Rapid screening of potential metallic glasses for biomedical applications


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This paper presents a rapid screening process to select potential titanium and zirconium based metallic glasses (MGs) for bio-material applications. Electrochemical activity of 7 MGs including 6 bulk metallic glasses and 1 thin-film deposited MG in simulation body and human serum is first inspected. A low-voltage potential state test is also developed to simulate the cell membrane potential that the implant MGs will suffer. Results show that the MGs composed of Ti65Si15Ta10Zr10 and Ta57Zr23Cu12Ti8 exhibit excellent electrochemical stability in both simulation body fluid and human serum. In addition, the copper content in the MGs plays an important role on the electrochemical activity. MGs with the copper content higher than 17.5% show significant electrochemical responses. The cytotoxicity of the solid MG samples and the corrosion released ions are also evaluated by an in-vitro MTT test utilizing the murine bone marrow stem cells. Results indicate that all the solid MG samples show no acute cytotoxicity yet the corrosion released ions show significant toxicity for murine bone marrow stem cells. The rapid screening process developed in the present study suggests that the Ti65Si15Ta10Zr10 metallic glass has high potential for biomedical applications due to its good electrochemical stability and very low cytotoxicity.

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1. Introduction

Materials used in medical devices either contact or are temporarily inserted or permanently implanted in the body, are typically described as biomaterials and have unique design requirements [1]. Biocompatibility of the implanted materials is one of the most important issues needed to be considered first while developing biomaterials. Biocompatibility of implanted materials depends on the time that it is exposed to the human body and the location in the body where it is applied or implanted. The implanted materials which contact with tissues must avoid inducing any toxic, irritating, inflammatory, allergic, or any carcinogenic actions [2–5]. Recently, some metals such as cobalt chromium alloys, tantalum (Ta), niobium (Nb) and titanium (Ti) have been used for implants, since they have excellent corrosion resistance [6]. Titanium (Ti) is the most popular metal for producing long-term implantable devices due to its excellent biocompatibility. However, the lower strength and low hardness of commercial pure titanium (CP Ti, typically ~300–500 MPa for tensile strength and ~1.5 GPa for hardness) are issues for some clinical applications. In this regard, a number of titanium alloys were developed for biomedical applications. However, some studies have reported that lower wear resistance of titanium alloys may produce toxic debris after long-term usage [7,8]. In Ti alloy (Ti–6Al–4V), it was reported that aluminum (Al) and vanadium (V) were dissolved [9]. Al is a growth inhibitor of bone and a possible cause of Alzheimer’s disease [10] and V has strong cytotoxicity. Cytotoxicity is often dependent on the ionization tendency of the metals. Highly corrosive materials in the body may release cytotoxic ions and cause cell apoptosis and necrosis after long-term use [11]. Therefore, some metallic glassy materials were studied for biomedical applications in the recent years since there is no grain boundary in the amorphous structure of metallic glasses (MGs). The metallic glass materials have become new candidates for developing potential orthopedic implants due to the high wear resistance for load-bearing applications [12]. Nevertheless, the undesired electrochemical corrosion between the grain boundaries might be suppressed or eliminated while using these amorphous structures [13]. Therefore, to realize the potential electrochemical responses for the newly developed MG materials is essential prior to the practical applications for these new materials.

Metallic glasses (MG) have a unique atomic structure, so they do not contain the microstructural defects such as vacancies, dislocations, twins or grain boundaries. Metallic glasses usually have more promising corrosion-resistant properties [14–17], high mechanical strength in the range of 800–3000 MPa and some plasticity [18–21], and superplastic processing capabilities within the super-cooled
liquid temperature region [22,23], making them highly feasible for biomedical implant applications. For example, the strength of Ti40 Cu36Pd14Zr10 [24] is about three times higher than pure Ti [25] and its elastic modulus is closer to bones. The surface structure of Ti40 Cu36Pd14Zr10 can be modified by laser pulses to make cells attach. Mg60Zn35Ca5 [26] or Fe73Nb3Si7B17 [27] MGs are being investigated as degradable functional materials. Unlike traditional steel or titanium, Mg60Zn35Ca5, as a biomaterial for implantation into bones as degradable functional materials. Unlike traditional steel or titanium, Mg60Zn35Ca5 [26] or Fe73Nb3Si7B17 [27] MGs are being investigated for bio-implant applications. A low-voltage of 80 mV (around the membrane potential) was used in the in vitro cell viability testing to mimic the contact condition of the MGs and cells to predict the cell potential induced corrosion of the metals. A standard potential state assay was used to monitor the induced current right after immersing the MGs into the simulation body fluid. The duration for this test was 30 min at a controlled temperature of 37 °C.

2.2. Electrochemical activity evaluation

The electrochemical activity of MGs was investigated using a three-electrode electrochemical cell. A standard Ag/AgCl electrode and a platinum wire were used as the reference and counter for the electrochemical tests, respectively. The electrochemical analysis was performed using a commercial electrochemical analyzer (CH 611C, CH Instruments Inc., USA) at a controlled temperature of 37 °C. The Hank’s SBF solution composed of 0.137 M of NaCl, 5.4 mM of KCl, 0.25 mM of Na2HPO4, 0.44 mM of KH2PO4, 1.3 mM of CaCl2, 1.0 mM of MgSO4, and 4.2 mM of NaHCO3 was used. Identical test was also performed in human serum to further investigate the electrochemical response of MGs in real body condition. The electrochemical responses between the MGs and solution were characterized using a standard cyclic voltammetry (CV) with the scanning potential from +1 V to −1 V and a scan rate of 0.1 V/s. This potential range includes the oxidation potentials for most of the metals used in this study. The possible electrochemical response would be induced in this scan potential range such that a rapid screening for the potential MG samples with a low electrochemical response can be achieved. This rapidly obtained information can be used as a reference for further potential-potential polarization or cyclic polarization tests.

In addition, the MG materials may contact cell tissue in practical applications. A low-voltage of 80 mV (around the membrane potential of cell) was applied in another electrochemical test. The electrochemical stability can be examined by tracing the induced current versus time. This low-potential electrochemical test was used to mimic the contact condition of the MGs and cells to predict the cell potential induced corrosion of the metals. A standard potential state assay was used to monitor the induced current right after immersing the MGs into the simulation body fluid. The duration for this test was 30 min at a controlled temperature of 37 °C.

2.3. In-vitro cell viability testing

The cell viability test was performed using a standard MTT assay [35]. Pluripotent murine mesenchymal cells, D1 (ATCC) cloned from Balb/c mouse bone marrow stem cells [36] were used in the vitro cell culture experiment. D1 bone marrow stem cells were cultured in low glucose Dulbecco’s modified Eagle’s medium (DMEM) containing 10% fetal bovine serum (FBS), 1.5 g/L sodium bicarbonate, 1% NEAA, 1% vitamin C and 1% penicillin and streptomycin [37]. The culture medium was prepared at 37 °C in a humidified atmosphere with 5% of CO2. The D1 cells for this in-vitro test were prepared in a 6-well cell culture dishes, cloned with the cell density of 5 × 10^4 cells/mL. The produced MGs and the reference pure Ti with the weight of 20 mg were firstly washed by 75% alcohol for antisepsis then immersed into the culture dishes with 5 mL of medium with D1 cells and then cultured for 72 h. It is noted that the group tested with
pure titanium screw for orthopedic implantation was used as the positive control group for the MTT assay. Alternatively, the medium for the low-voltage electrochemical test might contain released ions and reaction products from the MGs. The effect for the release ions on the living cells was further investigated by culturing the D1 cells with different MGs and tested mediums. Another 4 h at 37 °C of cell incubation was performed prior to the optical density (OD) measurement. DMSO so-

iced using the OD values measured with the reading wavelength of 570 nm and the reference wavelength of 630 nm [35,38].  

3. Results and discussion  

3.1. MG characterization  

All of the MGs are firstly characterized by XRD and DSC to ensure the metallic glassy nature, as shown in Fig. 1. The diffuse hump in the XRD scan and the appearance of glass transition and crystallization temperatures, Tg and Tx, both demonstrate that the prepared MGs are amorphous. The XRD peak in Fig. 1(a) for the Ta57Zr23Cu12Ti8 thin film metallic glass, the DSC signal is rather weak in determining the accurate Tg and Tx, so the data are not included. Their mechanical properties, such as the elastic modulus, yield strength, and hardness, have also been studied in our previous reports [39–41]. Table 1 summarizes their basic materials properties, and the comparison with those of the reference pure Ti.

3.2. Electrochemical activity of produced MGs  

Cyclic voltammetry is a rapid and efficient way to predict the possible electrochemical response between the MG and medium. Fig. 2 presents the cyclic voltammograms from the 5th CV cycle (which is considered to be in a more stable condition and may avoid the possible artifacts related to the selected stating potential, +1 V in this study) for all MG sample and the reference metal of Ti. Results show that there was only minor electrochemical response for the reference pure Ti, and the MGs with the composition of Ta57Zr23Cu12Ti8 and Ti65Si15Ta10Zr10. However, the other MGs with the composition of Ti40Cu36Pd14Zr10, Ti45Cu35Zr20, Zr53Cu30Al8Pd4.5Nb4.5, Zr61Cu17.5Ni10Al8.5Si4, and Zr53Cu30Ni9Al8 exhibited various degrees of current responses. Hydrolysis phenomena or even decomposition of some of the MG samples was also observed during the CV scan. The apparent current response at the positive potential region indicated that there was appreciable oxidation reaction for the MGs in the simulated physiological environment. It is noted that the MGs with the Cu content higher than 17.5% exhibited apparent electrochemical response in the CV tests. The Cu-containing MGs would suffer from stronger corrosion in acidic and salt-rich environment. Alternatively, the MG with the highest Cu content in Ti40Cu36Pd14Zr10 exhibited a significant current response at the applied voltage of −0.34 V and 0.36 V, corresponding to the characteristic redox potentials of pure copper. These two potentials were validated by repeating the test with pure copper. The cyclic voltammetry tests showed that the MGs with high electrochemical activities may not be potential for bio-

itical applications. Thus, samples (4) to (8), namely, Ti40Cu36Pd14Zr10, Ti45Cu35Zr20, Zr53Cu30Al8Pd4.5Nb4.5, Zr61Cu17.5Ni10Al8.5Si4, and Zr53Cu30Ni9Al8 are excluded to be potential bio-implant materials. Cu is known to potentially cause allergy problems, thus the Cu-containing MGs are still considered to be less favorable for long-term implant application.

Fig. 3(a) presents the close-up CV curves for the three metals with low current response. The enlarged CV curves also confirmed that there were no significant redox peaks for the two MGs of Ta57Zr23Cu12Ti8 and Ti65Si15Ta10Zr10. The charge current for Ta57Zr23Cu12Ti8 even showed smaller response in comparison with the typical implant material of pure Ti, indicating the good electrochemical stability in high-ionic environment of Hank’s solution. In addition, human serum was also used to further investigate the electrochemical activity of the two MGs with low EC response in Hank’s solution (Fig. 3(b)). Results also

Table 1  

Summary of the basic mechanical properties (elastic modulus E, yield stress YS, hardness H) and physical properties (glass transition temperature Tg and crystallization temperature Tx) of various MGs and the reference pure Ti. The heating rate for DSC is 20 °C/min.

<table>
<thead>
<tr>
<th>Material</th>
<th>E, GPa</th>
<th>YS, GPa</th>
<th>H, GPa</th>
<th>Tg, °C</th>
<th>Tx, °C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pure Ti</td>
<td>128</td>
<td>0.4</td>
<td>1.5</td>
<td>−</td>
<td>−</td>
</tr>
<tr>
<td>Ti50Si15Ta10Zr10</td>
<td>110</td>
<td>2.3</td>
<td>7.0</td>
<td>464</td>
<td>515</td>
</tr>
<tr>
<td>Ti40Cu36Pd14Zr10</td>
<td>104</td>
<td>2.1</td>
<td>6.2</td>
<td>402</td>
<td>443</td>
</tr>
<tr>
<td>Ti45Cu35Zr20</td>
<td>100</td>
<td>2.0</td>
<td>5.5</td>
<td>331</td>
<td>374</td>
</tr>
<tr>
<td>Zr53Cu30Al8Pd4.5Nb4.5</td>
<td>85</td>
<td>1.7</td>
<td>5.0</td>
<td>424</td>
<td>494</td>
</tr>
<tr>
<td>Zr53Cu30Ni9Al8</td>
<td>86</td>
<td>1.7</td>
<td>5.0</td>
<td>425</td>
<td>500</td>
</tr>
<tr>
<td>Zr61Cu17.5Ni10Al8.5Si4</td>
<td>105</td>
<td>1.7</td>
<td>5.2</td>
<td>390</td>
<td>444</td>
</tr>
<tr>
<td>Ta57Zr23Cu12Ti8</td>
<td>120</td>
<td>3.0</td>
<td>7.5</td>
<td>−</td>
<td>−</td>
</tr>
</tbody>
</table>
indicated that there was no significant EC response for these two MGs in physiological environment. However, Ta$_{57}$Zr$_{23}$Cu$_{12}$Ti$_8$ exhibited slight reduce current at around $-0.4$ V which might be also caused by the minor copper content (12 at.%) in this MG. Alternatively, the current response for Ti$_{65}$Si$_{15}$Ta$_{10}$Zr$_{10}$ was smaller than that of pure Ti, indicating the good EC stability of Ti$_{65}$Si$_{15}$Ta$_{10}$Zr$_{10}$ MG. It is also noted that the measured current responses in human serum were much smaller than that measured in Hank’s solution. This was caused by the deposition and shielding of the protein on the MG or electrode surfaces. According to the results of cyclic voltammetry assay, two out of the seven MG showed good electrochemical stability in both Hank’s solution and human serum. The electrochemical test is a rapid screen to select potential materials for biomedical applications.

The membrane potential of living cell is typically around 80 mV. The material used in bio-applications especially that contacting with living tissue may suffer from an electric potential of 80 mV. In order to further evaluate the electrochemical stability and the potentiality of the produced in biological environments, a low-voltage potential state test was performed. The current response of MGs and the reference pure Ti were recorded while the samples were immersed into simulation body fluid with the application of a potential of 80 mV for 30 min. Fig. 4(a) shows the amperometric $i$–$t$ curves for all the samples in this potential state test. Results showed that the MGs of Ti$_{40}$Cu$_{36}$Pd$_{14}$Zr$_{10}$, Ti$_{45}$Cu$_{35}$Zr$_{20}$, Zr$_{61}$Cu$_{17.5}$Ni$_{10}$Al$_{7.5}$Si$_{4}$, Zr$_{53}$Cu$_{30}$Ni$_{9}$Al$_{8}$ and Zr$_{53}$Cu$_{30}$Al$_{8}$Pd$_{4.5}$Nb$_{4.5}$ exhibited significant current response under such a small voltage, indicating there were significant electrochemical responses for these materials. It is also noted that the current value of Zr$_{53}$Cu$_{30}$Ni$_{9}$Al$_{8}$ decreased with time since the decomposition of the bulk MG happened during the test. The surface area of the tested MG sample became smaller and the current response decreased with time.

Fig. 4(b) presents the close-up current response for the $i$–$t$ curves for the samples of Ta$_{57}$Zr$_{23}$Cu$_{12}$Ti$_8$, Ti$_{65}$Si$_{15}$Ta$_{10}$Zr$_{10}$ and pure Ti. The current responses of these three metals in the potential test were two orders smaller than that of other MGs. It is clear that the current response of Ti$_{65}$Si$_{15}$Ta$_{10}$Zr$_{10}$ exhibited very small current in 30 min.

![Fig. 2. The comparison of cyclic voltammogram responses for pure Ti, Ta$_{57}$Zr$_{23}$Cu$_{12}$Ti$_8$, Ti$_{65}$Si$_{15}$Ta$_{10}$Zr$_{10}$, Ti$_{65}$Cu$_{36}$Pd$_{14}$Zr$_{10}$, Ti$_{40}$Cu$_{35}$Zr$_{20}$, Zr$_{61}$Cu$_{17.5}$Ni$_{10}$Al$_{7.5}$Si$_{4}$, Zr$_{53}$Cu$_{30}$Ni$_{9}$Al$_{8}$, and Zr$_{53}$Cu$_{30}$Al$_{8}$Pd$_{4.5}$Nb$_{4.5}$ MGs.](image)

![Fig. 3. The comparison of cyclic voltammograms for Ta$_{57}$Zr$_{23}$Cu$_{12}$Ti$_8$ and Ti$_{65}$Si$_{15}$Ta$_{10}$Zr$_{10}$ MGs and pure Ti in (a) Hank’s solution and (b) human serum.](image)

![Fig. 4. (a) The measured $i$–$t$ curves for various MG and the control group of Ti, with the applied voltage of 80 mV. (b) The close-up $i$–$t$ curves for the three samples with low current response.](image)
However, Ta57Zr23Cu12Ti8 exhibited greater current response compared to the other metals in this close-up figure. The measured current for Ta57Zr23Cu12Ti8 increased to around 35 μA in the first 200 s and kept stable to the end of this test of 1800 s, indicating that there was no conformation change for the sample. The induced current might be caused by the electrochemical reaction of specific ion in the simulation body fluid. The potential state test again confirmed the good electrochemical stability of the Ti65Si15Ta10Zr10 and Ta57Zr23Cu12Ti8. It is also noted that the XRD spectrum presented in Fig. 2(a) shows that there is minor crystallization of the Ta phase in the Ti65Si15Ta10Zr10 amorphous matrix. Several researches have reported that the formation of easily oxidized nanocrystalline phases in the MG could enhance corrosion resistance of metallic glass matrix [30,42]. Hence, the Ti65Si15Ta10Zr10 owns the lowest electrochemical activity compared to other Ti-based MGs in the Hank’s solution and human serum, as a result of the formation of easily oxidized nanocrystalline Ta phases.

3.3. SEM observation and EDS analysis

Electrochemical tests showed that some MGs exhibited strong electrochemical reactions with the simulation body fluid, indicating that electrochemical corrosion happened during the tests. Fig. 5 shows the SEM images of Ti40Cu35Pd15Zr10, Ti45Cu35Zr10, Zr61Cu17.5Ni10Al7.5Si4, Zr53Cu39Ni9Al8, Zr53Cu39Al6Pd4.5Nb4.5, and Ti65Si15Ta10Zr10 after 30 min of low-voltage potential state test. Results show that the MGs suffered from different degrees of corrosion except for the Ti65Si15Ta10Zr10 MG. The surface morphology of Ti65Si15Ta10Zr10 remained smooth after the potential state test, indicating that no electrochemical corrosion was observed on the surface. The SEM observations are consistent with the results obtained with the potential state tests. It is noted that the corrosion did not occur uniformly throughout the surface of the MGs but started with localized pitting corrosion, as shown in Fig. 5(a)–(e). Several previous works have reported that the chloride ions in the solution played an important role for the corrosion behavior of Ti, Zr and Cu based MGs [43–45]. The corrosion might be caused by the adsorption of chloride ion in the simulation body fluid.

In order to further inspect the component change of the MGs before and after the potential state test, energy dispersive spectrometer (EDS) was adopted to evaluate the element composition in the corroded area labeled with red square in Fig. 5. Fig. 6 shows the EDS results for MGs (denoted with: X1) and after (denoted with X2) the simulation cell potential test. Results show that the composition for the MGs with significant electrochemical response changed a bit after the potential state test. Oxygen content greatly increased and the metal composition ratios differed from that of before the potential state test. The measured atomic ratios for oxygen for the MGs after the test were 59.9%, 69.5%, 56.2%, 61.4%, and 68.0%, respectively, for a2–e2 in Fig. 5. The EDS results confirmed that metal oxidation was there for the MGs with significant current response. Moreover, chloric ion also appeared for the samples with electrochemical reactions, which might be caused by the chloric ion adsorption into the MGs [45]. Nevertheless, the EDS results showed the same compositions for Ti65Si15Ta10Zr10 before and after test. The chloride ion is one of the major factors that would cause the corrosion of the MGs in the SBF since a higher concentration of chlorine ions was observed in the corroded region. The EDS results indicated that the chloride ion played an important role on the corrosion behavior of the MGs with higher Cu contents (from 17.5 to 36 at.%). Cu will first react with Cl, and then the resulting products will transform to oxides. Appreciable peaks for chlorine atom can be observed in Fig. 6 (a2, b2, c2, d2 and e2), indicating the electrochemical reaction of Cu atoms with chlorine and oxygen ions. Table 2 presents the EDS measured atomic composition for the MGs and the oxygen content in the corroded region and the weight loss after the potential state test. It is noted that the MGs with significant electrochemical responses exhibited significant oxygen content in the corroded region after the EC test. In contrast, the measured oxygen ratio for this Ti65Si15Ta10Zr10 MG after test was 3.2%, indicating that only very minor oxidation occurred during the potential test. The EDS result again confirms the good electrochemical stability of Ti65Si15Ta10Zr10. The MGs containing high Cu atomic ratios show significant electrochemical response such that the Cu content is better to be reduced while developing biomedical materials. A lower Cu concentration in the MGs may reduce the risk for the rapid formation of Cu chloride and Cu oxide such that the electrochemical corrosion for the MGs in the SBF may be inhibited.

Fig. 5. The SEM images for the MGs after the potential state test.
3.4. Cell viability test

Cytotoxicity is an important early test for developing potential materials for biomedical applications. D1 cells were cultured with the produced MGs and one reference metal of Ti for 72 h to evaluate the cytotoxicity of the MGs. Note that no external electric potential was applied for this test such that the MGs would not corrode in a short time. On contrast, the SEM and EDS results confirmed that the electrochemical corrosion happened on the MGs with significant current response in the potential state test. Metal ions, released into the simulation body fluid, may also cause cytotoxicity. Therefore, the culture medium after the potential test was added into the culture medium (4% in volume). D1 cells were cultured in the mixed medium for 20 h for testing the cytotoxicity of the released metal ion caused by the electrochemical corrosion. Although the MG of Ta57Zr23Cu12Ti8 also showed excellent electrochemical stability, this thin-film MG so far still could not sustain in liquid environment for a long period of time for the cell viability test, due to the debonding effect. Therefore, the Ta-based MG was excluded in this cell viability test.

Fig. 7 shows the measured cell viability for the two designed conditions for testing the toxicity of the MGs and released ion. Note that all the cell viability rates were calculated using the mean viability value of D1 cells in medium after Ti potential test as the standard. The blue bar (left) for each sample shows the viability for culturing D1 cells with the corresponding MG for 72 h. Results showed that the viability for all groups was higher than 85%. One-way ANOVA (analysis of variance) result shows that the F-value for this test was only 0.686 (p = 0.664), indicating that there was no significant cytotoxicity for the MGs if no external electrical potential was applied. Alternatively, the red bars in Fig. 7 show the D1 cells cultured in 4% of medium after the mentioned potential state test for 30 min. As described above, the three Zr-based MGs of Zr61Cu17.5Ni10Al7.5Si4, Zr53Cu30Ni9Al8 and Zr53Cu30Al8Pd4.5Nb4.5 exhibited significant electrochemical response during the potential state test. The cell viability for these groups was lower than 50% compared to the control group. The pair t-test for the pure MG and ion-released medium of each MG group showed significant difference on the cell viability (p < 0.005). The two Ti-based MGs showed higher cell viability in comparison with the Zr-based MGs. However, the cell viability values for the Ti-based MGs also show significant difference compared to that of the control Ti (p < 0.02). The substances released from the MGs

<table>
<thead>
<tr>
<th>Composition before potential state test</th>
<th>EDS result after applying potential (30 min) (excluding O or Cl content)</th>
<th>O plus minor Cl in the corroded region</th>
<th>Weight loss (after test)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ti40Cu38Pd14Zr10</td>
<td>Ti40Cu38Pd14Zr10</td>
<td>59.9 at.%</td>
<td>16.9%</td>
</tr>
<tr>
<td>Ti45Cu35Zr20</td>
<td>Ti38Cu35Zr20</td>
<td>38.8 at.%</td>
<td>24.0%</td>
</tr>
<tr>
<td>Zr61Cu17.5Ni10Al7.5Si4</td>
<td>Zr56Cu28Ni8Al1.4Si0</td>
<td>56.2 at.%</td>
<td>18.0%</td>
</tr>
<tr>
<td>Zr53Cu30Ni9Al8</td>
<td>Zr56Cu28Ni8Al1.4Si0</td>
<td>56.2 at.%</td>
<td>18.0%</td>
</tr>
<tr>
<td>Zr61Cu17.5Ni10Al7.5Si4</td>
<td>Zr56Cu28Ni8Al1.4Si0</td>
<td>56.2 at.%</td>
<td>18.0%</td>
</tr>
</tbody>
</table>

Fig. 6. The EDS results for inspecting the composition labeled in red square in Fig. 6. (a) Ti40Cu38Pd14Zr10, (b) Ti45Cu35Zr20, (c) Zr61Cu17.5Ni10Al7.5Si4, (d) Zr53Cu30Ni9Al8, (e) Zr53Cu30Al8Pd4.5Nb4.5 and (f) Ti65Si15Ta10Zr10. (1: composition before potential state test, 2: composition after test).
might contain high toxic ions of Ni, Al or Cu, which are not preferred in living tissue. Although these MGs did not show significant acute toxicity on the D1 cells, the long-term electrochemical corrosion induced cytotoxicity may be an issue. Nevertheless, the difference for the cell viability of the Ti65Si15Ta10Zr10 group was not significant, indicating the low cytotoxicity of this MG even with applying the external electric potential of 0.08 V for 30 min. Results show that the Ti65Si15Ta10Zr10 MG is potentially for developing implantable biomaterial. The method developed in the present study provided a rapid and simple way to screen the potential MGs for biomedical applications.

4. Conclusions

A rapid process was developed to screen the potential materials for biomedical applications out of seven metallic glasses. Electrochemical responses of the produced MGs were highly correlated with the possibility for potential corrosion in bio-environments. The electrochemical activity of the MGs was first evaluated with simulation body fluid of Hank’s solution and human serum. Results indicated that the copper content in the MG played a role on the electrochemical activity of the material. MGs with the copper content higher than 17.5% showed significant electrochemical activity in all electrochemical tests. The MGs of the bulk Ti65Si15Ta10Zr10 and thin-film deposited showed that minor electrochemical response Ta7Zr28Cu12Ti8 exhibited excellent electrochemical stability in comparison with the reference material of pure titanium. All the bulk MGs did not show acute cytotoxicity in the MTT tests utilizing murine bone marrow stem cells, D1, in 72 h of incubation. Nevertheless, the corrosion released ions from the MGs with significant electrochemical activity exhibited significant cytotoxicity in the MTT tests. The Ti65Si15Ta10Zr10 MG has shown its potential for biomedical applications due to its very low electrochemical response and very low cytotoxicity. The method developed in the present study provided a simple yet efficient way to screen potential MG-based biomaterials.

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