A novel copper/polydimethylsiloxane nanocomposite for copper-containing intrauterine contraceptive devices


1Center for Biomedical Materials and Engineering, Harbin Engineering University, Harbin 150001, China
2Department of Materials Science and Engineering, College of Engineering, Peking University, Beijing 100871, China

Received December 6, 2012; revised April 4, 2013; accepted April 10, 2013
Published online 16 September 2013 in Wiley Online Library (wileyonlinelibrary.com). DOI: 10.1002/jbm.b.32962

Abstract: In this article, a novel composite of copper (Cu) nanoparticles and polydimethylsiloxane (PDMS) has been prepared and investigated for the potential application in Cu-containing intrauterine device. The Cu/PDMS composite with various mass fraction of Cu nanoparticles was fabricated via the hot vulcanizing process. The chemical structures and surface morphologies of the Cu/PDMS composites were characterized confirming the physical interaction between Cu nanoparticles and PDMS. The surface morphology observation using scanning electron microscope and atomic force microscope showed the agglomeration of Cu nanoparticles in PDMS matrix and the distribution of the agglomerations was more uniform with increased amount of Cu nanoparticles. The cupric ion release behaviors of the Cu/PDMS composites with different amounts of Cu nanoparticles were investigated in simulated uterine fluid at 37°C for 150 days. The corrosion morphologies of the Cu/PDMS composites were also characterized. Both the burst release rate of the cupric ion in the first few days and the steady release rate after 30-day immersion were improved. The cytotoxicity test has been done for the Cu/PDMS composites. © 2013 Wiley Periodicals, Inc. J Biomed Mater Res Part B: Appl Biomater, 101B: 1428–1436, 2013.

Key Words: copper nanoparticles, polydimethylsiloxane, metal ion release, biocompatibility, intrauterine device


INTRODUCTION

Despite comprehensive contraceptive availability, copper-containing intrauterine devices (Cu-IUD) is an increasingly used long-acting reversible contraceptive method worldwide due to the superior effectiveness,1 low cost, safety, reliability, convenience, reversibility, and cultural acceptance.2 However, the current applied Cu-IUD caused some side effects,3,4 such as pelvic inflammatory disease, abdominal pain, vaginal bleeding and menstrual disorders, which is believed to relate to the cupric ion burst release behavior of the copper content of the IUD. In addition, the low release rate of the cupric ion after long-term insertion of the IUD probably leads to the contraception failure of the Cu-IUD.

Therefore, the cupric ion release rate should be controlled appropriately throughout the usage of the Cu-IUD by improving either the corrosion performance of the copper content or the design of the Cu-IUD. The pretreatment of the Cu materials using organic inhibitors (purine and thiourea) were carried out to reduce the burst release of cupric ions.5 Ultrafine-grained bulk Cu was proposed to replace the commercial coarse-grained Cu in our previous work with lower cupric ion burst release and higher efficiency long-term release.6 Different from the conventional Cu-IUD, novel types of Cu-IUD have been developed and investigated for almost 10 years. Cai, Xie, and Xia’s group contributed great efforts on designing the copper/low-density polyethylene (Cu/LDPE) nanocomposite as the new generation of Cu-IUD.7–14 The burst release of cupric ion has been suppressed to some extent, and the continuous release amount was guaranteed for the novel Cu/LDPE nanocomposites in simulated uterine fluid (SUF).7,8 Furthermore, the studies on the electrochemical behavior,9 mechanical properties10,11 and ethylene oxide sterilization11 of the Cu/LDPE nanocomposites show the great application potential of the Cu/LDPE nanocomposites IUD with low pregnancy rate, high contraceptive efficacy and satisfactory acceptability.12,13 Recently, a porous Cu/LDPE composite14 for Cu-IUD has been developed as well as the anti-inflammatory drug/Cu/LDPE functional composite.12,13 Suo and coworkers14,15 reported another new composite material, cross-linked composite based on polyvinyl alcohol (PVA) that contains CuCl2, applied in Cu-IUD. This new composite material exhibited...
greatly improved effectiveness of CuCl₂ without formation of Cu₂O corrosion products. However, the mechanical property and the biocompatibility can be further improved for the Cu-IUD application.

The polymer based copper nanoparticles containing composite is suggested to be a good candidate as the active material for the intrauterine device. Polydimethylsiloxane (PDMS) is a well-known traditional biomaterial applied in catheters, drainage tubing, insulation for pacemakers, membrane oxygenators, ear and nose implants and biomedical devices because PDMS is transparent, nonfluorescent, biocompatible and nontoxic. In addition, the mechanical properties of PDMS are easily tuned in physiologically relevant ranges. PDMS had also been used in the first generation IUD as an inert biomaterial; however, the contraception rate was low because there was no active material. In the present work, Cu/PDMS composite was fabricated by adding Cu nanoparticles into PDMS matrix as new Cu-IUD candidate material with excellent biocompatibility and high contraception activity. The chemical structures and surface morphologies of the Cu/PDMS composites with different amount of Cu nanoparticles were characterized. The cupric ion release behaviors and the cytotoxicity of the Cu/PDMS composites were also investigated for the potential application in Cu-IUD.

EXPERIMENTAL METHODS

Sample preparation

The nanocomposites were obtained by mechanically mixing the commercial pure copper nanoparticles (99.97%, ~50 nm, purchased from Goodfellow Cambridge Limited Company) into the hydroxy-terminated polydimethylsiloxane (PDMS) solution with cross-link agents. Then the hot vulcanizing process was carried out to produce the Cu/PDMS composites. The detailed procedures were as follow: different amount of copper nanoparticles (5 wt%, 10 wt%, 15 wt%, and 25 wt%) were mixed well within the hydroxy-terminated polydimethylsiloxane and 5 wt% tetraethylorthosilicate and 0.2 wt% dibutyltin dilaurate, then the mixture solutions were poured into Teflon dishes to form the thin layer solutions followed vacuum drying at 90°C for 7 days. Then the Cu/PDMS films were cut into round disks with diameter of 10 mm and thickness of 2 mm.

Structure and morphology characterization

The phase compositions and chemical structures of the obtained Cu/PDMS round disks were characterized using a Philip X’Pert Pro diffractometer and a Spectrum One Fourier transform infrared (FTIR) spectrophotometer (Perkin-Elmer), respectively. The morphology observation for the Cu/PDMS films was carried out on a Zeiss VP FESEM and the equipped energy-dispersive spectrometer were used to observe the corrosion surface morphology and to identify the corrosion products and its surface composition.

Cellular response of fibroblasts cells

Murine fibroblast cells (L-929) were adopted to evaluate the cytotoxicity and responses of Cu/PDMS composite round disks by the way of indirect assay according to a standard procedure ISO 10993-5. PDMS had also been used in the first generation IUD as an inert biomaterial; however, the contraception rate was low because there was no active material. In the present work, Cu/PDMS composite was fabricated by adding Cu nanoparticles into PDMS matrix as new Cu-IUD candidate material with excellent biocompatibility and high contraception activity. The chemical structures and surface morphologies of the Cu/PDMS composites with different amount of Cu nanoparticles were characterized. The cupric ion release behaviors and the cytotoxicity of the Cu/PDMS composites were also investigated for the potential application in Cu-IUD.

RESULTS

Structures of the Cu/PDMS composite

Figure 1 is the XRD patterns of the Cu/PDMS composite disks with different amount of Cu nanoparticles. It can be

![Figure 1. XRD patterns of pure PDMS and Cu/PDMS nanocomposites.](image)
seen that there is only one amorphous lump at 15–16° for pure PMDS. The peaks at 43.36° in the XRD patterns for the composites can be attributed to the main peak of Cu (111) (JCPDS no. 04-0836, a = 0.3615), indicating the existence of Cu nanoparticles in the composites. In addition, the intensity of the Cu (111) peak increases with the increase in the Cu nanoparticles amounts in the Cu/PDMS composites.

Figure 2 shows the FTIR spectra of Cu nanoparticles, pure PDMS and Cu/PDMS composite disks. The adsorption peak at 636 cm$^{-1}$ in the FTIR spectrum can be attributed to Cu$^{2+}$–O bond$^{25}$ probably due to the trace amount of Cu$_2$O from surface oxidation of Cu nanoparticles, which, however, cannot be detected by the XRD (there is no sign of Cu$_2$O in the Cu/PDMS composites in Figure 1). The characteristic bands for PDMS terminated with hydroxyl group are found in the FTIR spectrum of pure PDMS in Figure 2. The presence of hydroxyl group in silicon polymer is in the region 3400–3600 cm$^{-1}$ as stretching vibration frequency. Further confirmation for PDMS is the evidence from the adsorption peaks at 2966 cm$^{-1}$, 1263 cm$^{-1}$, 1096 cm$^{-1}$, 1018 cm$^{-1}$, and 797 cm$^{-1}$ corresponding to stretching vibration of C–H in i–CH$_3$ group, in-plane bending motion of C–H in Si–CH$_3$, asymmetric and symmetric stretching vibration of Si–O–Si, in plane bending or rocking motion of C–H in Si–CH$_3$, respectively.$^{26,27}$ The FTIR spectra of Cu/PDMS composites exhibit both the Cu$^{2+}$–O bond absorption peak and the characteristic bands of pure PDMS. The adsorption peak of Cu$^{2+}$–O at 636 cm$^{-1}$ becomes more obvious with the increase in the Cu nanoparticles (indicated by the dash line in Figure 2). It is noteworthy that Cu$^{1+}$–O interaction at the surface could be more when the increased Cu nanoparticles were embedded into PDMS.

The comparison of the FTIR spectra of Cu nanoparticles, pure PMDS and Cu/PDMS composites suggests that no chemical interactions between the Cu nanoparticles and PMDS occurred when the two ingredients were mixed to fabricate the composite. The Cu/PDMS composite is a simple hybrid of Cu nanoparticles and PDMS and their properties would not be interfered by each other.

The morphologies of the pure PDMS and the Cu/PDMS composites with different amount of Cu nanoparticles are shown in Figure 3. It can be seen from Figure 3(a) that the Cu/PDMS composite with 5% Cu nanoparticles has clean and smooth surface. The Cu nanoparticles are not found from the top surface of the composite, only the drapes due to vacuum drying are shown. Comparatively, the Cu/PDMS composite with 10% nanoparticles addition displays relatively smooth surface [Figure 3(b)], whereas small fraction of aggregations of nanoparticles can be seen on the surface [inset in Figure 3(b)]. When the amount of the added Cu nanoparticles increases to 15%, more aggregated nanoparticles are shown on the surface [inset in Figure 3(c)] than those on the 10% Cu/PDMS composite surface. However, the distribution of the nanoparticle in the PDMS matrix seems not uniform [Figure 3(c)]. Figure 3(d) shows a drastic change in the Cu/PDMS composite morphology when the addition of Cu nanoparticles was increased to 25%. High fraction of Cu aggregations is imbedded in PDMS and the sizes of these Cu nanoparticles aggregations are not uniform from the high magnification view [inset in Figure 3(d)].

Atomic force microscopy (AFM) is carried out to further analyze the surface morphology of the Cu/PDMS composites. Figure 4 shows the AFM three-dimensional (3D) morphologies of the Cu/PDMS composites with different amount of Cu nanoparticles. It can be seen from Figure 4(a) that there is no obvious surface undulation on 5% Cu/PDMS composite. The highest point is about 124.1 nm and the mean surface roughness is about 8.7 nm. Figure 4(b) shows several bumps on the surface for the 10% Cu/PDMS composite. The highest position is about 195.8 nm and the mean surface roughness is about 22.0 nm. The surface undulation becomes severe when the Cu nanoparticles addition increased to 15% [Figure 4(c)]. The height of the surface undulation can reach to 620.5 nm and the mean surface roughness increases to 76.6 nm. Large lump can be seen from Figure 4(d) on the surface of the 25% Cu/PDMS composite, it could be the aggregation of the Cu nanoparticles. The mean surface roughness is around 153.4 nm. The AFM results agree well with the scanning electron microscopic image observation that the more the addition of Cu nanoparticles, the rougher the surfaces of the Cu/PDMS composites.

Cupric ion release behavior of the Cu/PDMS composite

Figure 5 shows the release rates of cupric ions from the Cu/PDMS composites with different amount of Cu nanoparticles in 50 mL SUF at 37°C for 150 days. All curves exhibit the similar cupric ion release behaviors. In the first day of immersion, very high amounts of cupric ion, up to 430.56 µg/day for the 25% Cu/PDMS composite, are released from all the Cu/PDMS composites, which is due to the direct dissolution of the Cu nanoparticles on the surfaces of the Cu/PDMS composites.$^{28}$ The release rates of the Cu/PDMS composites decrease sharply in the second day of the immersion and tend to slow down in the third day and...
afterward. After immersed in the SUF for 30 days, the release rates of the cupric ion from the Cu/PDMS composites became relatively stable until 150 day.

Regardless of the direct dissolution from the composite surface, the abrupt drop of the cupric ion release from the 5% and 25% Cu/PDMS composite start from 119.4 μg/day and 139.8 μg/day on the first day and end at 39.3 μg/day and 7.0 μg/day after 30 days of immersion respectively. The 10% and 15% Cu/PDMS composites releases 117.8 μg/day and 115.1 μg/day on the first day and 15.8 μg/day and 28.6 μg/day on the 30th day of immersion. The steady release rates of the Cu/PDMS composites with 5%, 10%, 15%, and 25% Cu nanoparticles after 50 days are about 1.4 μg/day, 8.3 μg/day, 12.8 μg/day, and 25.3 μg/day, respectively. It can be seen that the burst release of cupric ion from the Cu/PDMS composites are similar for 5%, 10%, and 15% addition of Cu nanoparticles, only the 25% Cu/PDMS composite has a little bit higher burst release. The release rates of the Cu/PDMS composite during the steady stages increase proportionally with increased Cu nanoparticles amount, following the order of $R_{5\%\text{Cu/PDMS}} < R_{10\%\text{Cu/PDMS}} < R_{15\%\text{Cu/PDMS}} < R_{25\%\text{Cu/PDMS}}$.

The steady release rate of the cupric ion from the Cu/PDMS composite is comparable to the Cu/LDPE composites. Therefore, it is evidence that the cupric ion release from the Cu/PDMS composite is controllable by adjusting the addition of the Cu nanoparticles. Moreover, the burst release of the cupric ion from the Cu/PDMS composites is much lessened compared to the bulk Cu materials.

The morphologies of corrosion products on the surfaces of the Cu/PDMS composites after immersed in SUF for 150 days are shown in Figure 6. For the 5% Cu/PDMS composite, the porous and fluffy corrosion product layer on its surface is not distributed uniformly and the thickness of the corrosion product layer is about 15 μm [Figure 6(a)]. The elemental analysis on the corrosion product exhibits the Cu and O as well as Ca, Cl, and P suggesting that the corrosion products include probably CaCO$_3$, CaCl$_2$, and CaHPO$_4$ besides the main product of Cu$_2$O. Figure 6(b) shows that the corrosion products in 3D spherical appearance

FIGURE 3. Surface morphology of (a) PDMS + 5% Cu, (b) PDMS + 10% Cu, (c) PDMS + 15% Cu, and (d) PDMS + 25% Cu.
(~30 μm) evenly distributed on the surface but not fully covered. The high magnification view in Figure 6(b) shows similar corrosion morphology of 10% Cu/PDMS composite to that on the surface of the 5% Cu/PDMS composite. The elements consisted in the corrosion product are also the same with those in the 5% Cu/PDMS composite. The corrosion product layer covers fully on the surface of the 15% Cu/PDMS composite and the porous and fluffy layer seems much thicker [Figure 6(c)]. There is no difference on the compositional elements of the corrosion product. The corrosion product layer on the surface of the 25% Cu/PDMS composite displays similar morphology and elemental composition to those on the surface of the 15% Cu/PDMS composite; however, the layer is much thicker and not uniform.

The corrosion product layers on the surfaces of the Cu/PDMS composites increase in thickness, but the corrosion products are the same. Therefore, the corrosion morphology and product seem not affected significantly by the cupric ion release rate because the release rates increase parallelly with the amount of the Cu nanoparticles.

**Cytotoxicity evaluation**

Figure 7 shows the results of MTT assay for the 100% and 10% extracts of the Cu/PDMS composites with different amount addition of Cu nanoparticles after L929 cell culture for 3 days. The concentration of Cu$^{2+}$ ions in the 100% extracts of the four Cu/PDMS composites are 6.029 μg/mL, 10.102 μg/mL, 10.845 μg/mL, and 12.201 μg/mL respectively, and correspondingly, the concentration of Cu$^{2+}$ ions in the diluted extracts are 0.803 mg/L, 1.010 mg/L, 1.085 mg/L, and 1.220 mg/L. It can be observed from Figure 7(a)
FIGURE 6. Corrosion morphology of the Cu/PDMS composite with (a) 5%, (b) 10%, (c) 15%, and (d) 25% Cu nanoparticles immersed in SUF for 150 days. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]
that 100% extracts of all Cu/PDMS composites exhibited relatively high cytotoxicity to L929 cells comparing to the negative group \( p < 0.05 \). The cell viabilities of the Cu/PDMS composites decrease further after 2 and 3 days culture. However, the cell viabilities of all the Cu/PDMS composites are higher than the positive group during the whole culture time. The cell viability of the L929 cell in the extract of the 5% Cu/PDMS composite is around 60% relative to the negative group which can be categorized to level two of cytotoxicity.\(^{24}\) While the cytotoxicity of other composites is higher with the increased addition of the Cu nanoparticles and they can be categorized to level three. The cytotoxicity of the Cu/PDMS composites decreases obviously in the diluted extracts [Figure 7(b)]. It can be seen from Figure 7(b) that the cell viabilities of all the diluted extracts from Cu/PDMS composites increase during the culture time. In addition, from Figure 7(b), it also can be seen that the viability increases after 3 days cultivation for all four Cu/PDMS composite films with different Cu nanoparticles amounts. It is reported that the cell viability cannot be suppressed or can be favored when the concentration of metallic ions was lower than a critical concentration.\(^{29,30}\) Thus, the increased cell viability in our experimental data is probably related to the fact that the cupric ion concentrations in the 10% extracts of the Cu/PDMS composites were too low to suppress the cell viability, especially for prolonged cultivation. The effect of the Cu nanoparticles amount on the cytotoxicity of the composites with the diluted extracts is similar to that with the 100% extracts. However, it also can be seen that the 25% Cu/PDMS composite shows slightly better cell viability than the 15% Cu/PDMS composite since the second day of the culture. The different concentrations of cupric ion in the 100% and 10% extracts of the Cu/PDMS composite films induce the variations in the cell viability. High cupric ion concentration in 100% extract causes the low cell viability, whereas the low cupric ion concentration in the diluted extract eliminates the cytotoxicity. The two extracts with different concentrations can be considered to correspond to the burst release and steady release of the cupric ions.

Compared to coarse-grained and ultrafine-grained bulk copper materials,\(^{6}\) the cell viability of the Cu/PDMS composites is significantly higher \( p < 0.05 \) probably due to the biocompatible PDMS matrix material and the slow release of the cupric ions.

**DISCUSSION**

The cupric ion release rate is of significance for active materials application in IUD, such as coarse-grained bulk Cu, ultrafine-grained bulk Cu, Cu nano/microparticles embedded in polymer matrixes, or cupric salts in polymer matrix. A better control of the cupric ion release from the Cu nano/microparticles in polymer materials seems more achievable than the bulk Cu materials. Table I summarized the cupric ion release behaviors from various composite materials, among them, Cu/LDPE nanocomposite is the most important one, which had been designed and studied extensively. Research on cupric ion transformation from Cu nanoparticles with different particle sizes in SUF showed that the corrosion mechanism and the corrosion intermediate products of Cu nanoparticles are identical to that of bulk copper.\(^{31}\) It is not only the sample size of the investigated composite materials but also the immersion solution volume that have remarkable influences on the release behaviors of the cupric ions,\(^{32}\) therefore, the burst release amounts of cupric ion in the Table I vary significantly and the units are not consistent either. However, it can be seen that the burst release of cupric ion for most of the composite materials, including Cu/PDMS composites, occurred in the first month of immersion and the highest amount of released cupric ion was in first few days, which is similar to the cupric ion release behaviors of bulk Cu materials. Moreover, the stabilized cupric ion release rates during the long-term immersion are comparable in spite of the differences in sample size and immersion volume. For example, the \( \gamma \)-shaped porous 25% IDM/Cu/LDPE nanocomposite IUD showed similar burst release time, burst release amount and stabilized release amount with our Cu/PDMS composites (the release amount had been converted to the IUD with exposure surface area of 200 mm\(^2\)). The similar values of the cupric ion...
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Copper/LDPE nanocomposite</td>
<td>T1.5 mm, Φ 15 mm 176 mm × 2 mm SUF(50 mL)</td>
<td>3 in 30 days immersion</td>
<td>Cu 10 wt %</td>
<td>~117 µg/day</td>
<td>7</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Cu 30 wt %</td>
<td>~225 µg/day</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Cu 15 wt %</td>
<td>~220 µg/day</td>
<td>8</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Cu 30 wt %</td>
<td>~220 µg/day</td>
<td></td>
</tr>
<tr>
<td>35 wt % Cu/LDPE microcomposite</td>
<td>T2 mm, Φ 20 mm SUF(50 mL)</td>
<td>1st month in 220 days immersion</td>
<td>Cu 25 wt %</td>
<td>~180 µg/day</td>
<td>28</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Cu 30 wt %</td>
<td>~220 µg/day</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Cu 30 wt %</td>
<td>~220 µg/day</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Cu 30 wt %</td>
<td>~220 µg/day</td>
<td></td>
</tr>
<tr>
<td>T-shaped 15 wt % Cu/LDPE</td>
<td>Transverse arms (Φ 2 mm, L 30 mm) Longitudinal stem (Φ 2 mm, L 32 mm) Two</td>
<td>30 days in 240 days immersion</td>
<td>Original IUD</td>
<td>~24 µg/day</td>
<td>11</td>
</tr>
<tr>
<td>nanocomposite IUD</td>
<td>hemispheres (Φ 2.5 mm) SUF (50 mL)</td>
<td></td>
<td>Sterilized IUD</td>
<td>~22 µg/day</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>~5 µg/day</td>
<td></td>
</tr>
<tr>
<td>4% CuCl2/20% SiO2/PVA film</td>
<td>T0.12 mm SUF(500 mL)</td>
<td>No obvious burst release in 350 days</td>
<td>0.45 µg/mm² 1st day</td>
<td>2.37 µg/mm² 360 days</td>
<td>18</td>
</tr>
<tr>
<td>γ-Shaped 25% Cu/LDPE nanocomposite IUD</td>
<td>Transverse arms (Φ 2 mm, L 30 mm) Longitudinal stem (Φ 2 mm, L 32 mm) Two</td>
<td>~30 days in 100 days</td>
<td>0.825 µg/mm² 30 days</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>hemispheres (Φ 2.5 mm) SUF (50 mL)</td>
<td></td>
<td>Nonporous</td>
<td>~2.75 µg/mL</td>
<td>14</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Porous</td>
<td>~3.75 µg/mL</td>
<td></td>
</tr>
<tr>
<td>γ-Shaped porous 25% IDM/Cu/LDPE nanocomposite IUD</td>
<td>Transverse arms (Φ 2 mm, L 30 mm) Longitudinal stem (Φ 2 mm, L 32 mm) Two</td>
<td>~30 days in 70 days</td>
<td>20.55% porosity</td>
<td>~130 µg/day</td>
<td>13</td>
</tr>
<tr>
<td></td>
<td>hemispheres (Φ 2.5 mm) SUF (50 mL)</td>
<td></td>
<td>13.7% porosity</td>
<td>~123 µg/day</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>6.85% porosity</td>
<td>~112 µg/day</td>
<td></td>
</tr>
<tr>
<td>Cu/PDMS nanocomposite</td>
<td>Equivalent surface area 200 mm² SUF(50 mL)</td>
<td>~30 days in 160 days</td>
<td>Cu 5 wt %</td>
<td>119.4 µg/day</td>
<td>1.4 µg/day</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Cu 10 wt %</td>
<td>117.8 µg/day</td>
<td>8.3 µg/day</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Cu 15 wt %</td>
<td>115.1 µg/day</td>
<td>12.8 µg/day</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Cu 25 wt %</td>
<td>139.8 µg/day</td>
<td>25.3 µg/day</td>
</tr>
</tbody>
</table>

**TABLE I. Summary of the Cupric Ion Release Behaviors of Cu and Polymer Composite Materials**
release rate of the Cu/PDMS composites to the well-studied Cu/LDPE composites suggest that the new type Cu and polymer composite in the present study is also highly potential as IUD active material in the terms of the cupric ion release behavior.

CONCLUSIONS

The novel Cu/PDMS composites with various amounts of Cu nanoparticles have been prepared and the properties were investigated for the potential application in Cu-IUD. The Cu nanoparticles were physically mixed in the matrix of PDMS with the cross-linked agents via the hot vulcanizing process. The added Cu nanoparticles exhibited agglomeration in the PDMS matrix and the agglomeration were distributed more uniformly with the increased addition of Cu nanoparticles. Regardless of the direct release of the Cu nanoparticles from the composite surface, the burst release rates of the cupric ion in the first immersion day were similar for 5%, 10%, and 15% Cu/PDMS, and it is a little bit higher for the 25% Cu/PDMS. The steady release rates of the cupric ion of the Cu/PDMS composites after 30 days immersion were proportional to their Cu nanoparticles amounts. The cupric ion release rate of the Cu/PDMS composite can be adjustable by varying the Cu nanoparticles addition without concerning the burst release. In terms of the cupric ion release behavior and cytotoxicity tests, the Cu/PDMS composites with 15%, 25%, and probably higher mass fraction of Cu nanoparticles are appropriate for the Cu-IUD application from the present study.

REFERENCES