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Effect of passivation on the dissolution behavior of Ti6A14V and vacuum-brazed Ti6A14V in Hank's ethylene diamine tetra-acetic acid solution
Part I *Ion release*

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This work aims to investigate the effects of three factors, namely: (1) two differently prepared materials (as-polished Ti6A14V and 2 h brazed Ti6A14V); (2) three different surface passivation treatments (34% nitric acid passivation, 400 ℃ heated in air, and aged in 100 ℃ deionized water); and (3) periods of immersion time (up to 32 days), on trace element release in Hank's ethylene diamine tetra-acetic acid (EDTA) solution. After passivation and autoclaving treatment, the specimens were immersed in 8.0 mM EDTA in Hank's solution and maintained at 37 ℃ for periods of time up to 32 days. The 400 ℃ -treated specimens exhibit a substantial reduction in constituent release, which may be attributed to the higher thickness and rutile structure of the surface oxides. For acid-passivated and water-aged treatments, a highly significant decrease in the trace levels of Ti, A1, and V is detected from the brazed Ti6A14V compared to those obtained from the Ti6A14V specimens. It is hypothesized that an anatase–rutile transformation of surface TiO_2 is likely to occur, accelerated by the elements of copper and nickel in the brazed specimens. In addition, a significant time-related decrease in constituent release rate is observed for all kinds of specimens throughout the 0–8 day experimental period. The implication of the results is discussed.

1. Introduction

Titanium or its alloys, primarily Ti6A14V, are frequently used as implant materials because of their favorable mechanical and elastic properties and the widespread evidences of excellent biocompatibility. Some studies clearly demonstrated that commercially pure (CP) Ti or Ti6A14V implants can be osseointegrated, direct contact between living bone and the implant, at the light microscopy level [1–3]. In this respect, CP Ti and Ti6A14V appear to exhibit bioactive properties in the presence of tissue, allowing the growth of bone directly onto its surface, compared to stainless steel and cobalt chromium alloys [4, 5]. The reasons for the apparent success of CP Ti and Ti6A14V implants are threefold. First, CP Ti or Ti6A14V, although a highly reactive metal, form a dense, coherent passive oxide film, preventing the ingress of corrosion products into the surrounding tissue [6–9]. Second, the rate of bone remodeling is related to the difference in elastic moduli between bone and its replacement [10]. Normally the larger this difference, the more rapid bone changes take place. CP Ti and Ti6A14V are particularly good in this regard for their lower modulus of elasticity. A third factor promoting osseointegration is the biochemical properties of the oxide layer of TiO_2 [11, 12]. The oxide layer of TiO_2 is known to have at least two types of hydroxyl groups, basic and acidic OH, attached to the metal by chemisorption [13–15]. The oxide layer of TiO_2 is nonconducting, nevertheless electrons can still tunnel through the layer, leading to conformational changes and denaturing of proteins [11].

Applications of porous coatings for the fixation of surgical implant prostheses through bone ingrowth have extended significantly after the 1980s [16–19]. A number of concerns have been raised, however, regarding the long-term performance of implants with porous coatings. These include the effects of increased ions release and corrosion products of metal due to increased larger surface areas in an aggressive body fluid environment. In order to increase the corrosion resistance, surface

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passivation protocol using nitric acid (ASTM-F86), originally developed for stainless steel and cobalt-base alloy surgical implants [20], was also adopted as one of several tentative passivation treatments for orthopaedic titanium alloy implants [21]. However, a highly significant increase in the trace levels of Ti, Al and V from nitric acid passivated Ti6A14V compared to those obtained from non-passivated Ti6A14V are observed in serum-containing culture medium [22, 23]. The reconsideration of surface treatment for reducing metal ion release of titanium alloy implant has been studied in several researches [24, 25].

In order to achieve a strongly bonded porous-coated device suitable for bone ingrowth, sintering temperature for Ti6A14V alloy in excess of the α to β transition temperature is necessary. Typically, the particles (wire or powder) are sintered at 1250 ℃ for 1 to 3 h in a non-oxidizing atmosphere (vacuum or very pure inert gas). The process will result in a transformation from equiaxed grain, suggested for surgical implants, to lamellar α-β microstructure, which will seriously decrease the fatigue properties of Ti6A14V alloy [26–29]. For solving the mechanical properties of titanium-base alloy, Bugle [30] has suggested the diffusion bonding method to manufacture the titanium porous coating, and Crivella and Stouse [31] have adopted a joinder agent including copper, which decreased the manufacture temperature to below the β transus. By a similar vacuum-brazing method, the porous coating can also be manufactured below the β transus, and the endurance limit of porous coated Ti6A14V alloy, under axial loading condition, was 215 MPa in comparison with 105 MPa by conventional sintering method (1300 ℃) [32]. Meanwhile, the corrosion rates for sintered and brazed specimens were comparable [33], and the brazed specimens possessed the same properties of oxide film, oxide thickness and chemical composition, in comparison with non-brazed Ti6A14V alloy [34].

The purpose of this investigation was to measure the ion release from different experimental materials with passivation treatments into simulated body fluid. In this study, two differently prepared materials (as-polished Ti6A14V and 2 h brazed Ti6A14V) were compared. Each group of materials was subjected to three different surface passivation treatments (34% nitric acid passivation, 400 ℃ heated in air, and aged in 100 ℃ de-ionized water) with further autoclaving treatment. Specimens were immersed in 8.0 mM ethylene diamine tetra-acetic acid in Hank's solution and maintained at 37 ℃ for periods up to 32 days. The differential immersion protocols were performed in order to maintain sink conditions of Hank's ethylene diamine tetra-acetic acid (EDTA) solutions. The solutions were analyzed by inductively coupled plasma-mass spectrometer (ICP-mass).

2. Materials and methods

2.1. Experimental materials

The disc plate used in this study was a surgical grade Ti6A14V alloy (ASTM F136-92). For brazed specimens, foil 0.05 mm in thickness of Ti–15Cu–15Ni (in wt %) (m.p. 934 ℃) was selected as filler for vacuum-brazing treatment, in which the foils were placed on 12.7 mm ϕ × 2.0 mm Ti6A14V alloy disc plate and conducted in a high-temperature vacuum furnace (less than 1.333×10^{-3} Pa). The brazed specimens were heated at 5 ℃ min^{-1} to 970 ℃, soaked for 2 h, and followed by furnace cooling to room temperature. Two kinds of experimental materials used in this study were: (a) Ti6A14V alloy and (b) Ti6A14V brazed at 970 ℃ for 2 h. The as-received Ti6A14V and brazed materials were ground through successive silicon carbide papers to 1500 grit, then subjected to sonication in acetone and rinsed three times in double distilled water. The experimental materials after polishing are denoted as H and B2 in accordance with the preparation of experimental materials, respectively.

2.2. Passivation treatment

After polishing and cleaning, each group of specimens was passivated by the following procedure: (a) immersed in 34% nitric acid for 1 h (P); (b) 400 ℃ in air for 45 min (T); and (c) aging in boiling de-ionized water for 24 h (A). After passivation, the passivated samples are referred with P, T or A adding to the notations for experimental materials. After passivation treatment, all the specimens were subjected to sonication five times in de-ionized water and packed in double-sealed autoclaving bags and steam sterilized at 121 ℃ for 30 min and dried at 121 ℃ for 15 min.

2.3. Immersion protocol

A total of six groups (two materials × three passivations) was investigated, and for each group eight specimens were prepared. All specimens were immersed in Hank's solution with 8.0 mM EDTA. The eight specimens in each of the six groups were placed individually in the sterilized bottles with a surface area to solution volume ratio (SA/V) of 0.1 cm^{-1}. The bottles were covered with lids that permitted gas exchange and were placed into a 37 ℃ incubator containing 5% CO_2/balance air and 100% relative humidity. Sterile techniques were maintained throughout the experiment. Additional control groups consisted of bottles with an identified volume of test solution, but without specimens. The differential immersion experiments were selected by exchanging the test solution periodically. For each time period (1, 2, 4, 8, 16, and 32 days), the incubated medium was poured from each bottle into a cleaned and labeled polypropylene tube which was then sealed. Another solution was inoculated into each bottle for the next immersion period. The collected solutions were analyzed for Ti, Al, V, Cu and Ni using the inductively coupled plasma-mass spectrometer (ICP-mass, Hewlett Packard model 4500 series).

3. Results

The effects of three factors, namely: (1) two differently prepared materials (as-polished Ti6Al4V and 2 h brazed Ti6Al4V); (2) three different surface passivation treatments (34% nitric acid passivation; 400 ℃ heated in air, and aged in 100 ℃ de-ionized water); and (3) periods of immersion time (up to 32 days) on trace element release

TABLE I Normalized concentration of titanium from the differential immersion experiments. Mean ± standard deviation (ng ml^{-1} cm^{-2})

Time of immersion (days)	HP	HT	HA	B2P	B2T	B2A
1	50.29 ± 14.55	7.40 ± 1.09	45.61 ± 6.61	34.96 ± 2.06	6.21 ± 1.52	30.85 ± 6.75
1–2	35.81 ± 5.90	6.19 ± 1.10	29.63 ± 4.02	24.53 ± 3.01	5.08 ± 1.12	21.33 ± 4.51
2–4	56.83 ± 6.55	9.35 ± 1.83	47.09 ± 5.53	38.35 ± 4.36	7.61 ± 1.22	33.45 ± 4.45
4–8	81.58 ± 11.43	14.02 ± 2.14	75.26 ± 7.11	63.11 ± 9.87	12.16 ± 2.38	52.57 ± 9.30
8–16	147.34 ± 20.18	16.20 ± 3.84	127.57 ± 10.64	108.43 ± 12.83	13.29 ± 1.59	94.72 ± 11.20
16–32	284.35 ± 35.60	31.62 ± 6.60	253.18 ± 37.57	207.89 ± 28.22	22.20 ± 9.59	185.46 ± 27.37

Note: numbers of samples = 8.

were investigated in the experiment. The statistical significances of the influence of the experimental factors are tested and verified using Fisher analysis of variance (F-test). If not specified, P values ≤ 0.01 were considered significant throughout the paper.

The mean values and standard deviations of titanium ion release for each group are presented in Table I. Thermal 400 ℃ passivation for both experimental materials (HT and B2T) significantly reduce the titanium ion release compared to acid-passivated and boiling-water-aged specimens (HP, HA, B2P and B2A) throughout the 32-day experimental period ($P < 0.0005$), whereas there is no statistical difference found between HT and B2T during all immersion periods. For the nitric acid and aging passivation groups, the concentrations of titanium ion release are significantly related to the experimental materials (H and B2) rather than the difference in passivation treatment. The concentration of titanium ion release for nitric acid and aging passivated specimens can generally be ranked in the following decreasing order: HP/HA, B2P/B2A with statistical significance ($P < 0.005$). The measured trace releases of titanium of HP specimens are higher than HA specimens throughout the experimental period, but no statistical differences are found in all immersion periods. Similarly, higher concentrations of titanium release from nitric acid passivation are also observed for brazed specimens (B2P) compared to the aging treatment (B2A), but no statistical differences are found between the acid and aging treatment for the brazed experimental materials. The concentrations of titanium ion release during each time period are added cumulatively to obtain the concentration as a function of immersion period, as shown in Fig. 1. As shown in this figure, the 400 ℃ treatment for the two experimental materials (HT and B2T) apparently reduces the titanium ion release to the lowest levels compared to the other two passivation treatments, and the specimens with nitric acid or aging passivation treatment can still be divided into two groups according to the experimental materials: HP/HA, B2P/B2A. As shown in Fig. 1, the transient period of 0–8 days is observed for all kinds of specimens. The dissolution rates, derived from dividing the concentration of titanium ion measured per unit exposed surface area of the sample by the elapsed immersion time, are shown in Fig. 2; where a decrease in titanium release rate as a function of time is observed in all kind of specimens throughout the 0–8 day immersion periods ($P < 0.01$). After 8-day immersion, the titanium ion release rate becomes steady for all kinds of specimens, and the levels are around 1.68 ng cm^{-2}/day for HT and B2T; 12.29 ng cm^{-2}/day for B2P and B2A; and 16.80 ng cm^{-2}/day for HP and HA.

The mean values and standard deviations of aluminum ion release for each group are presented in Table II. Likewise, thermal 400 ℃ passivation on the two experimental materials significantly reduces the aluminum ion release compared to acid-passivated and boiling-water-aged specimens (HP, HA, B2P and B2A) throughout the 32-day experimental period ($P < 0.005$), but no significant differences are found between HT and B2T during all immersion periods. For nitric acid and aging passivation treatment, the aluminum ion trace levels are significantly related to the experimental materials rather than the differences in passivation treatments. The concentration of aluminum ion release for nitric acid and aging passivated specimens can generally be ranked in the following decreasing order:

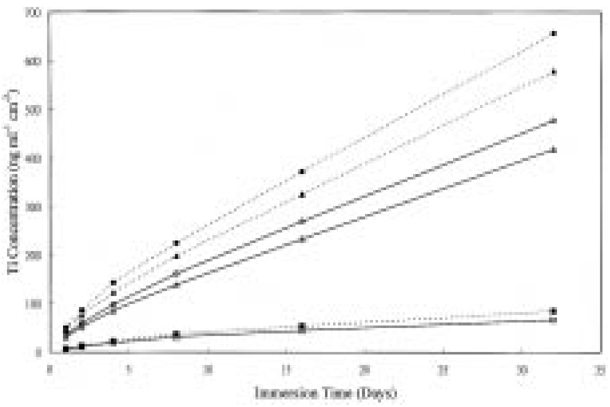

Figure 1 Dissolution of titanium ion as a function of time for Ti6A14V and B2 specimens immersed in EDTA-containing Hank's solution. (●) HP; (■) HT; (▲) HA; (○) B2P; (□) B2T; (△) B2A.

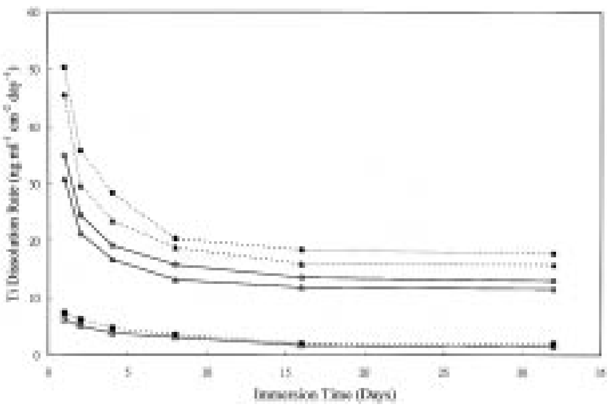

Figure 2 Dissolution rate of titanium ion as a function of time for Ti6A14V and B2 specimens immersed in EDTA-containing Hank's solution. (●) HP; (■) HT; (▲) HA; (○) B2P; (□) B2T; (△) B2A.

TABLE II Normalized concentration of aluminum from the differential immersion experiments. Mean ± standard deviation ($ng\,ml^{-1}\,cm^{-2}$)

Time of immersion (days)	HP	HT	HA	B2P	B2T	B2A
1	12.86 ± 2.62	4.37 ± 0.66	11.12 ± 1.06	9.09 ± 1.70	3.74 ± 0.49	8.65 ± 1.47
1–2	8.91 ± 1.41	3.05 ± 0.65	8.32 ± 1.57	6.64 ± 0.92	2.72 ± 0.46	6.38 ± 0.95
2–4	12.93 ± 1.72	4.28 ± 0.78	11.86 ± 1.38	10.37 ± 0.65	4.16 ± 0.75	8.92 ± 1.61
4–8	20.11 ± 2.61	5.14 ± 0.96	17.78 ± 1.96	14.92 ± 2.34	4.66 ± 0.57	14.14 ± 1.89
8–16	36.61 ± 5.53	7.13 ± 1.14	32.18 ± 4.91	26.02 ± 3.99	7.31 ± 0.72	22.29 ± 4.57
16–32	69.62 ± 6.45	16.45 ± 2.43	66.12 ± 12.56	51.06 ± 9.93	15.14 ± 2.16	48.30 ± 6.60

Note: numbers of samples = 8.

TABLE III Normalized concentration of vanadium from the differential immersion experiments. Mean ± standard deviation ($ng\,ml^{-1}\,cm^{-2}$)

Time of immersion (days)	HP	HT	HA	B2P	B2T	B2A
1	2.17 ± 0.43	0.52 ± 0.07	1.93 ± 0.23	1.59 ± 0.28	0.51 ± 0.04	1.47 ± 0.44
1–2	1.58 ± 0.48	0.36 ± 0.07	1.49 ± 0.40	1.23 ± 0.41	0.33 ± 0.07	1.13 ± 0.34
2–4	2.50 ± 0.40	0.50 ± 0.12	2.28 ± 0.35	1.83 ± 0.34	0.53 ± 0.10	1.71 ± 0.30
4–8	3.92 ± 0.50	0.70 ± 0.14	3.56 ± 0.28	2.99 ± 0.53	0.72 ± 0.13	2.52 ± 0.68
8–16	6.52 ± 1.10	1.19 ± 0.28	5.85 ± 0.49	4.49 ± 0.74	1.23 ± 0.23	3.73 ± 0.90
16–32	14.36 ± 1.58	2.05 ± 0.30	12.78 ± 1.64	9.45 ± 1.41	2.09 ± 0.46	8.67 ± 1.82

Note: numbers of samples = 8.

HP/HA, B2P/B2A ($P<0.01$). Higher levels of aluminum ion release from nitric-acid passivation are also observed for Ti6Al4V and brazed specimens compared to the aging treatment, whilst the significant differences are not found between nitric acid and aging treatment from the same experimental materials throughout the 32-day experimental period. The concentrations of aluminum ion release during each time period are added cumulatively to obtain the concentration as a function of immersion period, as shown in Fig. 3, where the same tendency influenced by the factors of experimental materials, passivation treatment and time are also observed for aluminum ion release compared to the trace release of titanium. The Al trace levels are significantly decreased in medium obtained from the thermal treatment (HT and B2T) compared to those obtained from the other two passivation treatments, and the levels of aluminum ion release from specimens passivated by the nitric acid or aging treatment can still be divided into two groups according to the experimental materials: HP/HA, B2P/B2A. The result of dissolution rates is shown in Fig. 4, where a decrease in aluminum release rate as a function of time is observed in all kinds of specimens throughout the 0–8 day immersion periods ($P<0.01$). After soaking for 8 days, the aluminum release rate becomes steady for all kinds of specimens, and the levels are, in average, 0.99 $ng\,cm^{-2}$/day for HT and B2T; 3.10 $ng\,cm^{-2}$/day for B2P and B2A; and 4.24 $ng\,cm^{-2}$/day for HP and HA.

The mean values and standard deviations of vanadium ion release for each group are presented in Table III. The effect of passivation treatments and experimental materials on the vanadium ion release behaves with the same tendency as the titanium and aluminum release. There are significant reductions in trace levels of vanadium in 400℃ passivated Ti6Al4V and brazed specimens compared to the nitric acid and aging passivation groups throughout the 32-day experimental periods ($P<0.005$), but no significant differences are found statistically between HT and B2T during all immersion periods. For nitric acid and aging passivation treatment, the trace levels of vanadium are also significantly related to the experimental materials rather than the passivation treatment throughout all immersion periods. The concentration of vanadium ion release for nitric acid and aging passivated specimens

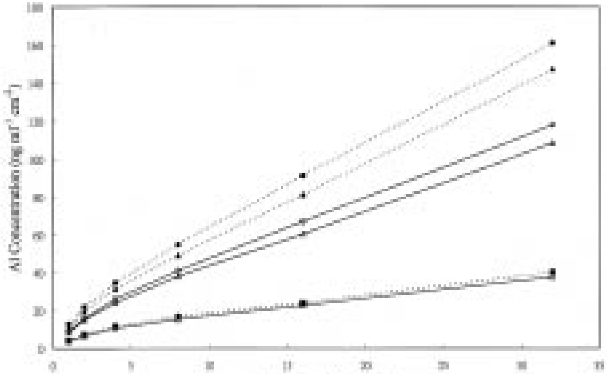

Figure 3 Dissolution of aluminum ion as a function of time for Ti6A14V and B2 specimens immersed in EDTA-containing Hank's solution. (●) HP; (■) HT; (▲) HA; (○) B2P; (□) B2T; (△) B2A.

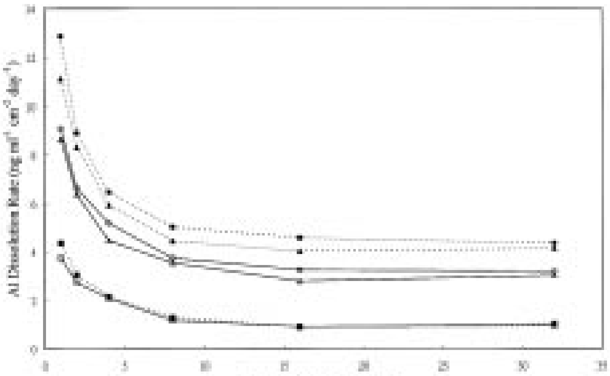

Figure 4 Dissolution rate of aluminum ion as a function of time for Ti6A14V and B2 specimens immersed in EDTA-containing Hank's solution. (●) HP; (■) HT; (▲) HA; (○) B2P; (□) B2T; (△) B2A.

TABLE IV Normalized concentration of copper from the differential immersion experiments. Mean ± standard deviation ($ng\,ml^{-1}\,cm^{-2}$)

Time of immersion (days)	B2P	B2T	B2A
1	2.69 ± 0.68	0.77 ± 0.14	2.29 ± 0.27
1–2	1.67 ± 0.19	0.56 ± 0.11	1.55 ± 0.16
2–4	2.47 ± 0.30	0.71 ± 0.11	2.38 ± 0.48
4–8	3.51 ± 0.81	0.40 ± 0.09	2.91 ± 0.57
8–16	6.56 ± 1.15	0.44 ± 0.09	5.89 ± 0.74
16–32	10.93 ± 1.37	0.70 ± 0.17	10.09 ± 0.94

Note: numbers of samples = 8.

can generally be ranked in the following decreasing order: HP/HA, B2P/B2A ($P < 0.01$). Fig. 5 shows the cumulative vanadium ion as a function of time. For 400 ℃ treatment in air, the experimental materials (HT and B2T) exhibit the lowest trace levels of vanadium in comparison to the acid-passivated and boiling-water-aged specimens. The concentration of vanadium ion release for nitric acid and aging passivated specimens can generally be ranked in the following decreasing order: HP/HA, B2P/B2A. The result of dissolution rate of vanadium ion is shown in Fig. 6, where a decrease in vanadium release rate with time is observed in all kinds of specimens throughout the 0–8 day immersion periods ($P < 0.01$). After soaking for 8 days, the vanadium ion release rate becomes steady for all kinds of specimens, and the levels are, in average, 0.13 $ng\,cm^{-2}$/day for HT and B2T; 0.57 $ng\,cm^{-2}$/day for B2P and B2A; and 0.85 $ng\,cm^{-2}$/day for HP and HA.

The mean values and standard deviations of copper ion release for brazed specimens are presented in Table IV. The 400 ℃ treatment results in a significant reduction in the copper ion release compared to the acid-passivation and boiling-water-aged treatment throughout the 32-day experimental periods ($P < 0.005$). Apparently higher levels but without statistical significance of copper release from the acid-passivated specimens (B2P) are observed for the brazed specimens compared to the aging treatment (B2A) throughout 32-day experimental periods. Fig. 7 shows the cumulative of copper ion release as a function of time, in which similar influences by the factors of passivation treatment and time are also observed for copper ion release compared to the trace releases of titanium, aluminum and vanadium. The result of dissolution rates is shown in Fig. 8, where a decrease in copper release rate is observed in the brazed specimens throughout the 0–8 day immersion periods ($P < 0.01$). After 8-day immersion, the copper release rate becomes steady for all kinds of brazed specimens, and the levels are 0.04 $ng\,cm^{-2}$/day for B2T; 0.63 $ng\,cm^{-2}$/day for B2A; and 0.68 $ng\,cm^{-2}$/day for B2P.

The mean values and standard deviations of nickel ion release for brazed specimens are presented in Table V. Fig. 9 shows the cumulative nickel ion as a function of time, and the result of dissolution rates is shown in Fig. 10. The effect of passivation and time on the trace levels of nickel exhibits a similar behaviour of titanium, aluminum, vanadium, and copper ion releases, where significantly lower ion release levels are found in the 400 ℃ treatment compared to the other two passivated treatments ($P < 0.01$). A time-related significant decrease in nickel release is observed in all the brazed specimens throughout the 0–8 day immersion periods ($P < 0.01$). After 8-day immersion, the nickel release rate becomes steady for all kinds of brazed specimens, and the levels are around 0.05 $ng\,cm^{-2}$/day for B2T; 0.66 $ng\,cm^{-2}$/day for B2A; and 0.68 $ng\,cm^{-2}$/day for B2P.

To summarize, 400 ℃ treatment significantly decreases titanium, aluminum, vanadium, copper, and nickel trace element in EDTA-containing medium with Ti6Al4V and brazed specimens, compared to the elements detected in such samples which are obtained from the acid-passivated and boiling-water-aged treatment. For the acid-passivated and aging treatment, the amounts of titanium, aluminum, vanadium, copper, and nickel ion release are primarily related to the experimental materials rather than the passivation treatments, and the levels of trace element can be statistically ranked in the following decreasing order: HP/HA, B2P/B2A. There is a transient dissolution rate during the 0–8 day incubation period, and the dissolution rate of titanium,

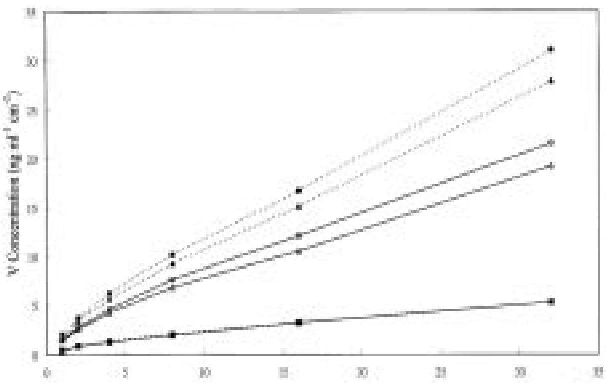

Figure 5 Dissolution of vanadium ion as a function of time for Ti6A14V and B2 specimens immersed in EDTA-containing Hank's solution. (●) HP; (■) HT; (▲) HA; (○) B2P; (□) B2T; (△) B2A.

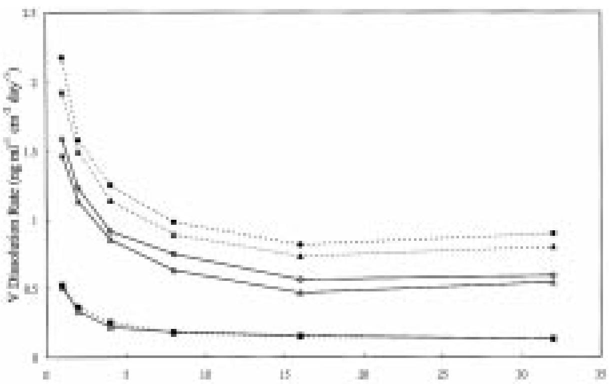

Figure 6 Dissolution rate of vanadium ion as a function of time for Ti6A14V and B2 specimens immersed in EDTA-containing Hank's solution. (●) HP; (■) HT; (▲) HA; (○) B2P; (□) B2T; (△) B2A.

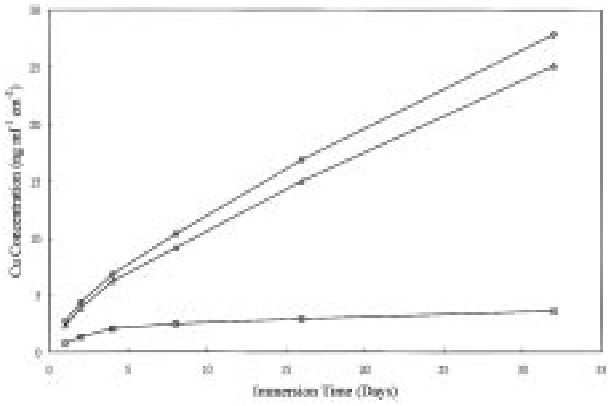

Figure 7 Dissolution of copper ion as a function of time for B2 specimens immersed in EDTA-containing Hank's solution. (○) B2P; (□) B2T; (△) B2A.

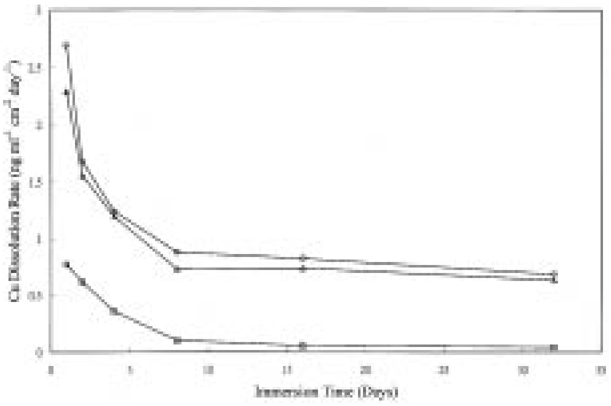

Figure 8 Dissolution rate of copper ion as a function of time for B2 specimens immersed in EDTA-containing Hank's solution. (○) B2P; (□) B2T; (△) B2A.

aluminum, and vanadium from all groups of specimens becomes steady after immersion for 8 days. Similar results for copper and nickel from groups of the brazed specimens can also be observed.

4. Discussion

The study shows that a substantial reduction in constituent releases from the 400 ℃ thermally treated Ti6Al4V and the brazed specimens incubated for 32 days in EDTA-containing Hank's solution, compared to the levels of elements from the acid-passivated and boiling-water-aged specimens. Both experimental materials of Ti6A14V and B2 treated by 400 ℃ show similar ion release statistically. In our previous study, the nanosurface properties of the passivated films, including chemical composition, chemical structure, and oxide thickness, for Ti6Al4V and B2 materials as a function of passivation (nitric acid immersion, 400 ℃ treatment in air, and aging in boiling water) and autoclaving treatment (steam sterilized at 121 ℃ for 30 min and dried at 121 ℃ for 15 min) were evaluated. As shown in Table VI, the 400 ℃ thermally treated samples with autoclaving possess a thicker oxide thickness and lower contents of suboxide phases, which could reduce ion release from implant in clinical use. The factors affecting ion release from the oxidized surface of metal are: (a) nature and strength of the metal–oxide bond; (b) oxide thickness; (c) defect structure of the oxide (vacancies, interstitial elements, etc.); (d) degree of ordering within the oxide; and (e) anisotropic behavior from preferred dissolution sites on the specific crystallographic planes [35]. Except for the thicker oxide thickness which is conductive to the lower ion release from the 400 ℃ treated specimens, the oxide structure might play another important role. Browne and Gregson have investigated the titanium oxide films on the surfaces of Ti6Al4V alloy specimens heat-treated at 400 ℃ in air for 45 min and found a change in the surface oxide structure from mixed titanium oxides to a more stable rutile structure by transmission electron microscope (TEM) [35]. Rutile is more dense and has a closer packed structure with fewer paths for ion diffusion, and therefore the structure will improve dissolution resistance. In comparison, electron

TABLE V Normalized concentration of nickel from the differential immersion experiments. Mean ± standard deviation (ng ml^{-1} cm^{-2})

Time of immersion (days)	B2P	B2T	B2A
1	2.50 ± 0.80	0.76 ± 0.15	2.15 ± 0.66
1–2	1.50 ± 0.29	0.57 ± 0.14	1.36 ± 0.37
2–4	2.37 ± 0.31	0.74 ± 0.14	2.07 ± 0.45
4–8	3.78 ± 0.68	0.40 ± 0.06	3.11 ± 0.57
8–16	5.78 ± 0.97	0.66 ± 0.13	5.00 ± 0.97
16–32	10.81 ± 1.41	0.80 ± 0.12	10.58 ± 1.39

Note: numbers of samples = 8.

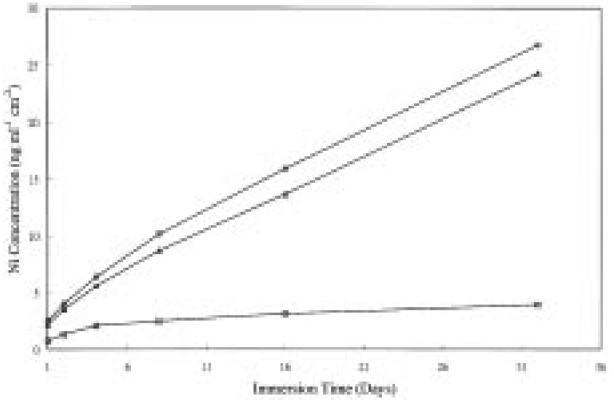

Figure 9 Dissolution of nickel ion as a function of time for B2 specimens immersed in EDTA-containing Hank's solution. (○) B2P; (□) B2T; (△) B2A.

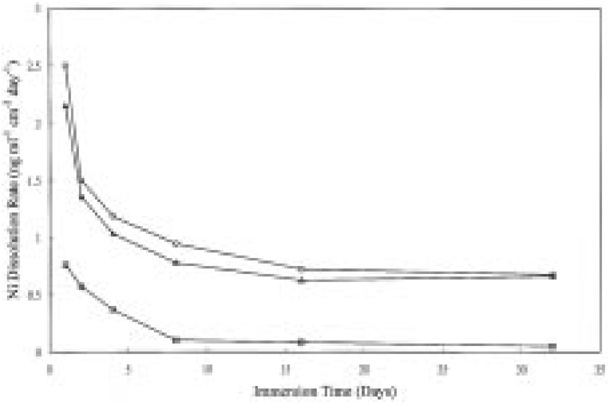

Figure 10 Dissolution rate of nickel ion as a function of time for B2 specimens immersed in EDTA-containing Hank's solution. (○) B2P; (□) B2T; (△) B2A.

TABLE VI Nanosurface properties by XPS analyses for the passivated specimens with autoclaving treatment

Materials	Passivation treatment	Surface composition (wt %) Ti	Al	V	Cu	Ni	Oxide thickness (nm)	Contents (wt %) of suboxides (Ti^{3+} + Ti^{2+})
H	P	80.82	15.46	3.72			2.45	14.31
B2	P	85.72	11.30	2.98	nil	nil	2.53	14.50
H	T	81.69	14.82	3.49			4.14	8.12
B2	T	76.28	11.31	2.21	5.84	4.36	4.20	7.49
H	A	81.56	14.60	3.84			2.92	11.54
B2	A	85.40	11.89	2.71	nil	nil	3.19	11.59

diffraction revealed the nitric-acid passivated oxide to be composed of regions of mixed titanium oxides including anatase and rutile, together with areas of amorphous titanium oxides in the same study of Browne and Gregson [35]. Effah *et al.* also mentioned that the nitric-acid passivated surface oxide on titanium is composed mainly of mixed anatase and rutile both before and after immersion in SBF with or without containing 8.0 mM EDTA [36]. In this study, the reduction in constituent elements release could be attributed to both advantages of thicker thickness and rutile structure of oxides for Ti6Al4V and B2 specimens passivated by 400 ℃ treatment.

For acid-passivated and boiling-water-aged treatment, the trace levels of constituent elements (Ti, Al and V) are significantly related to experimental materials (H and B2), but the statistical differences are not observed between the two methods of passivation process (P and A). These findings are unexpected, since the brazed specimens containing lower contents of Al and V and higher contents of Ti by energy dispersive spectroscopy (EDS) analysis were thought to exhibit lower trace levels of Al and V and higher trace levels of Ti in Hank's/EDTA solution. A plausible explanation for this discrepancy is that the addition of copper and nickel will change the properties of surface oxides on the brazed specimens. Iida and Ozaki have studied the effect of impurities on phase transformation of titanium oxides from anatase to rutile. As shown in Table VII, the fraction of the anatase-rutile transformation is strongly dependent on impurities [37]. Only 1.0 mol % CuO addition significantly accelerated the transformation even a lower 100 ℃ heat treatment was applied. The accelerating effect of CuO in transformation could be caused by two possible mechanisms: (1) addition of CuO could induce a reaction to form a new CuO–TiO_2 phase for earlier nucleation of the rutile phases; (2) the copper ions, dissolved in Ti sublattice of TiO_2 with formation of oxygen vacancies to preserve electrical neutrality, would also likely accelerate the transformation. As shown in Table VII, the addition of 1.0 mol % NiO also promoted the anatase–rutile transformation [37].

In our previous study, the effect of autoclaving (steam sterilized at 121 ℃ for 30 min and dried at 121 ℃ for 15 min) on Ti6Al4V and B2 specimens was well studied by X-ray photo electron spectroscopy (XPS), and the results indicated that the oxide thickness for all passivated (nitric-acid passivation, 400 ℃ treatment in air, and aging in boiling water) specimens increased during the 121 ℃ treatment [34]. Autoclaving process could be the reason for no statistical differences found between nitric acid passivated and aging treated specimens of both experimental materials (Ti6Al4V and B2). Wisbey *et al.* have found that 100 ℃ aged Ti6Al4V and titanium exhibited a substantial reduction in metal-ion release compared to nitric-acid passivation during immersion in 0.17 M NaCl plus 2.7 mM EDTA [25], where γ-ray process was adopted for sterilization. In the present study, only a small advantage in ion release is found for the age-passivated specimens against the acid-passivated specimen. The advantage of age-passivation at the boiling water temperature might be undermined since both the aged specimen and the acid-passivated specimen were subject to the high-temperature 121 ℃ steam sterilization.

There is a significant reduction in constituent trace element release throughout the 0–8 day experimental period, and the transition period is observed for all kinds of specimens. In our other study, the oxide thickness of all kind of specimens increased with the immersion period [38]. The dissolution kinetics can depend on at least three mechanisms: surface chemical reactions, electrical field effects, and mass diffusion. For the differential experiments, the release rate should not change with the transport of the dissolution product through the concentration boundary layer. During immersion in the EDTA-containing Hank's solution, oxidation of specimens occurs simulataneously with oxide dissolution. Both may be driven by an electrical field established as a result of the potential drop across

TABLE VII Effect of additives (1.0 mol %) on the fraction (wt %) of transformation from anatase to rutile [37]

Additive	3 h at 700 ℃ Anatase	Rutile	3 h at 800 ℃ Anatase	Rutile	3 h at 900 ℃ Anatase	Rutile
None	100	0	100	0	18	82
CuO	97	0	0	100	0	100
NiO	100	0	79	21	0	100

TABLE VIII Surface chemical composition (wt %) by EDS analyses for as-polished Ti6A14V and brazed Ti6A14V prior to passivations

Materials	Ti	Al	V	Cu	Ni
H*	90	6	4		
B2	85.28	2.81	2.01	4.45	5.45

*Nominal.

the oxide [39]. As the oxide thickens, the net potential differences across it decrease and the driven force is reduced. This may be a factor in the improved dissolution resistance exhibited by the thicker oxides.

5. Conclusions

A work is carried out to investigate the effects of three factors on trace element release in Hank's/EDTA solution: experimental materials (Ti6A14V and brazed Ti6A14V), passivation, and time. The results from this study can be concluded as follows:

1. Passivation by 400 ℃ thermal treatment for both Ti6A14V and brazed Ti6A14V investigated exhibits a substantial reduction in the constituent release compared to the acid-passivated and water-aged treatment. Vacuum brazing treatment does not impose a statistically meaning effect on the Ti6A14V materials in terms of constituent element release.
2. For acid-passivated and boiling-water-passivated specimens, vacuum brazing treatment causes an unexpected significant reduction in constituent element release against the untreated Ti6A14V material. A plausible explanation is provided.
3. The constituent element release rate decrease with time for all kinds of specimens throughout the 0–8 day experimental period. The thicker oxides may be a factor in the improved dissolution resistance.

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