

Adsorption and removal of strontium in aqueous solution by synthetic hydroxyapatite

Yuichi Nishiyama¹ · Tadashi Hanafusa¹ · Jun Yamashita² · Yoko Yamamoto² · Toshiro Ono¹

Received: 22 March 2015

© The Author(s) 2015. This article is published with open access at Springerlink.com

Abstract Hydroxyapatite (HAP) is a main mineral constituent of bone and tooth and has an outstanding biocompatibility. HAP is a possible sorbent for heavy metals in wastewater due to its high adsorption capacity and low water solubility. We developed a removal system of ⁹⁰Sr from aqueous solution by HAP column procedure. More than 90 % of ⁹⁰Sr was adsorbed and removed from the ⁹⁰Sr containing solution. Divalent cations, Ca²⁺, had little effect on the removal of ⁹⁰Sr up to a concentration of 1 mmol L⁻¹. This clearly indicates that the HAP column technique is advantageous with respect to the capacity to adsorb ⁹⁰Sr from water present in the environment.

Keywords Strontium · Hydroxyapatite · Adsorption · Desorption · Divalent cation

Introduction

Large amounts of radioactive nuclides were released into the environment due to the Fukushima Daiichi Nuclear Power Plant accident on March 11, 2011. The released radioactive nuclides were deposited on the soil, houses, trees, plants, water, and other structures over a wide area of

Tohoku as well as the Kanto region [1–4]. Among them, long-lived radioactive nuclides, such as ¹³⁴Cs (half-life: 2.06 year), ¹³⁷Cs (half-life: 30.17 year), and ⁹⁰Sr (half-life: 28.79 year), which are considered to be harmful to humans, are of great concern in terms of environmental contamination. Environmental monitoring has been performed by detecting γ -rays [5]. The long-lived γ -emitter ¹³⁷Cs has been used to evaluate decontamination, because it is easily detected using various instruments including GM and scintillation counters, and is more precisely determined with a Ge semiconductor detector. However, the pure β^- -emitter ⁹⁰Sr requires a complicated extraction and purification process for analysis. Therefore, few studies on ⁹⁰Sr release have been performed so far.

There are several methods to remove of metal ions from wastewater, such as chemical precipitation [6], ion exchange [7], membrane treatment [8], and adsorption [9, 10]. Adsorption is one of the most commonly used methods due to its simplicity and selectivity. For the separation of strontium ions, various types of organic [11, 12] and inorganic [13] adsorbents have been reported. Hydroxyapatite (HAP, Ca₁₀(PO₄)₆(OH)₂) is the main mineral constituent of bones and teeth. It has been widely used as a biomaterial for hard tissues because of its marked biocompatibility [14]. It possesses a high affinity for proteins and has been applied for separating them [15]. Recently, HAP has attracted particular interest in treating wastewater containing heavy metals due to its high adsorption capacity and low water solubility [16–19].

The aim of this study was to develop a system to remove strontium from aqueous solution with an adsorption procedure. We focused on HAP prepared by a different calcination temperature as sorbent materials, and showed the effective adsorption and desorption of strontium with the HAP column procedure.

✉ Toshiro Ono
onot@md.okayama-u.ac.jp

¹ Department of Radiation Research, Advanced Science Research Center, Okayama University, 2-5-1 Shikata-cho, Kita-ku, Okayama 700-8558, Japan

² Institute of Plant Science and Resources, Okayama University, 2-20-1 Chuo, Kurashiki, Okayama 710-0046, Japan

Experimental

Reagent

Strontium nitrate was obtained from Wako Pure Chemical Industries (Osaka, Japan). Sr standard solution (1 mg mL^{-1}) for atomic absorption spectrometry was also from Wako Pure Chemical Industries. Ultrapure HNO_3 was purchased from Sigma Aldrich (Tokyo, Japan). $^{90}\text{SrCl}_2$ ($1.05 \times 10^4 \text{ Bq mL}^{-1}$) in 0.1 N HCl was purchased from Japan Radiation Association (Tokyo, Japan).

Sorbents

Several kinds of synthetic HAP and tricalcium phosphate (TCP) were prepared (Taihei Chemical Industrial, Co., Ltd., Osaka, Japan). Their characteristics (calcination temperature and particle size) are listed in Table 1. The morphology of HAP particles was examined using scanning electron microscopy (S-3200 N, Hitachi, Ltd., Tokyo, Japan) and is illustrated in Fig. 1. Synthetic zeolite (Type A3) was purchased from Wako Pure Chemical Industries.

Batch sorption studies

Adsorption studies were carried out using the batch technique. One milliliter of Sr^{2+} solution ($100 \text{ } \mu\text{g L}^{-1}$) was

Table 1 Physico-chemical characteristics of sorbents

Sorbents	Calcination temperature ($^{\circ}\text{C}$)	Particle size (mm)
Hydroxyapatite		
HAP-1 ^a	200	ND
HAP-2	500	0.25–0.35
HAP-3	900	0.25–0.35
HAP-4	900	0.35–0.50
HAP-5 ^a	900	ND
Tricalcium phosphate		
TCP-1	200	0.15–0.25
TCP-2	200	0.25–0.35
TCP-3	200	0.35–0.50
TCP-4	200	0.50–0.84
TCP-5	500	0.25–0.35
TCP-6	900	0.25–0.30
TCP-7	900	0.35–0.50
TCP-8	1250	0.35–0.50
TCP-9	1250	1.7–2.8
Zeolite		
Zeolite A3	–	0.50–1.18

^a Their sizes are not different from HAP-2, HAP-3, and HAP-4, as shown in Fig. 1

ND not determined

mixed with 0.02–0.12 g of HAP, TCP, or zeolite particles, respectively. The initial pH was adjusted to values ranging from 4.0 to 9.6 using 1 mmol L^{-1} sodium acetate buffer, phosphate buffer, and carbonate buffer, respectively. Each mixture was incubated for 10 or 60 min at room temperature with shaking. After incubation, they were centrifuged at 6000 rpm for 5 min and the supernatant was collected. The Sr^{2+} concentration in the supernatant was determined by atomic absorption spectrometry. The adsorption efficiency (A_{eff}) was calculated as:

$$A_{\text{eff}}(\%) = 100 \times \left(1 - \frac{C}{C_0}\right) \quad (1)$$

where C_0 is the initial Sr^{2+} concentration ($\mu\text{g L}^{-1}$) in the solution and C is the Sr^{2+} concentration ($\mu\text{g L}^{-1}$) in the supernatant.

Adsorption equilibrium

Adsorption equilibrium studies were performed by equilibrating 0.1 g of HAP with 10 mL of Sr^{2+} solution at varying concentrations ($0\text{--}1000 \text{ mg L}^{-1}$) at 20°C and at an initial pH of 7.0. After 24-h incubation, the reaction mixtures were centrifuged at 6000 rpm for 5 min and aliquots of supernatants were determined for the Sr^{2+} concentration by atomic absorption spectrometry. The amount of Sr^{2+} adsorbed at equilibrium, q_e (mmol g^{-1}) was calculated as:

$$q_e = \frac{C_0 - C_e}{C_s} \quad (2)$$

where C_0 is the initial Sr^{2+} concentration (mmol L^{-1}), C_e is the residual Sr^{2+} concentration at equilibrium (mmol L^{-1}), and C_s is the HAP concentration (g L^{-1}).

Adsorption of ^{90}Sr

A tracer amount of $^{90}\text{Sr}^{2+}$ was added to $100 \text{ } \mu\text{g L}^{-1}$ of $\text{Sr}(\text{NO}_3)_2$ solution, containing divalent cations (Ca^{2+} and Mg^{2+}) in the range of $0\text{--}100 \text{ mmol L}^{-1}$. Adsorption of $1 \text{ mL } ^{90}\text{Sr}$ solution (105 Bq mL^{-1} , pH 7.0) was evaluated using column method. Radioactivity of the supernatants or eluates as the total beta activity was measured by a low background gas flow beta counter (LBC-4202, Hitachi Aloka Medical, Ltd., Tokyo, Japan).

Condensation and separation using column apparatus

Sr^{2+} was adsorbed and condensed on an HAP-filled column. A total of 0.2 g HAP was emerged in 1 mL of distilled water and transferred to a $0.8 \times 4\text{-cm}$ chromatography column (Bio-Rad Laboratories, Inc., Hercules, CA, USA). The column was washed and equilibrated twice with

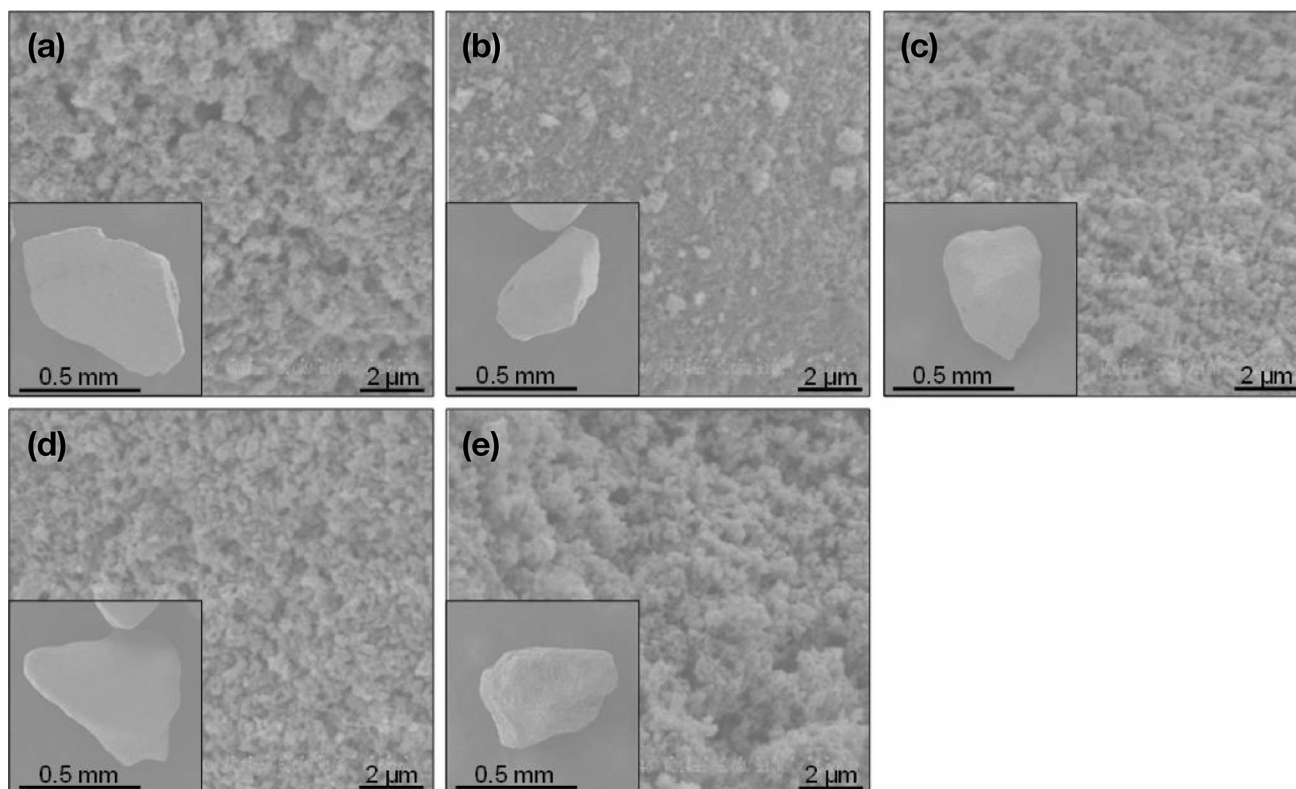


Fig. 1 SEM images of HAP particles. **a** HAP-1, **b** HAP-2, **c** HAP-3, **d** HAP-4, and **e** HAP-5

phosphate buffer (pH 7.0). Then, 10 mL of Sr^{2+} solution (15 ng mL^{-1} , pH 7.0) was loaded and the effluent was collected. After the adsorption of Sr^{2+} onto the HAP column, it was eluted by adding a total of 5 mL of $100 \text{ mmol L}^{-1} \text{ Ca}^{2+}$ ion solution, and 1 mL of each eluate fraction was collected. The Sr^{2+} concentration of each eluate was measured by atomic absorption spectrometry.

Atomic absorption spectrometry

A flame atomic absorption spectrometer (Z-9000, Hitachi, Ltd., Tokyo, Japan) equipped with a hollow cathode lamp (wave length, 490 nm) was used for Sr^{2+} determination. Analytical working solutions containing 0, 10, 25, 50, and 100 μg L^{-1} of Sr^{2+} were prepared by the appropriate dilution of 1 g L^{-1} standard solution with ultrapure nitric acid. The absorbance of blank, analytical solution, and sample solution was measured successively with the optimized operating conditions.

Results

Batch adsorption

Five kinds of HAP particle and nine kinds of TCP particle were tested for their Sr^{2+} adsorption properties with the

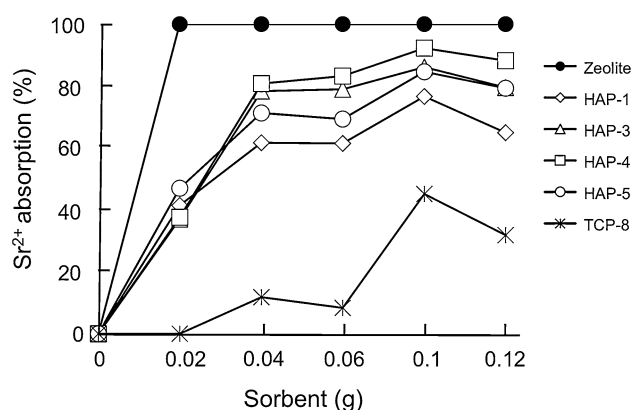


Fig. 2 Effect of sorbent amount on Sr^{2+} adsorption

batch method. The effect of the amount of sorbent was investigated. As shown in Fig. 2, the adsorption of Sr^{2+} rose with an increasing amount of HAP, and reached a maximum plateau at 0.04 g of HAP. A total of 0.05 g of each sorbent and 1 mL of Sr^{2+} solution were thus incubated for 10 and 60 min. Four kinds of HAP particle, HAP-1, HAP-3, HAP-4, and HAP-5, adsorbed Sr^{2+} as efficiently as zeolite particles (Fig. 3). However, TCP particles showed less adsorption efficiency. We, therefore, choose HAP-1, HAP-3, HAP-4, and HAP-5 particles for further studies.

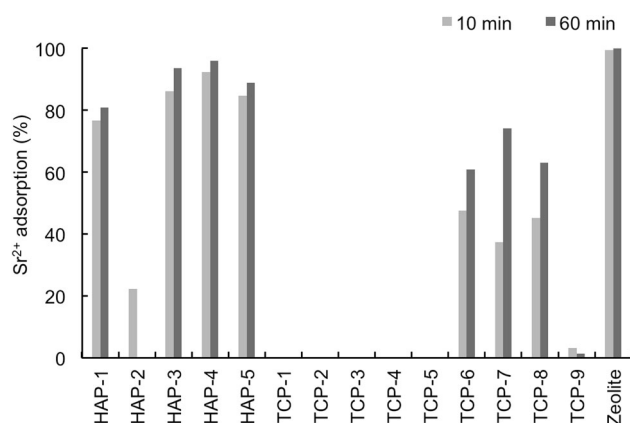


Fig. 3 Sr²⁺ adsorption efficiency of HAP, TCP, and zeolite. Analysis by batch method

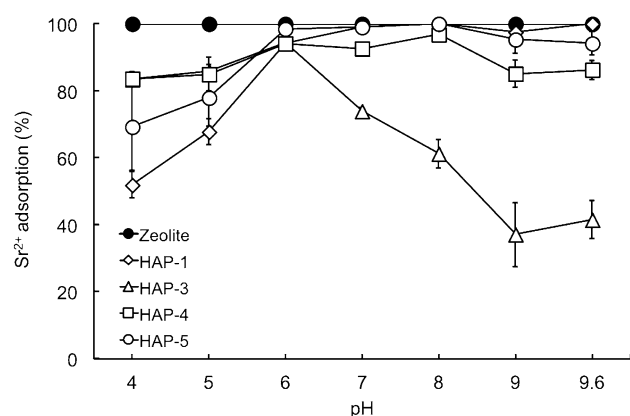


Fig. 4 Effect of pH on Sr²⁺ adsorption by HAP. Each value represents the mean $\pm$ SD of three independent experiments

Effect of pH

The effect of the pH on Sr²⁺ adsorption by the selected HAP particles was investigated. As shown in Fig. 4, the adsorption of Sr²⁺ increased with pH elevation. The plateau adsorption value reached pH 6, and was maintained in an alkaline pH range except for with HAP-3 particles.

Adsorption isotherm

Figure 5a shows the adsorption isotherm of HAP-5 particles at 20 °C. The adsorbed amount of Sr²⁺ rapidly increased and then gradually reached a maximum plateau. The adsorption curve corresponded to the Langmuir isotherm. The Langmuir isotherm was applied for equilibrium adsorption using the following equation:

$$\frac{C_e}{q_e} = \frac{1}{q_{\max} \cdot K} + \frac{C_e}{q_{\max}} \quad (3)$$

where C_e (mmol L⁻¹) is the equilibrium concentration of Sr²⁺, $q_{\max}$ (mmol L⁻¹) is the maximum amount of Sr²⁺ adsorbed on the HAP at equilibrium, and K (L mmol⁻¹) is a constant related to the adsorption. The constants of $q_{\max}$ and K were evaluated by the slope and intercept of the plot drawn between C_e/q_e versus C_e (Fig. 5b). The $q_{\max}$ and K value were determined to be 27 μ mol g⁻¹ and 8.0 L mmol⁻¹, respectively.

Column adsorption and separation

In order to investigate the column adsorption efficiency, 10 mL of Sr²⁺ solution (15 ng mL⁻¹, pH 7.0) was applied onto the HAP-5 and zeolite-loaded columns equilibrated with 1 mM phosphate buffer (pH 7.0), respectively. As shown in Fig. 6a, nearly 80 and 90 % of Sr²⁺ were adsorbed on the HAP-5 and zeolite columns, respectively. We conducted stripping of Sr²⁺ from the loaded columns using 100 mmol L⁻¹ CaCl₂ solution. A 1-mL fraction was collected at each step for Sr²⁺ determination using a flame atomic absorption spectrometer. Sr²⁺ was completely eluted from the HAP-5 column in the first to fifth fractions (Fig. 6b). However, no Sr²⁺ was stripped from the zeolite column. Ten milliliters of Sr²⁺ solution (15 ng mL⁻¹, pH 7.0) was then re-applied onto the Sr²⁺-stripped HAP-5 column. As shown in Fig. 6c, Sr²⁺ was successfully adsorbed onto the regenerated HAP-5 column.

⁹⁰Sr adsorption

We performed ⁹⁰Sr adsorption tests with column operation technique. The effect of competing divalent cations (Ca²⁺ and Mg²⁺) on the adsorption was evaluated as a function of cation concentrations using the HAP-5 column. As shown in Fig. 7a, more than 90 % of ⁹⁰Sr was adsorbed onto all HAP particles examined from competing cation-free solution. On the other hand, zeolite was less effective regarding its ⁹⁰Sr adsorption performance compared with HAP particles. Adsorption of ⁹⁰Sr was not influenced by the Ca²⁺ concentration up to 1 mmol L⁻¹. It decreased to 30 % in the presence of 100 mmol L⁻¹ Ca²⁺. Mg²⁺ had little effect on the removal of ⁹⁰Sr over the entire concentration range (Fig. 7b).

Discussion

In this study, we developed an effective method for separating strontium from aqueous solution on HAP particles with a column procedure. Nearly 80 % of Sr²⁺ was adsorbed on the HAP column. The adsorption equilibrium

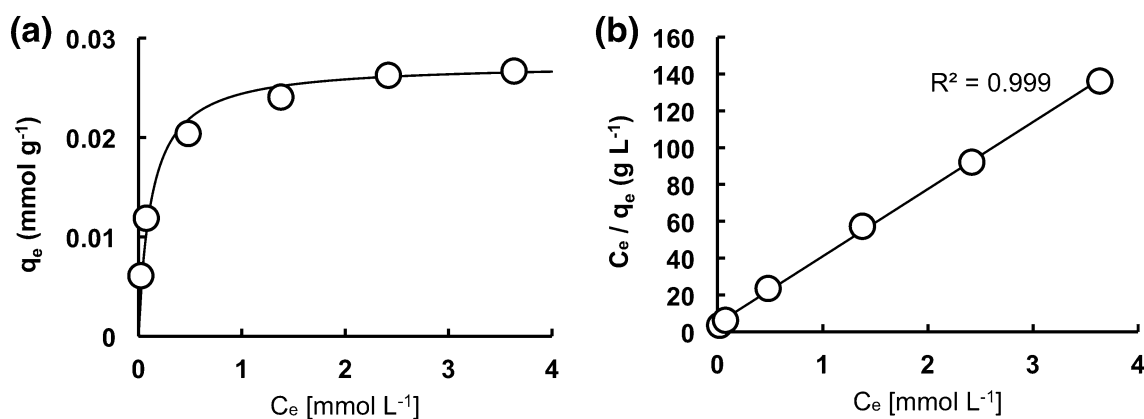
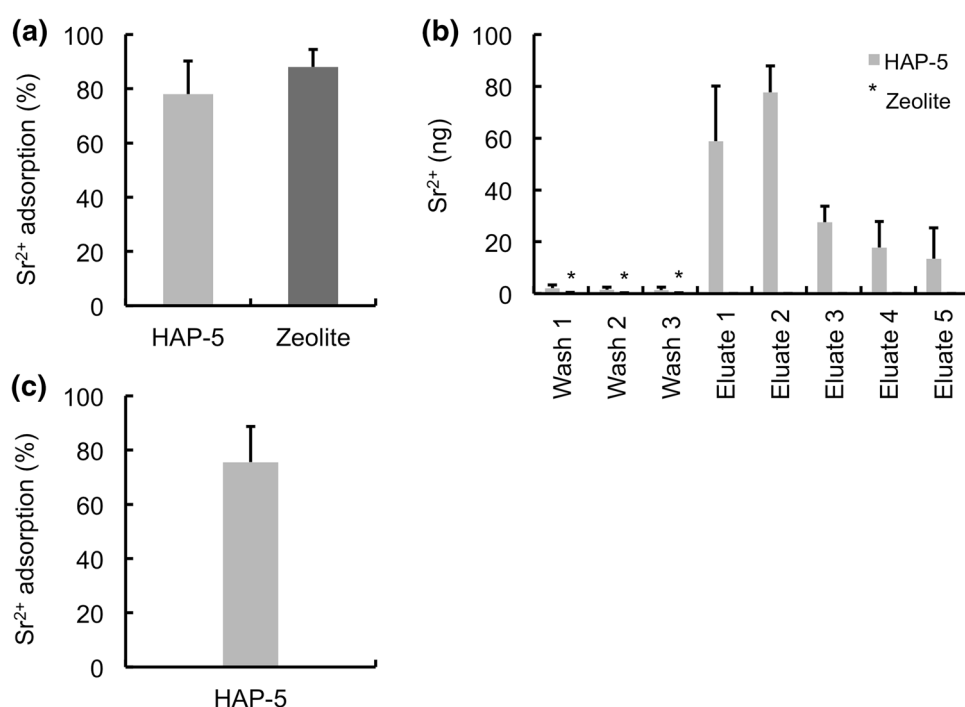


Fig. 5 Equilibrium adsorption of Sr^{2+} on HAP. **a** Adsorption isotherm. **b** Langmuir isotherm plot

Fig. 6 Column method. **a** Sr^{2+} adsorption onto HAP and zeolite column. **b** Desorption of Sr^{2+} by adding 0.1 mol L⁻¹ CaCl_2 solution as the eluent. **c** Reuse of HAP column. After stripping Sr^{2+} from the column, Sr^{2+} solution was re-applied onto the column. Each value represents the mean $\pm$ SD of three independent experiments



fitted the Langmuir isotherm equation. The maximum adsorption capacity was 27 $\mu\text{mol g}^{-1}$. The adsorbed Sr^{2+} was successfully stripped from the column using a small amount of Ca^{2+} solution. It resulted in 30–50 % condensation of Sr^{2+} from that in the initial solution. The regenerated column could be used for the second round of separation.

Zeolite has been traditionally used to remove radionuclides including ^{137}Cs and ^{90}Sr from radioactive wastewater, by ion exchange with Na^+ ions it contains [10, 20]. Zeolite showed almost the complete adsorption and removal of ^{90}Sr with the batch operation technique in our study. Using the column operation technique, however, it showed less effective ^{90}Sr adsorption compared to that of

HAP. Furthermore, different from the HAP column, desorption of Sr^{2+} from the zeolite column was not achieved. It clearly indicated that the HAP column operation technique had advantages with respect to its desorption capacity, environmental safety, and disposal of the unloaded column compared with the zeolite column.

The adsorption mechanism of HAP depends on several factors, such as the solution pH [21], physico-chemical properties [22], and presence of other metal ions [23]. Metal ion adsorption onto HAP is pH-dependent. The lower adsorption in the acidic solutions is attributed to the H^+ ions competing with the metal ions for exchange sites. We showed that Sr^{2+} adsorption increased with pH elevation. The highest adsorption was observed at a pH above 6.0.

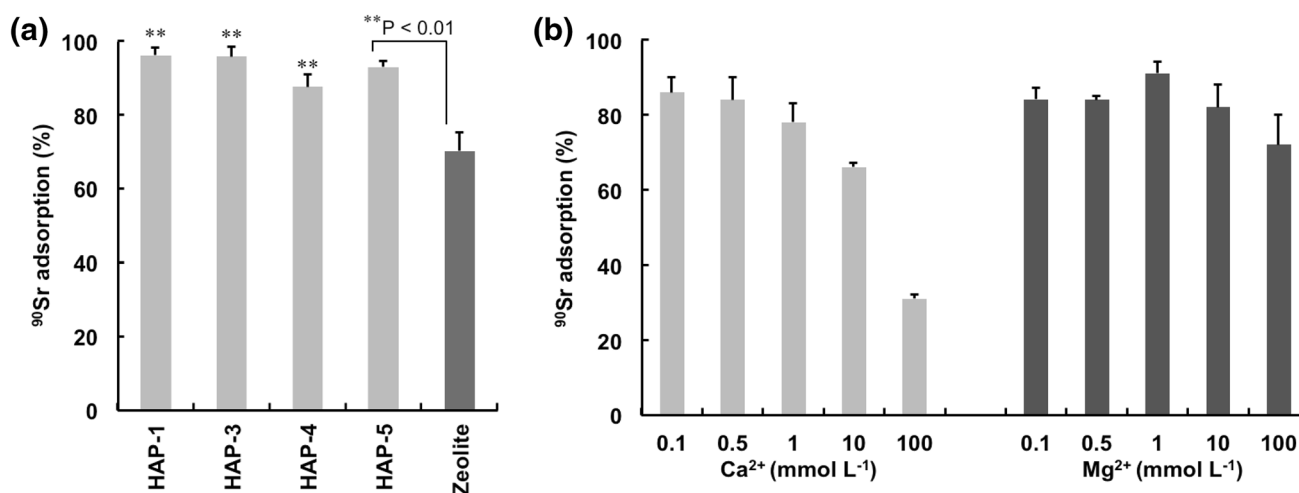


Fig. 7 Adsorption of ^{90}Sr onto HAP and zeolite column. **a** Adsorption efficiency from competing ion free solution. **b** Effect of competing Ca^{2+} and Mg^{2+} ions analyzed by HAP-5 column. Each value

represents the mean $\pm$ SD of three independent experiments. * $P < 0.01$ by unpaired Student's t test

The crystallinity of HAP has been shown to correlate with the metal ion adsorption behavior. Stötz et al. [24] and Roszkopfová et al. [19] showed that highly crystalline HAP particles, which were calcined at elevated temperatures of 700–1000 °C, had a lower adsorption capacity than low-level crystalline HAP particles. In this study, however, HAP particles calcined at 200 and 900 °C exhibited the same adsorption performance, indicating the absence of a correlation between crystallinity and Sr^{2+} adsorption.

Tricalcium phosphate ($\text{Ca}_3(\text{PO}_4)_2$, TCP) exhibits Sr^{2+} adsorption with a lower activity than HAP [25]. TCP does not show an apatite structure and the Sr^{2+} is thought to enter the heterogeneous structure of TCP with chemical reactions. We tested 9 kinds of TCP with different particle sizes, which were prepared by calcination at different temperatures (200–1250 °C). TCPs calcined at higher temperatures showed a moderate Sr^{2+} adsorption behavior. However, no Sr^{2+} adsorption was observed on TCPs calcined at a lower temperature (200 °C).

Another factor influencing Sr^{2+} adsorption is the presence of competing cations. Sr is an alkaline-earth metal element and it behaves similarly to Ca, Mg, and Ba. Smičiklas et al. [26] reported the effect of alkaline-earth metal ions (Ca^{2+} and Mg^{2+}) and alkaline metal ions (Na^+ and K^+) on Sr^{2+} adsorption onto HAP using the batch method. Competing cations decreased by 60–70 % on Sr^{2+} adsorption. Natural samples contain large quantities of Na^+ , K^+ , and Ca^{2+} . The separation of tracer amounts of ^{90}Sr from these cations is particularly important. In our study, Mg^{2+} had little effect on the removal of ^{90}Sr . The adsorption of ^{90}Sr was not influenced in the presence of 1 mmol L $^{-1}$ Ca^{2+} . It decreased by 20 % with an increase of Ca^{2+} to 10 mmol L $^{-1}$. The average amount of Ca^{2+} in natural water is 15–20 mg L $^{-1}$ (0.375–0.5 mmol L $^{-1}$) in Japan [27]. In some areas of

Europe, the Ca^{2+} level in natural water is several times higher than that in Japan, but does not exceed 10 mmol L $^{-1}$ [28]. Taken together, the present HAP column technique is useful to remove ^{90}Sr from the wastewater as well as natural water in the environment.

Conclusion

In this study, we developed a system to remove strontium from aqueous solution with an HAP column procedure. Divalent competing cations, Ca^{2+} , had little effect on the removal of ^{90}Sr . Our system may be useful to remove ^{90}Sr from wastewater.

Acknowledgments We are grateful to Dr. H. Nagatsuka (Department of Oral Pathology, Graduate School of Medicine, Dentistry, and Pharmaceutical Sciences, Okayama University) for providing HAP and TCP. We are also grateful to Mr. S. Iwasa (Central Research Laboratory, Okayama University Medical School) for atomic absorption spectrometry and Ms. T. Terada for preparation of the manuscript. This work was supported in part by the Grant for Strategies for the Efficient Operation of Okayama University.

Open Access This article is distributed under the terms of the Creative Commons Attribution 4.0 International License (<http://creativecommons.org/licenses/by/4.0/>), which permits unrestricted use, distribution, and reproduction in any medium, provided you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons license, and indicate if changes were made.

References

- Hirose K (2012) 2011 Fukushima Dai-ichi nuclear power plant accident: summary of regional radioactive deposition monitoring results. J Environ Radioact 111:13–17

2. Yamashita J, Enomoto T, Yamada M, Ono T, Hanafusa T, Nagamatsu T, Sonoda S, Yamamoto Y (2014) Estimation of soil-to-plant transfer factors of radiocesium in 99 wild plant species grown in arable lands 1 year after the Fukushima 1 Nuclear Power Plant accident. *J Plant Res* 127:11–22
3. Mikami S, Maeyama T, Hoshide Y, Sakamoto R, Sato S, Okuda N, Demongeot S, Gurriaran R, Uwamino Y, Kato H, Fujiwara M, Sato T, Takemiya H, Saito K (2015) Spatial distributions of radionuclides deposited onto ground soil around the Fukushima Dai-ichi Nuclear Power Plant and their temporal change until December 2012. *J Environ Radioact* 139:320–342
4. Harada KH, Niisoe T, Imanaka M, Takahashi T, Amako K, Fujii Y, Kanameishi M, Ohse K, Nakai Y, Nishikawa T, Saito Y, Sakamoto H, Ueyama K, Hisaki K, Ohara E, Inoue T, Yamamoto K, Matsuoka Y, Ohata H, Toshima K, Okada A, Sato H, Kuwamori T, Tani H, Suzuki R, Kashikura M, Nezu M, Miyachi Y, Arai F, Kuwamori M, Harada S, Ohmori A, Ishikawa H, Koizumi A (2014) Radiation dose rates now and in the future for residents neighboring restricted areas of the Fukushima Daiichi Nuclear Power Plant. *Proc Natl Acad Sci USA* 111:E914–E923
5. Saito K, Tanihata I, Fujiwara M, Saito T, Shimoura S, Otsuka T, Onda Y, Hoshi M, Ikeuchi Y, Takahashi F, Kinouchi N, Saegusa J, Seki A, Takemiya H, Shibata T (2015) Detailed deposition density maps constructed by large-scale soil sampling for gamma-ray emitting radioactive nuclides from the Fukushima Dai-ichi Nuclear Power Plant accident. *J Environ Radioact* 139:308–319
6. Volkovich VA, Griffiths TR, Thied RC (2003) Treatment of molten salt wastes by phosphate precipitation: removal of fission product elements after pyrochemical reprocessing of spent nuclear fuels in chloride melts. *J Nucl Mater* 323:49–56
7. Mishra SP, Tiwary D (1999) Ion exchangers in radioactive waste management. Part XI. Removal of barium and strontium ions from aqueous solutions by hydrous ferric oxide. *Appl Radiat Isot* 51:359–366
8. Hwang ED, Lee KW, Choo KH, Choi SJ, Kim SH, Yoon CH, Lee CH (2002) Effect of precipitation and complexation on nanofiltration of strontium-containing nuclear wastewater. *Desalination* 147:289–294
9. Ye X, Liu T, Li Q, Liu H, Wu Z (2008) Comparison of strontium and calcium adsorption onto composite magnetic particles derived from Fe_3O_4 and bis (trimethoxysilylpropyl) amine. *Colloid Surf A Physicochem Eng Asp* 330:21–27
10. El-Kamash AM (2008) Evaluation of zeolite A for the sorptive removal of Cs^+ and Sr^{2+} ions from aqueous solutions using batch and fixed bed column operations. *J Hazard Mater* 151:432–445
11. Zhang L, Zhou J, Zhou D, Tang Y (1999) Adsorption of cadmium and strontium on cellulose/alginate ion-exchange membrane. *J Membr Sci* 162:103–109
12. Krishna MVB, Rao SV, Arunachalam J, Murali MS, Kumar S, Manchanda VK (2004) Removal of ^{137}Cs and ^{90}Sr from actual low level radioactive waste solutions using moss as a phyto-sorbent. *Sep Purif Technol* 38:149–161
13. Başçetin E, Atun G (2006) Adsorption behavior of strontium on binary mineral mixtures of Montmorillonite and Kaolinite. *Appl Radiat Isot* 64:957–964
14. Zhou H, Lee J (2011) Nanoscale hydroxyapatite particles for bone tissue engineering. *Acta Biomater* 7:2769–2781
15. Kawasaki T, Takahashi S, Ikeda K (1985) Hydroxyapatite high-performance liquid chromatography: column performance for proteins. *Eur J Biochem* 152:361–371
16. Feng Y, Gong JL, Zeng GM, Niu QY, Zhang HY, Niu CG, Deng JH, Yan M (2010) Adsorption of Cd (II) and Zn (II) from aqueous solutions using magnetic hydroxyapatite nanoparticles as adsorbents. *Chem Eng J* 162:487–494
17. Smičiklas I, Dimović S, Plečaš I, Mitrić M (2006) Removal of Co^{2+} from aqueous solutions by hydroxyapatite. *Water Res* 40:2267–2274
18. Smičiklas I, Mitrić M, Pfendt P, Raičević S (2000) The point zero charge and sorption of cadmium (II) and strontium (II) ions on synthetic hydroxyapatite. *Sep Purif Technol* 18:185–194
19. Rosskopfová O, Galamboš M, Rajec P (2011) Study of sorption processes of strontium on the synthetic hydroxyapatite. *J Radioanal Nucl Chem* 287:715–722
20. Osmanlioglu AE (2006) Treatment of radioactive liquid waste by sorption on natural zeolite in Turkey. *J Hazard Mater* 137:332–335
21. Chen X, Wright JV, Conca JL, Peurrung LM (1997) Effects of pH on heavy metal sorption on mineral apatite. *Environ Sci Technol* 31:624–631
22. Šljivić M, Smičiklas I, Plečaš I, Mitrić M (2009) The influence of equilibration conditions and hydroxyapatite physico-chemical properties onto retention of Cu^{2+} ions. *Chem Eng J* 148:80–88
23. Corami A, Mignardi S, Ferrini V (2008) Cadmium removal from single- and multi-metal ($\text{Cd} + \text{Pb} + \text{Zn} + \text{Cu}$) solutions by sorption on hydroxyapatite. *J Colloid Interface Sci* 317:402–408
24. Stötzl C, Müller FA, Reinert F, Niederdraenk F, Barralet JE, Gbureck U (2009) Ion adsorption behavior of hydroxyapatite with different crystallinities. *Colloid Surf B Biointerfaces* 74:91–95
25. Ivanets AI, Shashkova IL, Kitikova NV, Drozdova NV, Saprunova NA, Radkevich AV, Kul'bitskaya LV (2014) Sorption of strontium ions from solutions onto calcium and magnesium phosphates. *Radiochemistry* 56:32–37
26. Smičiklas I, Onjia A, Raičević S, Janačković Đ, Mitrić M (2008) Factors influencing the removal of divalent cations by hydroxyapatite. *J Hazard Mater* 152:876–884
27. Nakaguchi Y, Masuda H, Nakajo T, Yamanaka K, Satoguchi Y (2013) Survey report of regional distribution of chemical component in Yodo River System. *Bull Osaka Mus Nat Hist* 67:45–81 (in Japanese)
28. Schröder S, Homøe P, Wagner N, Vataire A-L, Lundager Madsen H, Bardow A (2015) Does drinking water influence hospital-admitted sialolithiasis on an epidemiological level in Denmark? *BMJ Open* 5:e007835. doi:[10.1136/bmjopen-2014-007385](https://doi.org/10.1136/bmjopen-2014-007385)