness is lower than that of a human cortical bone. Therefore, HAp is currently applied only as a coating material for a metallic artificial bone or a filling material for a region without strong stress. On the other hand, some synthetic organic polymers have the flexibility to be easily formed in any shape but are essentially not osteoconductive.

Bone, which consists of organic and inorganic materials, has well balanced mechanical and biochemical properties. In the bone, the *c*-axes of plate-like HAp nanocrystals are orientated along collagen fibers, and both of them interact with one another. For the development of new artificial biomaterials with good formability and osteoconductivity, therefore, it is necessary to understand a chemical interaction between organic and inorganic materials, especially an

interaction between ions on a HAp surface and organic functional groups.

In the present study, we prepared the composites of HAp powder and derivatives of poly(ethylene glycol) (PEG). In order to elucidate the chemical interaction between them, Fourier transform infrared (FT-IR) spectroscopy was measured as a function of HAp/PEG mixing ratio and the corresponding change in melting point was analyzed with differential scanning calorimetry (DSC).

2. MATERIALS AND ANALYSES

HAp was prepared by a wet method using a $\text{Ca}(\text{OH})_2$ suspension and a H_3PO_4 aqueous solution at pH9. The precipitate obtained was dried at 333K for 24 hours and calcined at 1073K for 3 hours. Two kinds of PEG (Nippon Oil & Fats Co.) with functional groups of OH (PEG_{OH}) and COOH (PEG_{COOH}) were used as starting materials, whose average molecular weights were 3,000 and 4,000, respectively. HAp and PEG were mixed by a thermal kneading method: initially, PEG chips were melted at 343K for 3 minutes, and then

HAp powder was added into PEG with mixing at 50rpm for 10 minutes. Finally, 15wt% of water were added in the mixtures to advance the chemical interaction between HAp and PEG and freeze-dried. The same treatments were conducted for both pure PEG powders. The compositions of the mixtures are listed in Table I.

The surfaces of the composites and pure PEG were observed by scanning electron microscopy (SEM), and the chemical interaction was analyzed with FT-IR and DSC.

3. RESULTS AND DISCUSSION

3.1 The surface morphology of HAp/PEG composites

Fig.1 shows the SEM images of the surfaces of pure HAp, 30PEG_{COOH} and 30PEG_{OH}: here the abbreviation, for example 30PEG_{COOH}, means the composite of 30wt% PEG_{COOH} and 70wt% HAp. The surfaces of HAp particles in 30PEG_{COOH} were uniformly covered with PEG, while those of 30PEG_{OH} were partially covered with PEG and isolated PEG particles were found in places. This result indicated that PEG_{COOH} is adhesive to the HAp surface but PEG_{OH} not adhesive.

3.2 The chemical state of functional group

Fig.2 shows the FT-IR spectra of pure HAp, PEG_{COOH}, PEG_{OH} and their composites. For the pure PEG_{COOH}, the C=O stretching vibration mode of the COOH group was found near to 1750cm⁻¹ and 1799cm⁻¹: the former was assigned to the C=O vibration in the dimer PEG-COOH/HOOC-PEG bound through a hydrogen bond, and the latter to that in a monomer PEG-COOH⁴⁻⁶. The dimer dominantly existed in the pure PEG_{COOH} in comparison to the monomer. With respect to the HAp/PEG_{COOH} composites, the asymmetric stretching vibration mode of the ionized -COO⁻ was found near 1600cm⁻¹. When the mixing content of HAp was increased, the peak intensity of the -COO⁻ group increased in accordance with the decrease in intensity of the dimer COOH, indicating that the dimer dissociated to the COO⁻ groups in the composites. For the pure PEG_{OH}, the C=O stretching vibration mode of the COOH groups were very weakly observed at 1750cm⁻¹ (monomer) and at 1799cm⁻¹ (dimer) due to PEG-COOH formed by the partial oxidization of PEG_{OH}.

Table I Composition of mixture

Sample name	Functional group	PEG (wt%)	HAp (wt%)
30PEG _{OH}	OH	30	70
30PEG _{COOH}	COOH	30	70
50PEG _{COOH}	COOH	50	50
70PEG _{COOH}	COOH	70	30

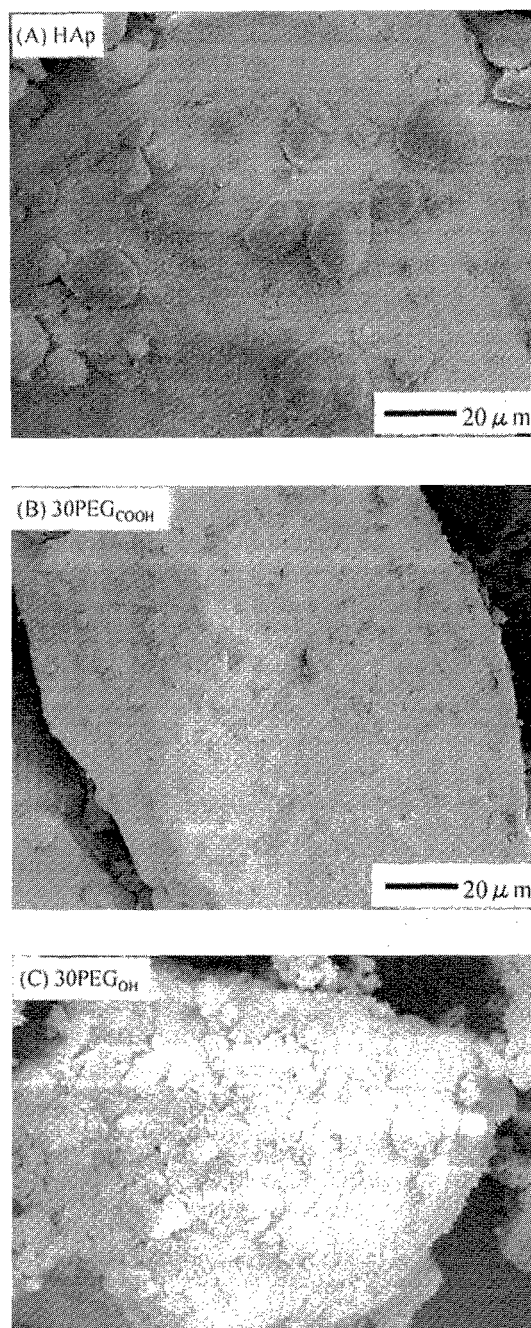


Fig. 1 The SEM micrographs for the surfaces of pure HAp, 30PEG_{COOH} and 30PEG_{OH}.

The composites were soaked in water for 30 minutes, filtered and dried; this treatment was expected to result in the fragmentation of the composite and the dissolution of an excess amount of PEG that did not interact with HAp powders. Fig.3 shows the FT-IR spectra of the composites soaked. As regards the HAp/PEG_{OH} composites, all absorption bands due to PEG_{OH} including CH₂ bands etc. disappeared and the bands assigned to HAp were only observed; this result meant that the chemical interaction between OH of PEG_{OH} and a HAp surface was not so strong. On the other hand, for the HAp/PEG_{COOH} composites, the band due to the COO⁻ groups was found in the neighborhood of 1600cm⁻¹ even after soaking. PEG_{COOH} therefore remained on the HAp surface, indicating that the chemical interaction between COO⁻ of PEG_{COOH} and a HAp surface was so strong to be stable in water.

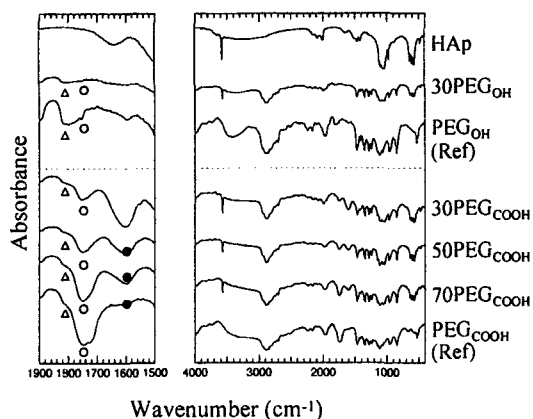


Fig. 2 The FT-IR spectra of HAp, PEG_{COOH}, PEG_{OH} and their composites. Δ : C=O stretching (monomer) \circ : C=O stretching (dimer) \bullet : COO⁻ stretching vibrations.

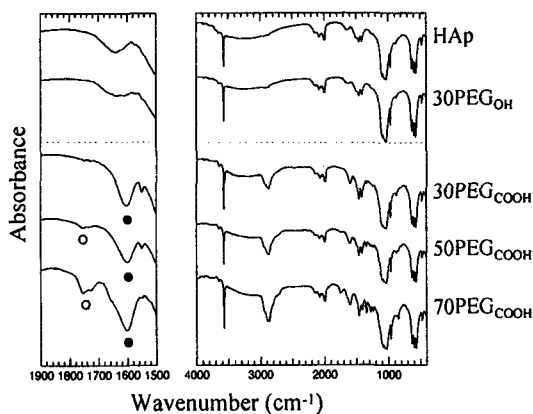


Fig. 3 The FT-IR spectra of the composites after soaking in water for 30 minutes and filtering. Δ : C=O stretching (monomer) \circ : C=O stretching (dimer) \bullet : COO⁻ stretching vibration.

3.3 The melting points of HAp/PEG composites

DSC curves for pure PEG_{COOH}, PEG_{OH} and their composites are shown in Fig.4. For the pure PEG_{COOH}, a melting point was 51.3°C while that for the HAp/PEG_{COOH} composites shifted discretely toward a higher temperature with the increase in mixing content of HAp: i.e. 55.7°C for 70PEG_{COOH} and 58.2°C for 30PEG_{COOH}. Furthermore, with respect to the intermediate sample 50PEG_{COOH}, two different melting points were simultaneously found at 55.7°C and 58.3°C, which were in agreement to those for 70PEG_{COOH} and 30PEG_{COOH}, respectively. As these melting points were very close to that of the pure PEG_{COOH}

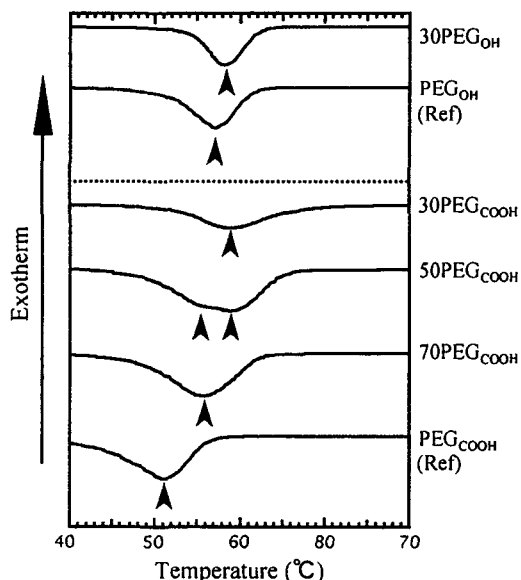


Fig. 4 DSC curves of the pure PEG_{COOH}, PEG_{OH} and their composites.

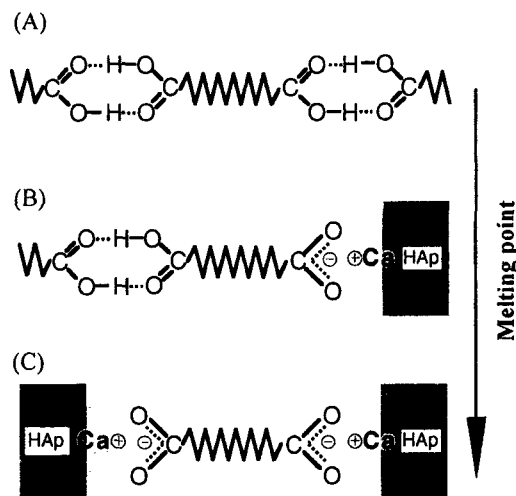


Fig. 5 The possible molecular states.

but apparently different from it, the origin of the different melting points could be essentially attributed to van der Waal's force between the PEG_{COOH} molecules which had different chemical bonds at both terminations. The existence of two different melting points in the composite suggested that the COOH groups had two different interactions between the PEG_{COOH} molecule and the HAp surfaces. The assignment will be discussed in detail in the next section.

For the pure PEG_{OH}, a melting point was observed at 57.1°C higher than for the pure PEG_{COOH}, being mainly due to the difference of molecular weights. The melting point for 30PEG_{OH} was 58.0°C, which was almost the same melting point as the pure PEG_{OH}; this meant that the interaction between PEG_{OH} and HAp was very weak, corresponding to the results of FT-IR spectroscopy.

3.4 Chemical interaction between HAp and PEG

Here, we discuss about the chemical bonding states between HAp and PEG_{COOH} on the basis of the experimental results of FT-IR and DSC. Fig.5 shows possible models for the chemical bonding states formed between PEG_{COOH} and HAp: Fig.5(A) is a bonding state for the pure PEG_{COOH} in which two COOH groups exist at both molecule ends, and Figs.5(B) and (C) are two different bonding states for the HAp/PEG_{COOH} composites whose terminated COOH groups are completely or partially changed to COO⁻ group.

In the model (A), both terminated COOH groups respectively form two hydrogen bonds with a COOH group of another PEG molecule to be a dimer state, since the IR absorption bands of COOH only could be observed for the pure PEG_{COOH} as is shown in Fig.2. In the model (B), one of both terminated COOH groups forms the dimer state, while another COOH group is changed to an ionized -COO⁻ which chemically interacts with an ion, probably calcium ion on a HAp surface. This model corresponds to the HAp/PEG_{COOH} composites with small contents of HAp, in which the IR absorption bands of COOH and COO both were simultaneously observed. In the model (C), both of terminated COOH groups are ionized to COO⁻ groups, which interact with calcium ions on HAp surfaces. This model corresponds to the HAp/PEG_{COOH} composites with large contents of HAp, in which the IR absorption band of COO only was found.

Suppose the van der Waal's interaction is

stronger among the PEG molecules terminated by ionized COO⁻ than among those terminated by non-ionized COOH, the increase in mixing content of HAp in the composites causes the melting point higher as seen in Fig.4. In the HAp/PEG_{COOH} composites, as the ionized COO⁻ ends can form COO⁻-Ca²⁺ bonds on HAp surfaces and the non-ionized COOH ends can form COOH-HOOC dimers between PEG molecules, it is considered that such different terminated states affect the attractive interaction between PEG molecules. Therefore, three molecular states shown in Fig.5 correspond to three different peaks observed by DSC shown in Fig.4: i.e. the lowest melting point 51.3°C to the model (A), the middle point 55.7°C to the model (B), and the highest point 58.2°C to the model (C).

4. CONCLUSIONS

In the present study, the composites of HAp and PEG were prepared by a thermal kneading method. FT-IR and DSC measurements indicated that ionized groups COO⁻ on PEG interacted with HAp surface but OH group on PEG very weakly interacted with it. Since collagen, the main organic component of bone, has COOH groups at its side chains, it is conjectured that HAp nanocrystals form a composite with collagen via the COO⁻-Ca²⁺ interaction in the bone. For the development of an organic/inorganic composite with strong mechanical property and osteoconductivity, therefore, it is important to control the COO⁻-Ca²⁺ interaction.

5. REFERENCES

1. L.L. Hench, *Science*, **226**, 630 (1987).
2. L.L. Hench, *J. Amer. Ceram. Soc.*, **74**, 1487-1510 (1991).
3. T. Kokubo, *J. Ceram. Soc. Jpn.*, **99**, 965-973 (1991).
4. D.R. Beech, *Archs oral Biol.*, **17**, 907-911, (1972).
5. A.D. Wilson, H.J. Prosser, D.M. Powis, *J. Dent. Res.*, **62**, 590-592, (1982).
6. D.S. Smith, *Brit. Dent. J.*, **125**, 381-384, (1968).
7. S. Crisp, H.J. Prosser, A.D. Wilson, *J. Mat. Sci.*, **11**, 36-48, (1976).

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