Published in final edited form as:

Appl Surf Sci. 2011 April 15; 257(13): 5605–5612. doi:10.1016/j.apsusc.2011.01.055.

Stability of Phosphonic Self Assembled Monolayers (SAMs) on Cobalt Chromium (Co-Cr) Alloy under Oxidative conditions

Rahul Bhure^a, Tarek M. Abdel-Fattah^d, Carl Bonner^{a,c}, Felicia Hall^c, and Anil Mahapatro^{*,b,c}

^aCenter for Materials Research (CMR), Norfolk State University, Norfolk, Virginia 23504

^bCenter for Biotechnology and Biomedical Sciences (CBBS), Norfolk State University, Norfolk, Virginia 23504

^cDepartment of Chemistry, Norfolk State University, Norfolk, Virginia 23504

^dApplied Research Center and Department of Biology, Chemistry, and Environmental Science, Christopher Newport University, Newport News, Virginia 23606

Abstract

Cobalt Chromium (Co-Cr) alloys has been widely used in the biomedical arena for cardiovascular, orthopedic and dental applications. Surface modification of the alloy allows us to tailor the interfacial properties to address critical challenges of Co-Cr alloy in medical applications. Self assembled monolayers (SAMs) of Octadecylphosphonic acid (ODPA) have been used to form thin films on the oxide layer of the Co-Cr alloy surface by solution deposition technique. The SAMs formed were investigated for their stability to oxidative conditions of ambient laboratory environment over periods of 1, 3, 7 and 14 days. The samples were then characterized for their stability using X-ray Photoelectron Spectroscopy (XPS), Atomic Force Microscopy (AFM) and Contact Angle Measurements. Detailed high energy XPS elemental scans confirmed the presence of the phosphonic monolayer after oxidative exposure which suggested that the SAMs were firmly attached to the oxide layer of Co-Cr alloy. AFM images gave topographical data of the surface and showed islands of SAMs on Co-Cr alloy surface, before and after SAM formation and also over the duration of the oxidative exposure. Contact angle measurements confirmed the hydrophobicity of the surface over 14 days. Thus the SAMs were found to be stable for the duration of the study. These SAMs could be subsequently tailored by modifying the terminal functional groups and could be used for various potential biomedical applications such as drug delivery, biocompatibility and tissue integration

Keywords

surface modification; self assembled monolayers (SAMs); phosphonic acids; cobalt chromium alloy

* Corresponding Author : Dr. Anil Mahapatro, Assistant Professor, Department of Chemistry, Norfolk State University, 700 Park Avenue, Norfolk, VA 23504 USA, amahapatro@nsu.edu, Tel: +001-757-823-8494.

Publisher's Disclaimer: This is a PDF file of an unedited manuscript that has been accepted for publication. As a service to our customers we are providing this early version of the manuscript. The manuscript will undergo copyediting, typesetting, and review of the resulting proof before it is published in its final citable form. Please note that during the production process errors may be discovered which could affect the content, and all legal disclaimers that apply to the journal pertain.

Introduction

A biomaterial can be defined as a material which is used to restore or replace function to a body tissue and is continuously and intermittently in contact with body fluids[1]. The three main classes of biomaterials include metals, polymers and ceramics. Along with these, biomaterials are also composed of certain natural materials like collagen and they also play a significant role in the multidisciplinary field of tissue engineering[2,3]. Cobalt Chromium (Co-Cr) alloy is a type of metallic alloy which has been used as a biomaterial in the human body. Cobalt Chromium alloy is rapidly gaining attention for a wide variety of applications in cardiology, orthopedics and dentistry [4-7]. On comparison with other metallic implant materials, cobalt chromium alloy has several superior properties which make it attractive. It has good wear resistance, crevice corrosion resistance and pitting resistance. It also has high abrasion resistance, fatigue strength along with good workability and ductility[8,9]. As a result Co-Cr is increasingly being used in various biomedical applications.

In the area of cardiovascular implant materials, Co-Cr is currently being used as coronary artery stents which are used for the treatment of coronary artery disease. Initially bare metal stents made up of stainless steel were used to prevent abrupt artery closure and they reduced the likelihood of clinical restenosis [10]. However, in recent years cobalt chromium alloy stents are emerging as the preferred material owing to many advantages such as radiopacity and radial strength, no adverse proliferative response, enhanced visibility and flexibility[11]. Bare metal stents in general are limited by the frequent occurrence of restenosis because of smooth muscle proliferation, resultant neointimal hyperplasia and target lesion revascularization[10]. To counter this, polymer based drug eluting stents (DES) were developed which reduced the occurrence of major cardiac events from 16.4 % with bare metal stents to 7.8% with drug eluting stents[12,13]. Drug eluting stents however have several drawbacks such as polymer fracture during stent expansion and inflammatory reaction to the polymer, which in turn could lead to restenosis[14,15]. Also hypersensitivity issues related with DES such as rashes, dyspnea, hives, itching and fevers have been reported[15]. Hence there is a need to develop alternate drug delivery strategies for coronary stents materials including those stents made up of Co-Cr alloy.

Other areas of biomedical applications for the cobalt chromium alloy include dental applications where they are used for fixed partial dentures and crowns along with composites like ceramics. In orthopedics, Co-Cr is used for total joint replacement (TJR) [16] and metal on metal implants[17]. However there are certain challenges related to both these applications. Metal hypersensitivity issues have been reported in Co-Cr removable partial dentures (RPD)[18]. In orthopedics, there are challenges such as increased concentrations of cobalt and chromium ions after metal on metal resurfacing arthroplasty of the hip[19] and post operative implant infections leading to repeat surgeries[20,21]. Hence there is a need to modify the surface of the Co-Cr alloy in order to address these critical biomedical challenges in the areas of cardiovascular, orthopedic and dental implants.

Self Assembled Monolayers (SAMs) could be used as a platform for tailored modification of Co-Cr alloy for subsequent modification. SAMs are a versatile tool to carry out surface modifications[22-24]. They are structures formed by the spontaneous chemisorption of surfactant molecules on surfaces and are typically in the size range of 1-3 nm. They present the opportunity to not only change the chemical properties at the surface, but also to tailor the surface to any desired chemical functionality by modifying the endgroup of the SAM. Different kinds of biomolecules such as protein[25], peptides[26], DNA[27], carbohydrates[26], antibodies[28] and therapeutics[29,30] have been attached to SAMs for biomedical applications. The most widely studied systems for the formation of SAMs has

been long chain alkanethiols on gold (Au) and alkyltrichlorosilanes on silicon. However these substrates are not widely used as biomaterials.

Phosphonic acids have been gaining a lot of interest as an organic moiety for formation of SAMs due to their ability to bind to a wide range of metal oxide surfaces and form robust SAMs having quality similar to the model system of alkanethiols on Au[31] hence we have chosen this for our study. It has been previously reported that long chain alkylphosphonates form well ordered and dense monolayers[32,33]. Octadecylphosphonic acid (ODPA) is a long chain phosphonate and has been widely studied for its bonding with a range of metal oxides[6,34,35]. Some of the other biomaterials on which phosphonic SAMs have been formed include titanium[34], stainless steel[35] and nitinol[36]. Although reports exist on phosphonic SAM formation on biometallic alloys mentioned above, we could only find two reports investigating the stability of SAM systems on biomaterials. Kanta et al. carried out studies to investigate the stability of phosphonic acids formed on titania when immersed in various solvents[37]. They concluded that the phosphonic SAMs on titania were stable after immersion for 18hr in different organic solvents. Mani et al. reported the stability of phosphonic acid on titanium and compared it with the stability of alkanethiol on Au[38]. They concluded that phosphonic SAMs of hydroxyl terminated (11 hydroxyundecyl) phosphonic acid were stable on the surface of titanium for up to a period of 14 days of ambient air exposure without any significant desorption. We could not find any reports of stability of Phosphonic SAMs on Co-Cr alloy. In this paper we present results demonstrating the formation and stability of phosphonic self assembled monolayers on Co-Cr alloy under oxidative conditions, which would be a preliminary stability criteria prior to physiological and biological stability. We have formed methyl terminated ODPA SAMs having uniform surface coverage on Co-Cr alloy. These SAMs were chemisorbed to the native oxide layer of the Co-Cr alloy using solution deposition technique. Ambient laboratory conditions were used as oxidative conditions for determining the stability of the SAMs. The resulting monolayers were characterized using XPS, Contact Angle and AFM, over the duration of study.

2. Experimental Section

2.1 Materials

Octadecylphosphonic acid (ODPA) $[(OH)_2PO(CH_2)_{17}CH_3]$ was obtained from Alfa Aesar (MA,USA) and used as received. Cobalt Chromium alloy (Co-Cr) foils were purchased from Goodfellow, Inc, Oakdale, PA. All solvents including tetrahydrofuran (THF), ethanol, nitric acid, and acetone were analytical grade, purchased from Sigma Aldrich Chemical Co. and used as received.

2.2 Formation of Octadecylphosphonic acid (ODPA) SAMs on Co-Cr alloy

Cobalt Chromium alloy (Co-Cr) substrates were ultrasonicated in ethanol, acetone and 10% nitric acid (10 mins each). The samples were then rinsed with solvent tetrahydrofuran (THF) and deionised water and immediately dipped in the solution containing approximately 20 ml of 1 mmol Octadecylphosphonic acid (ODPA) in THF. The SAM solution was maintained at 35 ° C for 48 hours in a hot water bath. After 48 hrs of immersion, the samples were rinsed in THF and de-ionized water. These samples were then ultrasonicated in acetone to remove loosely bound materials, after which they were rinsed in de-ionized water and subsequently air dried.

2.3 Oxidative stability measurements under ambient laboratory conditions

ODPA coated SAMs were exposed to ambient laboratory conditions after SAM formation for 1, 3, 7 and 14 days. The samples were exposed to light in laboratory conditions. After

oxidative exposure, samples were rinsed in de-ionized water, air dried and transferred to polyethylene wafer containers for characterization.

2.4 Characterization Techniques

2.4.1 X-ray Photoelectron Spectroscopy (XPS)—XPS was used to determine the atomic composition of the sample surface. XPS spectra were obtained using Kratos Axis Ultra DLD X-ray Photoelectron Spectrometer equipped with a monochromatic Al K alpha ($h\nu = 1486.6$ eV) and a dual anode Mg and Al source, with Mg K alpha source energy 1253.6 eV. Compositional survey and detailed scans were acquired using pass energy of 80 eV. High-resolution spectra were acquired for the samples using a pass energy of 20 eV. The binding energies were corrected by referencing the C 1s binding energy to 285 eV.

2.4.2 Atomic Force Microscope (AFM)—AFM was used to study the topography and surface roughness of the substrate. A Digital Instruments (Veeco Instruments Inc.) Scanning Probe Microscope with Nanoscope IV Controller Dimension 310™ SPM Head was used for the AFM studies. All the measurements for the metal alloy substrate were carried out in a non-contact mode at room temperature. The cantilever tips used were Tap 150-G (Budget Sensors) monolithic silicon probes with a resonant frequency of ~ 75 kHz and a force constant of 5 N/m. Nanoscope IV software was used to flatten the images, acquire topographic details and carry out sectional and roughness analysis on the data files. Bulk roughness calculation was done over a scan area of $(1 \times 1 \mu\text{m}^2)$ for each sample. For the roughness calculation, RMS (Root Mean Square) values were obtained for 5 samples of each system.

2.4.3 Contact Angle Measurements—Static contact angles were recorded using a FTA 100 contact angle measurement system. Contact angles were measured on both sides of the water drop. Droplet profiles were captured using a video comprising of 200 digital frames over a period of 10 seconds and transferred to a computer for angle measurement. De-ionized water was used for the measurement with a calculated surface tension value of 39.4 dynes/cm. The contact angle values reported here represent the mean $\pm$ standard deviations of at least three distinct spots on three different samples.

3. Results and Discussion

X-ray Photoelectron Spectroscopy (XPS) gives a detailed elemental composition of the surface. Figure 1 shows a typical XPS survey scan over a binding energy range of 0-1000 eV for (a) control cobalt chromium alloy and (b) ODPa SAMs deposited on Co-Cr alloy. In both spectra, peaks for the characteristic elements present in Co-Cr alloy such as Co and Cr are clearly visible. The C 1s intensity for SAM coated Co-Cr is significantly higher than that on the control sample. The presence of phosphonic ODPa SAM on Co-Cr is confirmed by the presence of P 2p and P 2s peaks which are clearly visible for SAM coated sample and are absent on the control Co-Cr sample. In our samples the P 2p peak is centered around 133.3 eV and the P 2s peak is centered around 188 eV. These values are in good agreement with the earlier reported values for ODPa SAMs on other substrates[35,39]. Thus XPS results confirm the successful deposition of ODPa SAMs on Co-Cr alloy.

Atomic Force Microscopy (AFM) was used to look at topography of samples before and after SAM deposition. In literature AFM imaging has been widely used for determining uniformity of SAMs on metal substrates [35,36,40]. The images obtained in non contact mode gave a direct observation of the morphology and homogeneity of monolayer coverage and thereby the quality of the film. Figure 2 shows the 3D topography images for the control Co-Cr and ODPa deposited Co-Cr (vertical axis Z = 50 nm). The image indicates that

phosphonic SAMs exhibit uniform coverage of the surface with a regular pattern of island formation. Earlier studies carried out for analyzing formation of SAMs using AFM have indicated that the monolayer forms by nucleation, growth and coalescence of submonolayer islands[41]. Smaller islands migrate over time and coalesce with larger islands to eventually form a uniform monolayer. In our system, we observed that the islands formed were in the range of ~ 60-100 nm. The island heights were not always uniform with the local topographical variations of the Co-Cr surface influencing the monolayer features. From Figure 2, we can observe that there are some islands which are slightly large and have greater height compared to the bulk of the islands which are small and uniformly distributed. This might be due to the fact that most of the literature reported for SAM deposition uses sputter coated substrates rather than bulk substrate where the bulk substrate tends to be more rough than sputter coated surfaces leading to larger surface variations[7,42,43]. The RMS roughness values of our samples obtained for bulk (control) Co-Cr and ODPa SAM Co-Cr were 4.9 nm and 6.3 nm respectively. The increase in the roughness is 1.4 nm which compares well with ODPa SAMs formed on titanium (~ 1.5 nm)[34] and mica (~ 1.8 nm) [41]. These freshly prepared SAMs on Co-Cr alloy were used for oxidative stability studies.

Table 1 gives the XPS determined atomic concentrations (%) for the control Co-Cr alloy, fresh ODPa sample and other samples for the duration of oxidative exposure. The bulk composition of our alloy differs from the XPS determined concentration of the surface oxide layer. The major components of the alloy are Co (42.5%), Cr (20%) and Ni (13%). Hanawa et al carried out studies investigating the nature of the Co-Cr alloy surface in a variety of chemical environments mimicking the biological environment[44]. They observed that the decrease in the ratio of Co/Cr was observed as there was a preferential dissolution of Co from the alloy. Mani et al. carried out studies for the formation of silane monolayers on Co-Cr alloy[7]. They observed a decrease in the metal oxide atomic concentrations after SAM deposition for the bulk Co-Cr sample. We observed a similar trend as the Co atomic concentration dropped from 4.15 % to ~ 0.6 % over the duration of the oxidative exposure. Hanawa et al. concluded that the oxide layer consists predominantly of chromium oxide along with other metal oxides[44]. We also found a similar trend with Cr being the majority element present on the surface oxide layer.

Detailed high energy elemental XPS scans are useful in determining the binding energies of the bound species on the surface and are helpful in predicting the chemical composition. Figure 3 gives a detailed high energy XPS scan for the P 2p region for oxidative stability studies. The 0 day SAMs sample represents the freshly formed ODPa SAMs on Co-Cr alloy surface. The spectra for control Co-Cr (not shown here) showed no P 2p peaks present. Here, the P 2p peak which is centered around 133.2 eV and represents the metal phosphonate peak and is very consistent for 1, 3, 7 and 14 days of oxidative exposure. Zorn et al. have reported the P 2p peak at 133.6 eV for the system of hexadecylphosphonic acid SAMs deposited on Ti-Nb alloy[39]. Ito et al. have reported the peak to be ~135 eV for the system of ODPa SAMs coated on GaN[45]. Raman et al. have reported the peak to be at 134.56 eV for ODPa SAMs deposited on stainless steel SS 316[35]. Textor et al. have assigned the binding energy of the P 2p peak at 134.7 eV for the attachment of the phosphonate head group of the octadecylphosphoric acid on tantalum oxide surface[46]. Based on these literature data and the experimental data shown in Figure 3, we conclude that the metal phosphonate peak for ODPa SAMs on Co-Cr represents a strongly bound monolayer and is consistent for the oxidative exposure during the duration of the study.

Figure 4 shows the detailed high energy spectra of the O 1s region for control Co-Cr and freshly deposited Co-Cr SAMs. Figure 5 gives a comparison of the O 1s spectra between the fresh SAMs and the duration of the oxidative exposure study. The position of the peak and the contribution of a particular spectra peak depend on the type of substrate and the chemical

deposited on it. For metal oxides, the O 1s spectra can be divided into three basic components. The peak at ~ 530 eV represents the O atoms present in the metal oxide layer along with surface terminal O, surface hydroxyl groups, bridging OH groups and chemisorbed or surface contamination [47-50]. For the bound phosphonic headgroup to the metal oxide layer, literature reports have shown that the P=O bond binds at ~ 531-532 eV and the P-OH binds at ~532.6-533.6 eV[39,46,47,51-53]. In figure 4, for the control Co-Cr sample, we attribute the peak at 530.5 eV to the bulk metal oxides of the surface oxide layer. We see that the contribution of this peak is significantly reduced in the ODPA SAMs sample spectra. For the control sample, the peak at ~ 531 eV which has a lower contribution to the spectra is attributed to the surface hydroxides and other surface contaminants. We see a significantly higher contribution of the peak at 531.7 eV which is attributed to the P-O bond of the bound phosphonate for the ODPA SAM deposited sample. This peak also has contribution from the P=O group with a binding energy near ~533.5 eV. From figure 5 we see that the trends in the bonding contributions are consistent and there is no change in the P-O peak for the bound ODPA SAM. We also see a decrease in the contribution of the O 1s signal at 530.5 eV from fresh SAMs to 14 days sample. This suggests that the oxide layer is getting covered over a period of time with some impurities from the atmosphere which are chemisorbed on the surface. This is corroborated by the data from Table 1 where we see a continuous decrease in the contributions of the metal peaks over time. At the same time we see a significant increase in the C 1s signal. So we believe that most of the impurities are carbonaceous and that our SAM system is attractive to them.

To analyze this hypothesis further we took a look at the detailed high energy XPS spectra for the C 1s region. Figure 6 shows the detailed high energy scan for C 1s for control Co-Cr and ODPA SAMs deposited Co-Cr. Figure 7 shows the C 1s scans for the duration of the oxidative exposure. From figure 6 we can clearly see the huge increase in the C 1s signal before and after SAM deposition. The C 1s signal is centered at binding energy value of 285 eV. However, the C 1s signal increases in intensity over the period of 14 days as outlined in Figure 7. This significant increase is mostly due to carbonaceous impurities adsorbed from the ambient atmosphere. We attribute this carbon contamination to be the reason for the attenuation of surface oxide signal in terms of the atomic concentrations of the metals.

Figure 8 shows the AFM 3D topographical images of ODPA SAMs on Co-Cr alloy for oxidative exposure over time periods of 1, 3, 7 and 14 days. We observe a continuation of the regular pattern of islands of SAMs which are uniformly covered over the surface. The RMS roughness values obtained for these samples were approximately the same as that of freshly formed SAMs on Co-Cr and we did not see a particular trend in the surface roughness values. Previous reported literature suggests that there is a large variation of RMS roughness values for SAM coating by solution deposition on account of exposure to various environmental conditions including ambient air[54]. It is believed that the sample preparation and characterization processes also play a role in the large variation of the RMS roughness values. Other factors possibly contributing to this variation include substrate morphology, substrate chemical composition, surface oxide chemistry, surface pretreatment procedures and the nature of SAM being deposited on the substrate[7]. Detailed analysis of our samples indicates that the Co-Cr alloy itself is very rough overall, with it having smoother areas in patches. This affects the final monolayer formation kinetics and plays a major role in determining the structure and uniformity of the islands. Based on the topographical images and the roughness analyses of our samples, we conclude that the ODPA SAMs are uniformly formed over the Co-Cr alloy surface and are present after oxidative exposure for a period of 14 days.

Contact angle formed by a liquid at an interface is sensitive to the molecular structure of the surface and provides a measure of hydrophilicity/ hydrophobicity of the SAM surface, order

and uniformity of the surface coverage [6,42,55]. Contact angle measurements have been used to determine the changes in the surface as a function of reaction conditions and the effects of the various reaction parameters on the SAM growth process. It has been observed that a 48 hr reaction for the solution deposition technique is enough for the formation of high quality SAMs[12]. The solution deposition time is a function of the contact angle value and thereby the quality and order of the monolayers. Hence, our exposure time for the surfactant solution in contact with the Co-Cr alloy was 48 hrs. Figure 9 gives static contact angle images for a) control Co-Cr, b) Fresh ODPAs (0 Day), c) 1 day, d) 3 days, e) 7 days and f) 14 days samples. Figure 10 shows the trend in the contact angle data for the duration of the study. Distilled water was used to carry out the contact angle measurements. The contact angle value obtained for the control Co-Cr alloy is $73.13 \pm 0.4^\circ$. The value obtained for the freshly formed ODPAs were $101.91 \pm 0.3^\circ$. This significant increase in the contact value suggests the formation of an ordered monolayer films with methyl terminated groups. This value is consistent with several other studies on the formation of well ordered SAMs[38,40,52]. From the trend seen in Figure 10, we can make out that the variation in the contact angle values is from $\sim 102^\circ$ for freshly formed SAMs to $\sim 93^\circ$ for SAMs with 14 days oxidative exposure. The values indicate that there is a slight reduction of the contact angle value; however the surface is still very hydrophobic and uniformly covered with SAMs. The SAMs are slightly disordered compared to freshly formed SAMs, but the change is not significant enough to convey degradation of the monolayer. Park et al. studied alkanethiols on Au and have reported that loosely packed monolayers expose a substantial amount of methylene groups in addition to the methyl groups, thereby increasing the wettability and decreasing the contact angle[56]. It has been reported that besides the chemical functionality on the surface, the surface roughness also plays an important role in determining the contact angle values[57,58]. Some reports have also attributed the changes in the contact angle values to adsorption of impurities from the atmosphere when the specimens were exposed to air[38,54]. Petri et al. studied the formation of amino terminated silane SAMs on silicon surfaces[54]. They concluded that the change in the surface wettability observed in their samples was probably due to the adsorption of hydrophobic impurities. This could also be the reason for the slight deviation of values for our system with a possible adsorption of hydrophilic impurities on the SAMs.

4. Conclusions

Surface modification of Cobalt Chromium alloy (Co-Cr) was carried out by using self assembled monolayers. Methyl terminated Octadecylphosphonic acid (ODPA) was used to form a monolayer on the surface of the alloy by solution deposition technique. The formation was confirmed collectively using XPS, AFM and contact angle measurements. The samples were then evaluated for their stability to oxidative exposure carried out in laboratory ambient conditions. XPS typical survey scan, contact angle measurements and AFM confirmed the presence of phosphonic SAMs at intervals of 1 day, 3 days, 7 days and 14 days. High energy detailed XPS scans gave an insight into the trends in the typical elemental compositions. The coverage of the ODPAs on Co-Cr is found to be affected by the carbonaceous contaminants which are adsorbed onto the sample. AFM images showed consistent islands of SAM on the surface and contact angle measurements confirmed surface hydrophobicity over a period of 14 days. Thus XPS, contact angle and AFM results confirm that monolayers are stable under the chosen oxidative study.

Acknowledgments

We would like to acknowledge the NIH Center for Biotechnology and Biomedical Science and the Center for Materials Research at Norfolk State University for financial support of the work. We would also like to acknowledge Surface Characterization Lab of College of William and Mary at Applied Research Center Jefferson Labs, Newport News for their assistance with the characterization techniques.

References

1. Agrawal C. Reconstructing the human body using biomaterials. JOM Journal of the Minerals, Metals and Materials Society. 1998; 50:31–35.
2. Langer R. Biomaterials in Drug Delivery and Tissue Engineering: One Laboratory's Experience. Accounts of Chemical Research. 1999; 33:94–101. [PubMed: 10673317]
3. Castner DG, Ratner BD. Biomedical surface science: Foundations to frontiers. Surface Science. 2002; 500:28–60.
4. Poncin P, Millet C, Chevy J, Proft JL. Comparing and Optimizing Co-Cr Tubing for Stent Applications. Medical Devices Materials II : Proceedings of the Materials and Processes for Medical Devices Conference. 2005:279–283.
5. Brunski, B.; Ratner, BD.; Hoffman, AS.; Schoen, FJ.; Lemons, JE., editors. Biomaterials Science. An Introduction to Materials in Medicine. Elsevier Academic Press; San Diego: 2004. p. 137
6. Bhure R, Abdel-Fattah TM, Bonner C, Hall JC, Mahapatro A. Formation of Nanosized Phosphonic Acid Self Assembled Monolayers on Cobalt-Chromium Alloy for Potential Biomedical Applications. Journal of Biomedical Nanotechnology. 2010; 6:117–128. [PubMed: 20738065]
7. Mani G, Feldman MD, Oh S, Agrawal CM. Surface modification of cobalt-chromium-tungsten-nickel alloy using octadecyltrichlorosilanes. Applied Surface Science. 2009; 255:5961–5970.
8. Teoh, SH. Engineering Materials for Biomedical Applications. World Scientific Publishing Co. Pte. Ltd; Singapore: 2004.
9. Shi L, Northwood DO, Cao Z. The properties of a wrought biomedical cobalt-chromium alloy. Journal of Materials Science. 1994:1233–1238.
10. Wessely R. New drug-eluting stent concepts. Nat Rev Cardiol. 7:194–203. [PubMed: 20195268]
11. Kereiakes D, Cox D, Hermiller J, Midei M, Bachinsky W, Nukta E, Leon MB, Fink S, Marin L, Lansky AJ. Usefulness of a cobalt chromium coronary stent alloy. Am J Cardiol. 2003:463–466. [PubMed: 12914881]
12. Mahapatro A, Johnson DM, Patel DN, Feldman MD, Ayon AA, Agrawal CM. The use of alkanethiol self-assembled monolayers on 316L stainless steel for coronary artery stent nanomedicine applications: an oxidative and in vitro stability study. Nanomedicine: Nanotechnology, Biology and Medicine. 2006; 2:182–190.
13. Babapulle MN, Joseph L, Bélisle P, Brophy JM, Eisenberg MJ. A hierarchical Bayesian meta-analysis of randomised clinical trials of drug-eluting stents. The Lancet. 2004; 364:583–591.
14. van der Giessen WJ, Lincoff AM, Schwartz RS, van Beusekom HMM, Serruys PW, Holmes DR, Ellis SG, Topol EJ. Marked Inflammatory Sequelae to Implantation of Biodegradable and Nonbiodegradable Polymers in Porcine Coronary Arteries. Circulation. 1996; 94:1690–1697. [PubMed: 8840862]
15. Nebeker JR, Virmani R, Bennett CL, Hoffman JM, Samore MH, Alvarez J, Davidson CJ, McKoy JM, Raisch DW, Whisenant BK, Yarnold PR, Belknap SM, West DP, Gage JE, Morse RE, Gligoric G, Davidson L, Feldman MD. Hypersensitivity Cases Associated With Drug-Eluting Coronary Stents: A Review of Available Cases From the Research on Adverse Drug Events and Reports (RADAR) Project. Journal of the American College of Cardiology. 2006; 47:175–181. [PubMed: 16386683]
16. Katti KS. Biomaterials in total joint replacement. Colloids and Surfaces B: Biointerfaces. 2004; 39:133–142.
17. Papageorgiou I, Brown C, Schins R, Singh S, Newson R, Davis S, Fisher J, Ingham E, Case CP. The effect of nano- and micron-sized particles of cobalt-chromium alloy on human fibroblasts in vitro. Biomaterials. 2007; 28:2946–2958. [PubMed: 17379299]
18. Hensten-Pettersen A. Casting Alloys: Side-Effects. Advances in Dental Research. 1992; 6:38–43. [PubMed: 1292460]
19. Langton DJ, Jameson SS, Joyce TJ, Webb J, Nargol AVF. The effect of component size and orientation on the concentrations of metal ions after resurfacing arthroplasty of the hip. J Bone Joint Surg Br. 2008; 90-B:1143–1151. [PubMed: 18757952]

20. Matl FD, Obermeier A, Repmann S, Friess W, Stemberger A, Kuehn KD. New Anti-Infective Coatings of Medical Implants. *Antimicrob Agents Chemother.* 2008; 52:1957–1963. [PubMed: 18362194]
21. Guinan JL, McGuckin M, Shubin A, Tighe J. A descriptive review of malpractice claims for health care-acquired infections in Philadelphia. *American Journal of Infection Control.* 2005; 33:310–312. [PubMed: 15947750]
22. Ulman A. Formation and Structure of Self-Assembled Monolayers. *Chemical Reviews.* 1996; 96:1533–1554. [PubMed: 11848802]
23. Love JC, Estroff LA, Kriebel JK, Nuzzo RG, Whitesides GM. Self-Assembled Monolayers of Thiolates on Metals as a Form of Nanotechnology. *Chemical Reviews.* 2005; 105:1103–1170. [PubMed: 15826011]
24. Bhure R, Mahapatro A. Silicon Based Nanocoatings on Metal Alloys and Their Role in Surface Engineering. *SILICON.* 2010; 2:117–151.
25. Spinke J, Liley M, Guder HJ, Angermaier L, Knoll W. Molecular recognition at self-assembled monolayers: the construction of multicomponent multilayers. *Langmuir.* 1993; 9:1821–1825.
26. Houseman BT, Gawalt ES, Mrksich M. Maleimide-Functionalized Self-Assembled Monolayers for the Preparation of Peptide and Carbohydrate Biochips. *Langmuir.* 2002; 19:1522–1531.
27. Huang E, Zhou F, Deng L. Studies of Surface Coverage and Orientation of DNA Molecules Immobilized onto Preformed Alkanethiol Self-Assembled Monolayers. *Langmuir.* 2000; 16:3272–3280.
28. Herrwerth S, Rosendahl T, Feng C, Fick J, Eck W, Himmelhaus M, Dahint R, Grunze M. Covalent Coupling of Antibodies to Self-Assembled Monolayers of Carboxy-Functionalized Poly(ethylene glycol): Protein Resistance and Specific Binding of Biomolecules. *Langmuir.* 2003; 19:1880–1887.
29. Mahapatro A, Johnson DM, Patel DN, Feldman MD, Ayon AA, Agrawal CM. Surface Modification of Functional Self-Assembled Monolayers on 316L Stainless Steel via Lipase Catalysis. *Langmuir.* 2006; 22:901–905. [PubMed: 16430246]
30. Mahapatro A, Johnson DM, Patel DN, Feldman MD, Ayon AA, Agrawal CM. Drug Delivery from Therapeutic Self-Assembled Monolayers (T-SAMs) on 316L Stainless Steel. *Current Topics in Medicinal Chemistry.* 2008; 8:281–289. [PubMed: 18393891]
31. Spori DM, Venkataraman NV, Tosatti SGP, Durmaz F, Spencer ND, Zurcher S. Influence of Alkyl Chain Length on Phosphate Self-Assembled Monolayers. *Langmuir.* 2007; 23:8053–8060. [PubMed: 17569549]
32. Helmy R, Fadeev AY. Self-Assembled Monolayers Supported on TiO_2 : Comparison of $\text{C}_{18}\text{H}_{37}\text{SiX}_3$ ($\text{X} = \text{H}, \text{Cl}, \text{OCH}_3$), $\text{C}_{18}\text{H}_{37}\text{Si}(\text{CH}_3)_2\text{Cl}$ and $\text{C}_{18}\text{H}_{37}\text{PO}(\text{OH})_2$. *Langmuir.* 2002; 18:8924–8928.
33. Gao W, Dickinson L, Grozinger C, Morin FG, Reven L. Self-Assembled Monolayers of Alkylphosphonic Acids on Metal Oxides. *Langmuir.* 1996; 12:6429–6435.
34. Gawalt ES, Avaltroni MJ, Koch N, Schwartz J. Self-Assembly and Bonding of Alkanephosphonic Acids on the Native Oxide Surface of Titanium. *Langmuir.* 2001; 17:5736–5738.
35. Raman A, Dubey M, Gouzman I, Gawalt ES. Formation of Self-Assembled Monolayers of Alkylphosphonic Acid on the Native Oxide Surface of SS316L. *Langmuir.* 2006; 22:6469–6472. [PubMed: 16830984]
36. Raman A, Gawalt ES. Self-Assembled Monolayers of Alkanoic Acids on the Native Oxide Surface of SS316L by Solution Deposition. *Langmuir.* 2007; 23:2284–2288. [PubMed: 17266343]
37. Kanta A, Sedev R, Ralston J. The formation and stability of self-assembled monolayers of octadecylphosphonic acid on titania. *Colloids and Surfaces A: Physicochemical and Engineering Aspects.* 2006; 291:51–58.
38. Mani G, Johnson DM, Marton D, Dougherty VL, Feldman MD, Patel D, Ayon AA, Agrawal CM. Stability of Self-Assembled Monolayers on Titanium and Gold. *Langmuir.* 2008; 24:6774–6784. [PubMed: 18512878]
39. Zorn G, Gotman I, Gutmanas EY, Adadi R, Salitra G, Sukenik CN. Surface Modification of Ti45Nb Alloy with an Alkylphosphonic Acid Self-Assembled Monolayer. *Chemistry of Materials.* 2005; 17:4218–4226.

40. Quinones R, Gawalt ES. Study of the Formation of Self-Assembled Monolayers on Nitinol. *Langmuir*. 2007; 23:10123–10130. [PubMed: 17725369]
41. Woodward JT, Schwartz DK. In Situ Observation of Self-Assembled Monolayer Growth. *Journal of the American Chemical Society*. 1996; 118:7861–7862.
42. Love JC, Wolfe DB, Haasch R, Chabinyc ML, Paul KE, Whitesides GM, Nuzzo RG. Formation and Structure of Self-Assembled Monolayers of Alkanethiolates on Palladium. *Journal of the American Chemical Society*. 2003; 125:2597–2609. [PubMed: 12603148]
43. Stettner J, Frank P, Griesser T, Trimmel G, Schennach R, Gilli E, Winkler A. A Study on the Formation and Thermal Stability of 11-MUA SAMs on Au(111)/Mica and on Polycrystalline Gold Foils. *Langmuir*. 2009; 25:1427–1433. [PubMed: 19119802]
44. Hanawa T, Hiromoto S, Asami K. Characterization of the surface oxide film of a Co-Cr-Mo alloy after being located in quasi-biological environments using XPS. *Applied Surface Science*. 2001; 183:68–75.
45. Ito T, Forman SM, Cao C, Li F, Eddy CR, Mastro MA, Holm RT, Henry RL, Hohn KL, Edgar JH. Self-Assembled Monolayers of Alkylphosphonic Acid on GaN Substrates. *Langmuir*. 2008; 24:6630–6635. [PubMed: 18522438]
46. Textor M, Ruiz L, Hofer R, Rossi A, Feldman K, Hahner G, Spencer ND. Structural Chemistry of Self-Assembled Monolayers of Octadecylphosphoric Acid on Tantalum Oxide Surfaces. *Langmuir*. 2000; 16:3257–3271.
47. Adden N, Gamble LJ, Castner DG, Hoffmann A, Gross G, Menzel H. Phosphonic Acid Monolayers for Binding of Bioactive Molecules to Titanium Surfaces. *Langmuir*. 2006; 22:8197–8204. [PubMed: 16952262]
48. Viorneri C, Chevolut Y, Lonard D, Aronsson BrO, Pchy Pt, Mathieu HJr, Descouts P, Grtzel M. Surface Modification of Titanium with Phosphonic Acid To Improve Bone Bonding: Characterization by XPS and ToF-SIMS. *Langmuir*. 2002; 18:2582–2589.
49. Sittig C, Textor M, Spencer ND, Wieland M, Vallotton PH. Surface characterization. *Journal of Materials Science: Materials in Medicine*. 1999; 10:35–46. [PubMed: 15347992]
50. Lu G, Bernasek SL, Schwartz J. Oxidation of a polycrystalline titanium surface by oxygen and water. *Surface Science*. 2000; 458:80–90.
51. Tosatti S, Michel R, Textor M, Spencer ND. Self-Assembled Monolayers of Dodecyl and Hydroxy-dodecyl Phosphates on Both Smooth and Rough Titanium and Titanium Oxide Surfaces. *Langmuir*. 2002; 18:3537–3548.
52. Hofer R, Textor M, Spencer ND. Alkyl Phosphate Monolayers, Self-Assembled from Aqueous Solution onto Metal Oxide Surfaces. *Langmuir*. 2001; 17:4014–4020.
53. Adolphi B, Jhne E, Busch G, Cai X. Characterization of the adsorption of -(thiophene-3-yl alkyl) phosphonic acid on metal oxides with AR-XPS. *Analytical and Bioanalytical Chemistry*. 2004; 379:646–652. [PubMed: 15133652]
54. Siqueira Petri DF, Wenz G, Schunk P, Schimmel T. An Improved Method for the Assembly of Amino-Terminated Monolayers on SiO2 and the Vapor Deposition of Gold Layers. *Langmuir*. 1999; 15:4520–4523.
55. Bain CD, Troughton EB, Tao YT, Evall J, Whitesides GM, Nuzzo RG. Formation of monolayer films by the spontaneous assembly of organic thiols from solution onto gold. *Journal of the American Chemical Society*. 1989; 111:321–335.
56. Park JS, Smith AC, Lee TR. Loosely Packed Self-Assembled Monolayers on Gold Generated from 2-Alkyl-2-methylpropane-1,3-dithiols. *Langmuir*. 2004; 20:5829–5836. [PubMed: 16459597]
57. Wang A, Tang H, Cao T, Salley SO, Ng KYS. In vitro stability study of organosilane self-assemble monolayers and multilayers. *Journal of Colloid and Interface Science*. 2005; 291:438–447. [PubMed: 15964581]
58. Quere D. Surface chemistry: Fakir droplets. *Nat Mater*. 2002; 1:14–15. [PubMed: 12618839]

Figure 1. Typical Survey Scan for XPS in the binding energy range of 0-1000 eV. The spectra shown are for (a) Control Co-Cr [bottom] and b) ODPa SAMS on Co-Cr [top]

Figure 2. Atomic Force Microscopy (AFM) images of 3D topography of the surfaces in non-contact mode. a) Control Co-Cr alloy before SAM deposition and (b) ODPA SAMs deposited on Co-Cr alloy. The vertical scale is Z=50nm

Figure 3. XPS determined detailed P 2p scans of ODPA SAMs for oxidative stability. The spectra shown are for a) 0 day Fresh SAMs; b) 1 Day; c) 3 day; d) 7 day and e) 14 day

Figure 4. Detailed XPS O 1s region for Control Co-Cr and ODPA SAM Co-Cr

Figure 5. XPS determined O 1s spectral overlay for Oxidative stability of ODPA on Co-Cr

Figure 6. Detailed XPS C 1s region for Control Co-Cr and ODPA SAM Co-Cr

Figure 7. XPS determined C1s spectral overlay for Oxidative stability of ODPA on Co-Cr

Figure 8. Atomic Force Microscope (AFM) 3D topography images for oxidative stability of ODPA SAMs on Co-Cr alloy. (a) 1 day; (b) 3 day; (c) 7 day and (d) 14 days exposure. The image size is 500×500 microns. The vertical axis value is $Z = 50$ nm

Figure 9. Static Contact Angle Measurements for oxidative stability on ODPa SAM deposition on Co-Cr alloy. a) Control Co-Cr; b) Fresh ODPa SAMs; c) Day 1; d) Day3; e) Day 7 and f) Day 14. Distilled water was used to carry out the measurement

Figure 10. Contact Angle Measurements trend for oxidative stability of ODPa SAMs on Co-Cr alloy

Table 1
XPS Determined Atomic Concentrations (%) of ODPa SAMs samples for oxidative exposure

Days	C 1s	O 1s	Co 2p	Cr 2p	Ni 2p	P 2p	Si 2p	S 2p
Control	29.18	45.69	4.15	13.69	1.78	0	4.01	1.5
0	44.32	37.94	3	9.21	0.97	0.81	3.16	0.59
1	69.27	21.02	1.02	3.61	0.4	0.67	3.65	0.37
3	78.83	14.38	0.57	1.80	0.25	0.61	3.4	0.14
7	70.97	19.62	1.21	3.53	0.37	0.78	3.18	0.35
14	76.16	16.59	0.63	2.27	0.33	0.83	3.0	0.19