SurFACTS in *Biomaterials*

Spring 2017
Volume 22 Issue 1
Twitter @SurfacesIBF
LinkedIn @surfaces in biomaterials foundation

Welcome from President Bill Theilacker

Dear Colleagues,

I am honored to serve as President for Surfaces in Biomaterials Foundation (SIBF) for the upcoming year (2016-2017)! I consider myself very fortunate to represent our members and will work hard to meet your expectations. I would like to take this moment to thank our outgoing president Chander Chawla, the Board of Directors, and Committee Members for their hard work and commitment to their various roles and responsibilities over the past year. We have a lot to be proud of!

Over the last year we held several special events. The summer Open House at Medtronic Operational Headquarters was a huge hit. Michael Wolf presented on ISO10993 Part 4 2016: the latest changes taking us into the 21st century of blood compatibility assessment and Anna Belu presented on surface analysis of biomaterials. The Fall Biointerface Workshop and Symposium in Minneapolis was also very well attended. The Workshop focused on "Sensing at the BioInterface." Speakers included Ron Siegel (Univ. of Minnesota), Raeann Gifford (Medtronic Diabetes), Natalie Wisniewski (Profusa), Diana Eitzman and Amy McNulty (3M), Gerald Cote (Texas A&M), and Jian-Ping Wang (Univ. of Minnesota). The keynote speaker for the Conference was Stephen Badylak from McGowan Institute. Stephen enlightened the audience on mechanisms by which biologic scaffolds influence cell behavior. The highlight of the Conference was the Point - Counterpoint discussion on how to introduce new materials led by Frank Bates (Univ. of Minnesota). Kimberly Chaffin (Medtronic), Chris Jenny (St. Jude Medical), Patrick Willoughby (Boston Scientific) and Elizabeth Cosgriff-Hernandez (Texas A&M University) served as panelists. The session originally scheduled for one hour was continued for two hours due to great audience participation in Q&A with the panel members.

Over the next year, the SIBF board will focus on re-engaging our membership, offering activities and launching initiatives that focus on our mission. The Foundation has a strong membership base with more than 1,160 members on our LinkedIn page. I encourage all of you to be active members and provide ideas how foundation can serve your needs better.

In closing, the Foundation is dedicated to technical challenges at the biointerface. I look forward to exploring creative solutions with you by fostering education and multidisciplinary cooperation among industrial, academic, clinical and regulatory communities.

Sincerely,

Bill Theilacker
President

P.S. I am looking forward to see you at the 27th Annual BioInterface Workshop & Symposium in San Diego (Oct. 2–4, 2017).

INSIDE THIS ISSUE

Save the Date!

27th Annual BioInterface Workshop & Symposium

Oct. 2–4, 2017 | The Catamaran Resort & Spa | San Diego, California USA

Join us in Sunny San Diego!

The 27th Annual BioInterface Workshop & Symposium will be held in San Diego, California on Oct. 2–4, 2017.

The Catamaran Resort is located on San Diego's Mission Bay and is the perfect location for one of the best technical and most stimulating events in the field of biomaterials science in 2017!

This year's highlights include our workshop entitled "Coatings"; our lively Point-Counterpoint Session; the presentation of our prestigious Excellence in Surface Science Award; our Student Poster competition; and two full days of solid technical sessions.

During our event you will be enriched by the science, and the high quality of interaction that is fostered by the unique blend of industry, academic, regulatory and clinical attendees. The size of the event allows you to connect, share and learn by relaxed contact with your fellow attendees.

Look out for our call for abstracts early February!

2017 BioInterface & Workshop Symposium Homepage (click here)

Event Highlights:

- Excellence in Surface Science Award Presentation
- Full Day Workshop on "Coatings"
- Seven Technical Sessions on the Following Topics:
  - Analytical Techniques for Surface Characterization of Biomaterials
  - Cardiac and Cardiovascular
  - Ophthalmic Devices and Therapies
  - Anti-Infective Technologies and Wound Healing
  - Anti-X
  - Neurovascular Devices and Therapies
  - Metallurgy
- Student Town Hall Meeting & Poster Contest
- Multiple Networking Specific Receptions ...and more!

Exhibitor and Sponsorship document (click here)

Towards the Understanding of Biocompatibility in Nitinol Medical Devices

Alan R. Pelton and Hannah Blaich, G. RAU Inc. Santa Clara, CA 95054

Introduction

Equiatomic Nickel Titanium (Nitinol) is an intermetallic compound characterized by a unique combination of properties, including shape memory, superelasticity, corrosion and fatigue resistance, is very attractive for biomedical applications [1]. Nevertheless, the high nickel content of the alloy (50.8 at% Ni) and its possible influence on biocompatibility continues to be a concern. Recent studies determined that thermal oxidation of Nitinol results in surprisingly poor corrosion resistance [2, 3] that may lead to the release of both Ti and Ni ions into the body. Although the human body has a high tolerance for Ti and is considered biologically inert [4], Ni release from implants may generate harmful allergic, toxic or carcinogenic reactions [5-8].

Chemical and electrochemical polishing are the standard methods to passivate Nitinol medical devices by removing the oxidized surfaces created by thermal treatments [9-11]. The purpose of this paper, therefore, is to review some recent work on the characterization of thermal oxide, mechanical polish, and passivated Nitinol surfaces and their resultant corrosion resistance and Ni-ion release behavior. In particular the use of high spatial and energy resolution characterization afforded by synchrotron x-ray techniques will be emphasized.

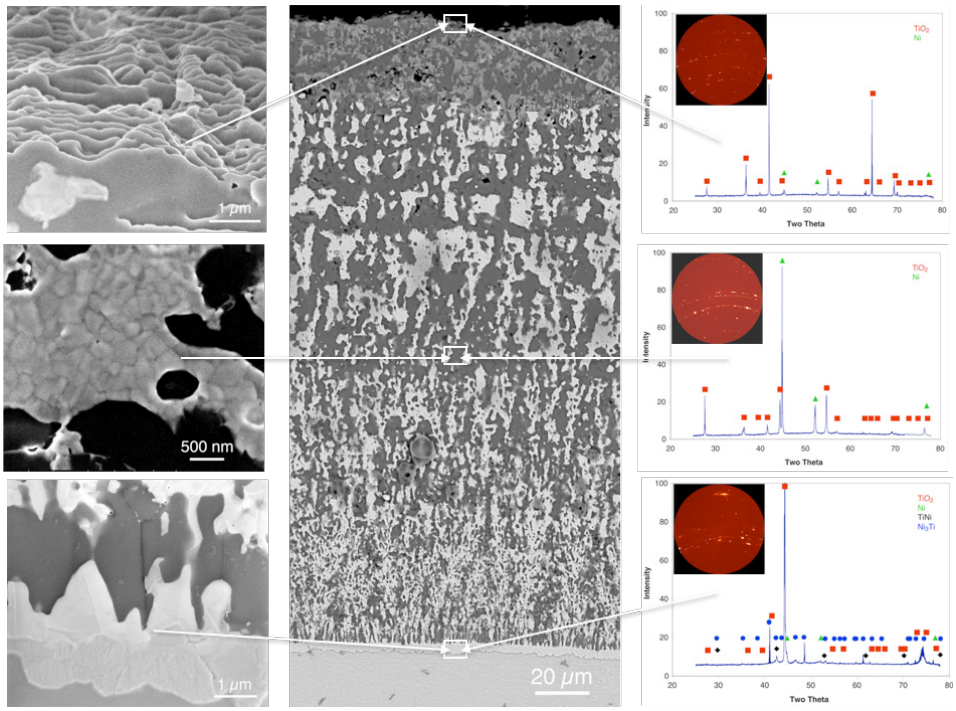

Figure 1. The center Focused Ion Beam (FIB) backscattered image is a cross-section of thermal oxide Nitinol. The FIB images to the left show higher magnification features of the structures whereas the X-Ray Diffraction patterns on the right provide high-resolution characterization of the structures for phase identification [12].

Characterization of Nitinol Microstructures and Phases

FIB and Synchrotron µXRD

The surfaces of passivated and thermal oxide Nitinol wires were characterized with Focused Ion Beam (FIB) and synchrotron micro-x-ray diffraction (µXRD). Nitinol wires were thermally oxidized at temperatures of 400-1000˚C and times of 3 to 300min [2, 3, 12]. FIB analyses were conducted in backscattered-electron-imaging mode to differentiate Ni- and Ti-rich phases. In addition, structural phases were identified based on the analysis of powder diffraction patterns obtained with monochromatic x-ray beam (8keV) of spot size 2 x 7µm at synchrotron beamline 7.3.3 at the Advanced Light Source (ALS) at LBNL/U.C. Berkeley [12]. Figure 1 illustrates the cross section microstructures of a thermal oxide surface that shows the presence of multiple phases (light phases are Ni-rich, darker phases are Ti-rich). Higher magnification images on the left of the main image show details of this complex structure. Analysis of the µXRD on the right confirmed that during the thermal oxidation process, Nitinol transforms into TiO2 (rutile), nano particles of pure Ni, and an interfacial layer of Ni3Ti [12].

Synchrotron XPS

The surfaces of passivated and mechanical polish Nitinol wires were also characterized by X-Ray Photospectroscopy (XPS) at the Stanford Linear Accelerator (SLAC) on beamline 10-1 [13]. The photon energy was tuned to discrete energies between 200-1000 eV in order to probe the Nitinol surfaces at different penetration depths. The spectra near Ti 2p and Ti 3p for both surfaces were consistent with the chemical bonding observed in TiO2. More interesting are the spectra near the binding energies of Ni 3p, as shown in Figure 2. At 1000 eV (~6.1 nm penetration depth) the primary signal

Towards the Understanding ... continues on pg. 4

Towards the Understanding ... continued from pg. 3

for both surfaces is consistent with Ni since the surface thickness is ~ 40nm. At 200 eV (~2.1 nm depth), however, there are significant differences in the XPS profiles. The mechanical polish surface shows significant metallic Ni as well as Ni hydroxide. In contrast, the passivated Nitinol surface shows a signal consistent with only Ni hydroxide. Furthermore, synchrotron Small-Angle X-ray Scattering [14] as well as Near Edge X-ray Absorption Fine Structure Spectroscopy [13] demonstrate that the passivated surface is amorphous. These results are consistent with pure Ti, whereby an amorphous metal-hydroxide passive layer forms in aqueous solutions rather than crystalline metal-oxides at higher temperatures [15]. Figure 3 summarizes the synchrotron XPS data for the Ti/Ni ratio as a function of penetration depth from these investigations. It is clear that the passivation treatments remove Ni from the surface (e.g., 200 and 400eV) compared with the mechanical polish surface treatment.

Corrosion and Ni Ion Release

The anodic polarization pitting corrosion behavior is assessed via ASTM F2129, where the medical device is the anodic component of the electrochemical cell and the current is determined against a Pt cathode. Potential is applied until either pitting occurs or until oxygen evolution is reached. In general, properly passivated Nitinol will reach oxygen evolution (~1000mV) whereas suboptimal surface finish results in decreasing pitting potentials (as low as -100mV) with increasing oxide thickness [2, 3]. Thermal oxides also accelerate Ni ion release; a recent systematic study demonstrated nearly three-orders of magnitude increase in 60-day cumulative Ni ion release (PBS, 37˚C) from Nitinol stents with five different surface finishes ranging from passivated to thermal oxide [16]. Similarly, a commercial braided wire Nitinol device

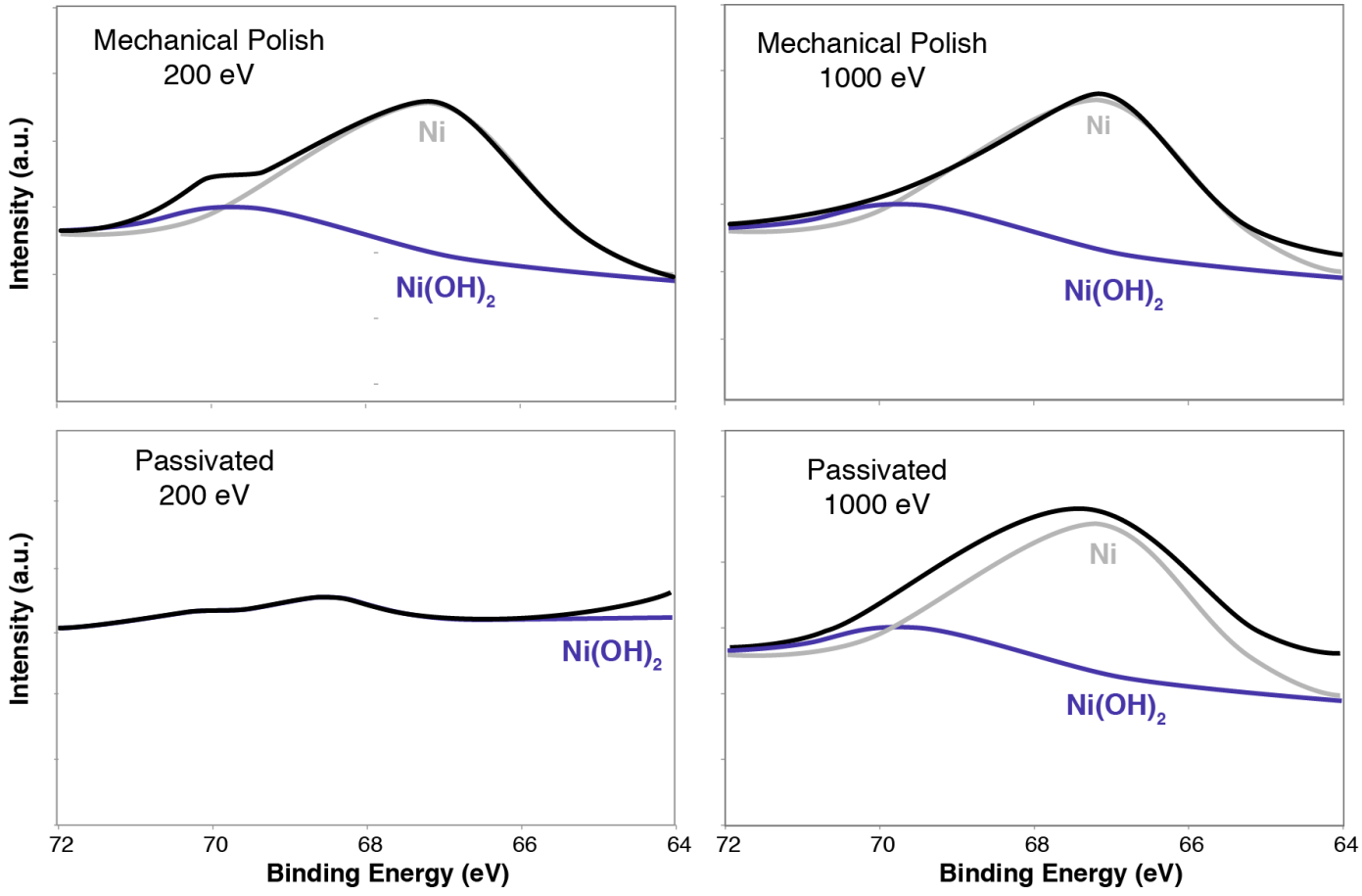

Figure 2. The spectra near Ni 3p for mechanical polish (top) and passivated (bottom) Nitinol at 200 and 1000 V. At 1000 eV (~ 6.1 nm depth) the signals from the two materials are similar. At 200eV (~2.1 nm depth), the data from mechanical polish surface shows a significant signal from metallic Ni in addition to Ni(OH)2. The passivated surface is consistent with that of chemical bonding of Ni(OH)2 [13].

Towards the Understanding ... continues on pg. 5

Towards the Understanding ... continued from pg. 4

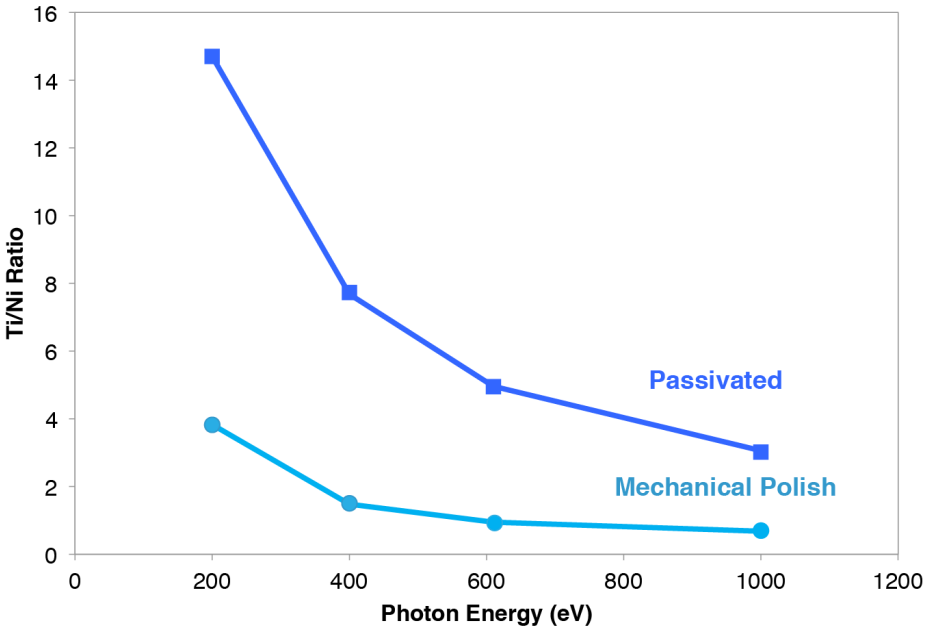

Figure 3. Ratio of Ti-to-Ni as a function of incident photon energy (penetration depth). The passivated surface has a much greater Ti/Ni ratio than that observed for the mechanical polish surface. These data are consistent with more optimal removal of Ni phases from the surface during electrochemical polishing treatments.

with an oxide thickness of ~320 nm shows two orders of magnitude greater Ni ion release over 60-day static immersion (PBS, 37˚C) compared with a passivated Nitinol device [17]. Given the complexity of Nitinol braided-wire devices, which have a propensity for in vivo fretting/wear, corrosion tests should be conducted after the devices have been subjected to simulated in vivo fatigue cycles. Figure 4 compares the corrosion pitting potential as a function of Nitinol braided-wire surface condition for up to 100 million cycles. The passivated devices reach 1000mV throughout the duration of fatigue, whereas the thermal oxide treatment results in a substantially lower and monotonically decreasing breakdown potential with increasing fatigue cycles. The inset SEM image shows fretting/wear that occurs between the Nitinol wires during fatigue cycling.

Figure 5 illustrates the differences in Ni-ion release for the braided-wire Nitinol devices with thermal oxide and passivated surfaces. For these tests, devices were deployed in silicone tubes, filled with PBS and then subjected to crush fatigue for up to 10 million cycles. The PBS was analyzed for Ni with mass spectroscopy per ISO 10993-15. After 1 million cycles there is not a significant difference between the thermal oxide and passivated results. However, after 10 million cycles, the thermal oxide Ni release is ~ 2.5 ppm, which is near the maximum limit of Ni in the blood (3ppm) suggested by the literature [5-8].

Implications for Nitinol Biocompatibility

Biocompatibility properties of metallic implants can be classified into four categories according to the degree of degradation of the surrounding tissue caused by tissue/metal interactions: Biodegradable, Bioactive, Inert, and Toxic [15]. The interaction between the

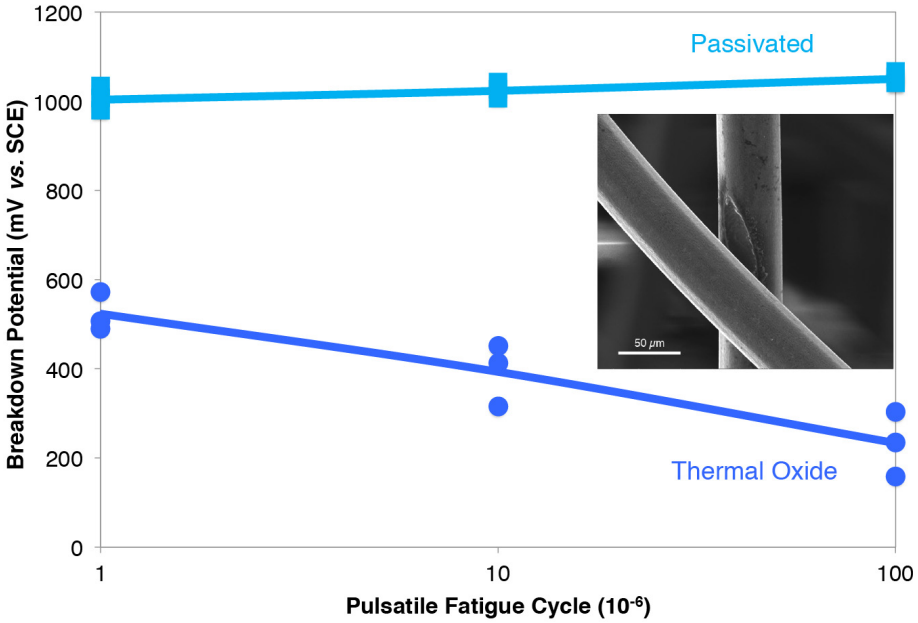

Figure 4. The corrosion behavior of passivated Nitinol is consistently high (~1000 eV) to 100 million fatigue cycles. The oxidized Nitinol shows a decreasing trend with increasing pulsatile fatigue cycles in PBS at 37˚C. The inset shows fretting behavior between two thermal oxide Nitinol wires that occurs during the pulsatile fatigue testing.

Towards the Understanding ... continues on pg. 6

Towards the Understanding ... continued from pg. 5

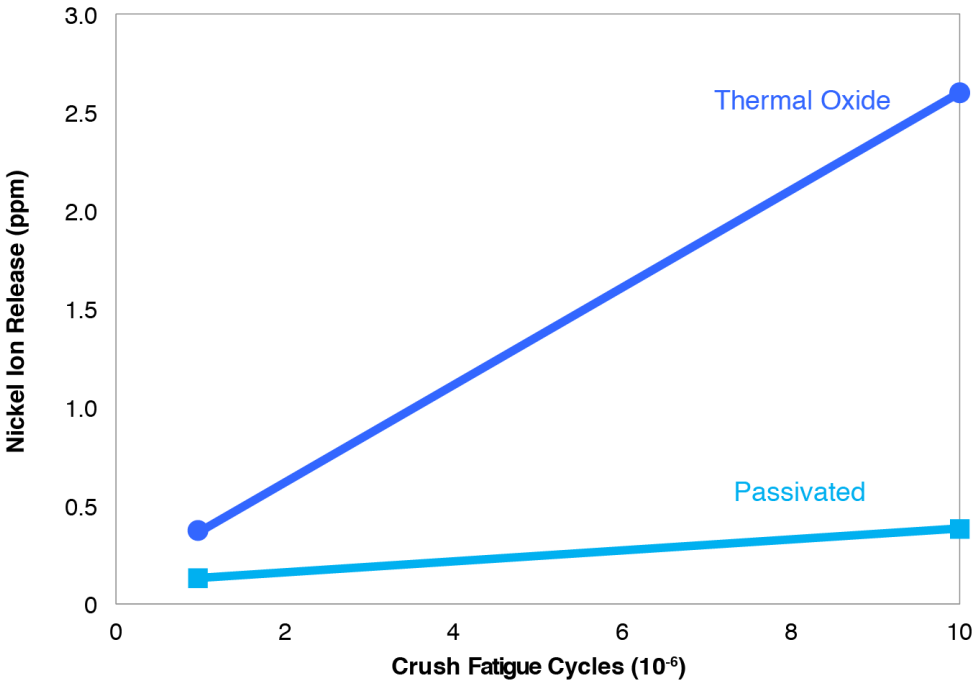

Figure 5. The Ni-ion release behavior of passivated Nitinol shows an insignificant increase between 1-10 million crush fatigue cycles in PBS at 37°C. After 10 million cycles the thermal oxide Nitinol increased by a factor of five and is close to the Ni limit (3 ppm) in blood suggested by the literature [5-8].

implant and tissue/electrolyte depends on the electrochemical reactions that involve metal ion transfer. Surfaces that result in a Toxic condition may lead to tissue necrosis. Consequently, surfaces that create minimal in vivo reactions, i.e., lower corrosion rates, will lead to enhanced biocompatibility. However, there are still no acceptance criteria for in vitro pitting corrosion of metallic implants. As such, the medical device industry has adopted the recommendations of Rosenbloom, et al. with an average pitting potential of 600 mV with no value less than 300 mV [18]. Whereas these are convenient targets for "passing" the ASTM 2129 anodic polarization test, there is some controversy over the method and the criteria [19]. Although a direct relationship between corrosion potential and Ni ion release has not been firmly established, it is known that certain levels of corrosion and therefore of Ni ion transfer will lead to adverse cellular reactions. For example, Shih, et al. deliberately corroded Nitinol wires in PBS and demonstrated that both the supernatant and the precipitated corrosive products were potentially toxic to vascular smooth muscle cells [7]. Therefore, until criteria are established that are based on objective evidence between in vivo and in vitro testing, it is recommended that optimal Nitinol surface passivation be followed to maximize the biocompatibility of medical devices.

References

1. *Stöckel, D., A.R. Pelton, and T. Duerig, Self-expanding Nitinol Stents: Material and Design Considerations. European Radiology, 2004. 14: p. 292-301.*
2. *Trépanier, C., et al., Corrosion Resistance of Oxidized Nitinol, in SMST-2003: International Conference on Shape Memory and Superelastic Technologies, A.R. Pelton and T. Duerig, Editors. 2003, International Society on SMST: Pacific Grove, CA. p. 367-373.*
3. *Zhu, L., J.M. Fino, and A.R. Pelton, Oxidation of Nitinol, in SMST-2003: International Conference on Shape Memory and Superelastic Technologies, A.R. Pelton and T. Duerig, Editors. 2003, International Society on SMST: Pacific Grove, CA. p. 357-366.*
4. *Hildebrand, H.F. and J.C. Hornez, Biological response and biocompatibility, in Metals as Biomaterials, J.A. Helsen and H.J. Breme, Editors. 1998, Wiley. p. 265-290.*
5. *Webster, J.D., et al., Acute Nickel Intoxication by Dialysis. Annals of Internal Medicine, 1980. 92(5): p. 631-633.*
6. *Sunderman, F.W., Potential Toxicity from Nickel Contamination of Intravenous Fluids. Annals of Clinical and Laboratory Science, 1983. 13(1): p. 1-4.*
7. *Shih, C.-C., et al., The cytotoxicity of corrosion products of nitinol stent wire on cultured smooth muscle cells. J Biomed Mater Res, 2000. 52: p. 395–403.*
8. *Messer, R.L.W., et al., Effect of Vascular Stent Alloys on Expression of Cellular Adhesion Molecules by Endothelial Cells. 2005. 15(1): p. 39-48.*
9. *Trépanier, C., et al., Effect of modification of oxide layer on NiTi stent corrosion resistance. Journal of Biomedical Materials Research, 1998. 43(4): p. 433-440.*
10. *Trepanier, C., R. Venugopalan, and A.R. Pelton, Effect of Passivation Treatments on Nickel Dissolution from Nitinol, in 6th World Biomaterials Congress. 2000: Kamuela, HI.*
11. *Decker, J., et al., The Effect of Material Removal on the Corrosion Resistance and Biocompatibility of Nitinol Laser-Cut and Wire-Form Products. Journal of Materials Engineering and Performance, 2011. 20(4): p. 802-806.*
12. *Pelton, A.R., et al., TiNi Oxidation: Kinetics and Phase Transformations, in Solid-to-Solid Transformations in Inorganic Materials 2005, James M. Howe, et al., Editors. 2005, TMS (The Minerals, Metals & Materials Society): Phoenix, AZ. p. 1029-1034.*
13. *Aksoy, F., et al., Study of Nitinol Surface Passivation Using Synchrotron Based X-ray Photoelectron Spectroscopy and Absorption Spectroscopy. SMST, 2011.*
14. *Mehta, A., V. Schroeder, and A.R. Pelton, Synchrotron small angle X—Ray Scattering of Nitinol Surfaces. unpublished work 2010.*
15. *Scharnweber, D., Degradation (in vitro-in vivo corrosion), in Metals as Biomaterials, J.A. Helsen and H.J. Breme, Editors. 1998, John Wiley & Sons: Chichester. p. 101-151.*
16. *Sullivan, S.J.L., et al., Effects of Oxide Layer Composition and Radial Compression on Nickel Release in Nitinol Stents. Shape Memory and Superelasticity, 2015. 1(3): p. 319-327.*
17. *Trepanier, C. and A.R. Pelton, Effect of Corrosion Resistance and Ni-Ion Release in Braided Wire Nitinol Medical Devices unpublished work 2011.*
18. *Rosenbloom, S.N. and R.A. Corbett, An Assessment of ASTM F 2129 Electrochemical Testing of Small Medical Implants - Lessons Learned. NACE Corrosion 2007, 2007.*
19. *Lonn, M.K., J.M. Metcalf, and B.D. Choules, In Vivo and In Vitro Nitinol Corrosion Properties. Shape Memory and Superelasticity, 2015. 1(3): p. 328-338.*

Emulsion Inks for 3D Printing of Porous Grafts

Prachi Dhavalikar, Nick Sears, Elizabeth Cosgriff-Hernandez, Department of Biomedical Engineering, Texas A&M University

One area of research in the Cosgriff-Hernandez lab at Texas A&M University focuses on the development of porous tissue engineering scaffolds fabricated using emulsion templating. High internal phase emulsions (HIPEs) are generated by dispersing an aqueous droplet phase into a continuous organic phase consisting of a macromer or prepolymer until the internal phase volume is

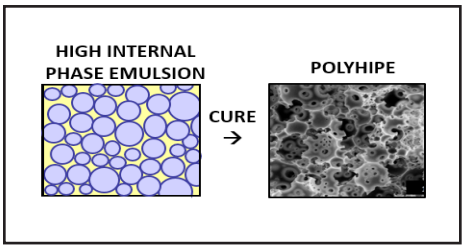

Figure 1: Emulsion templating of porous tissue grafts based on the polymerization of high internal phase emulsions.

greater than 74% of the total volume. Polymerization of the HIPE locks in the emulsion geometry to produce high porosity polyHIPE grafts, Figure 1. [1] Fumarate-based polyHIPEs have been investigated as injectable bone grafts. These injectable polyHIPEs can be stored for up to 12 months, cure with a mild exotherm (<38°C) within 2-5 minutes, support mesenchymal stem cell viability and osteogenic differentiation, and integrate well with bone. [2-3]

Recent studies have explored new applications of these HIPEs as emulsion inks for 3D printing as a means of creating complex geometries and architectures.[4] Prior to cure, the rheological properties of the HIPEs have key characteristics that make them adaptable to an extrusion-based printing platform. Namely, the low shear viscosity of the fumarate-based HIPE is high, which provides good shape retention after line extrusion when printing. The HIPE also displays a strong shear thinning behavior that permits extrusion with a relatively low applied force compatible with most stepper motors used in fused deposition modeling, **Figure 2A.** [5] Briefly, an open source 3D printer equipped with a motor-actuated plunger is used to deposit the HIPE layer-by-layer. The emulsion inks are photocured during deposition by constant UV irradiation to reduce line slump and improve print fidelity. To enable this 'cure-on-dispense', the 3D printer was modified with UV LED-lights attached at the nozzle to initiate radical crosslinking of the ink as it is being extruded, **Figure 2B**. It was determined that the low-shear viscosity of the emulsion ink and the cure rate were both critical variables in the print fidelity of the resulting construct. Printed constructs were fabricated with this setup that were able to replicate complex anatomical geometries with hierarchical porosity from the printed internal lattice structure and the emulsion-templated pore structure, **Figure 2C**. [4] The high porosity of the polyHIPE material combined with the printed lattice structure provides bone grafts with both high surface area and high permeability. These are critical components that have demonstrated impact on bone regeneration strategies. [6] Overall, the combination of the emulsion inks with cure-on-dispense provides a unique platform for generating complex architectures not available with traditional manufacturing techniques

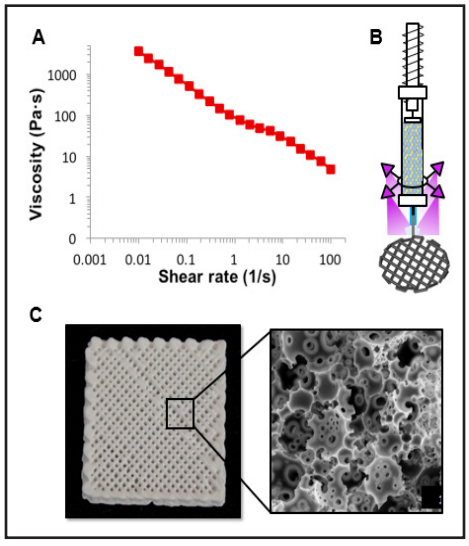

Figure 2: Log-plot of HIPE viscosity as a function of shear rate (A). Schematic representation of emulsion ink printing setup with the UV cure-on-dispense technology (B). Printed construct has dual-porosity as a result of the printed lattice structure and microscale emulsion templated porosity (C).

Although the dual porosity provided improved permeability and will likely promote cellular infiltration, the additional printed porosity resulted in a loss of compressive properties. To address this property loss, recent efforts have focused on multi-material printing to generate scaffolds with increased permeability without sacrificing mechanical strength. To this end, printed scaffolds were designed to mimic the native bone structure by reinforcing the highly porous emulsion inks with a dense cortical shell of thermoplastic polyester. The 3D printer was adapted for multi-modal printing by adding print cartridges for both paste extrusion and high temperature thermoplastic extrusion. [7] High positional accuracy in dual deposition was critical for both print fidelity and mechanical reinforcement. Cortical shells of both poly(ϵ-caprolactone) (PCL) or poly(lactic acid) (PLA) were investigated. Although both materials improved the compressive properties of the fumarate-based polyHIPE prints, the PLA shell was substantially better with a resulting compressive modulus of ~100 and compressive yield strength of ~10 MPa, **Figure 3**. [7] The combination of paste extrusion of these emulsion inks with traditional thermoplastic extrusion printing has generated scaffolds with superior mechanical properties while retaining high permeability and surface area that will significantly increase their potential as tissue engineered scaffolds for bone defects.

Overall, these studies highlight the potential of a new class of emulsion inks for 3D printing of tissue grafts and

Emulsion Inks ... continues on pg. 9

2016 Surface Science Award Winner

The Surfaces in Biomaterials Foundation annually selects an individual who has made significant contributions to the biomaterials field. It is the highest award given by the Foundation. The first award was presented in 1991 to Buddy Ratner, University of Washington. The award is presented at the Biointerface Conference.

This 2016 Excellence in Surface Science Award Winner is Antonio G. Mikos.

Antonio G. Mikos is the Louis Calder Professor of Bioengineering and Chemical and Biomolecular Engineering at Rice University. His research focuses on the synthesis, processing, and evaluation of new biomaterials for use as scaffolds for tissue engineering, as carriers for controlled drug delivery, and as non-viral vectors for gene therapy. His work has led to the development of novel orthopedic, dental, cardiovascular, neurologic, and ophthalmologic biomaterials.

Mikos is a Member of the National Academy of Engineering, the National Academy of Medicine, and the Academy of Medicine, Engineering, and Science of Texas. He is a Fellow of the American Associate for the Advancement of Science, the American Institute of Chemical Engineers, the American Institute for Medical and Biological Engineering, the Biomedical Engineering Society, the Controlled Release Society, the International Union of Societies for Biomaterials Science and Engineering, the Tissue Engineering and Regenerative Medicine International Society, and the National Academy of Inventors.

He has been recognized by various awards including the Lifetime Achievement Award of the Tissue Engineering and Regenerative Medicine International Society-Americas, the Founders Award of the Society for Biomaterials, and the Robert A. Pritzker Distinguished Lecturer Award of the Biomedical Engineering Society.

SIBF Surface Science Award Winners

- Antonios G. Mikos, Rice University, 2016
- Gail Naughton, Histogen Aesthetics, LLC, 2015
- Tom Fogarty, Stanford University and the Thomas Fogarty Institute for Innovation, 2014
- David Grainger, University of Utah, 2013
- Marcus Textor, ETH Zürich, 2012
- Nicholas A Peppas, University of Texas, 2011
- David F. Williams, Wake Forest Institute of Regenerative Medicine, 2010
- Gabor Somorjai, University of California, Berkeley, 2009
- Ken Stokes, Medtronic, 2008
- Alfred Mann, Alfred Mann Foundation, 2007
- Bob Ward, Polymer Technology Group - 2006
- Jack Bokros, Medical Carbon Research Institute - 2005
- Julio Palmaz, University of Texas Health Science Center - 2004
- Dave Castner, University of Washington - 2003
- Bill Costerton, Montana St. University - 2002
- Stu Williams, University of Arizona - 2001
- Jim Anderson, Case Western Reserve University - 2000
- George Whitesides, Harvard University - 1999
- Richard Van Dyne - Northwestern University - 1996
- Buddy Ratner, University of Washington - 1991

(No award was presented in 1992, 1993, 1994, 1995, 1997 or 1998)

Notice: SurFACTS is seeking a *Medical Device Editor candidate.*
Please send nominations to ingrid@impactvs.com.

Emulsion Inks ... continued from pg. 7

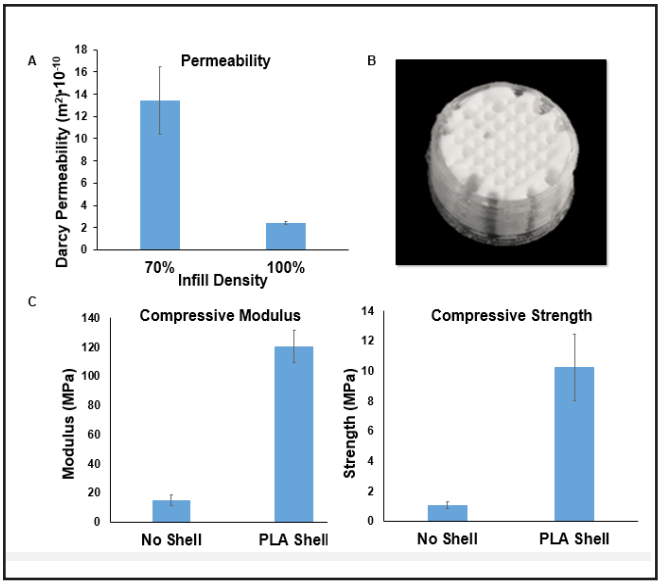

Figure 3: Effect of infill density on the permeability of the printed construct (A). Image of printed construct with HIPE emulsion ink reinforced with a PLA cortical shell (B) and resulting effect of cortical shell on compressive modulus and yield strength of constructs printed at 70 % infill (C).

the benefit of multi-modal printing to further improve the properties of the resulting grafts. Current efforts in this area have extended these applications to soft tissue regeneration with the development of hydrocolloid inks. The development of these inks and the corresponding printing adaptations has created a biomaterial platform with tremendous promise for the fabrication of a myriad of complex tissue engineered scaffolds.

References

1. ***Moglia, R.S., et al., Injectable PolyHIPEs as High-Porosity Bone Grafts. Biomacromolecules, 2011. 12(10): p. 3621-3628.***
2. ***Moglia, R.S., et al., Injectable Polymerized High Internal Phase Emulsions with Rapid in Situ Curing. Biomacromolecules, 2014. 15(8): p. 2870-2878.***
3. ***Robinson, J.L., et al., Achieving Interconnected Pore Architecture in Injectable PolyHIPEs for Bone Tissue Engineering. Tissue Engineering Part A, 2014. 20(5-6): p. 1103-1112.***
4. ***Sears, N.A., P.S. Dhavalikar, and E.M. Cosgriff-Hernandez, Emulsion Inks for 3D Printing of High Porosity Materials. Macromolecular Rapid Communications, 2016. 37(16): p. 1369-1374.***
5. ***Sears, N.A., et al., A Review of Three-Dimensional Printing in Tissue Engineering. Tissue Engineering Part B-Reviews, 2016. 22(4): p. 298-310.***
6. ***O'Brien, F.J., et al., The effect of pore size on cell adhesion in collagen-GAG scaffolds. Biomaterials, 2005. 26(4): p. 433-441.***
7. ***Sears, N., et al., Fabrication of Biomimetic Bone Grafts with Multi-Material 3D Printing. Submitted to Biofabrication.***

SurFACTS in Biomaterials is the official publication of the foundation and is dedicated to serving industrial engineers, research scientists, and academicians working in the field of biomaterials, biomedical devices, or diagnostic research.

Thank You to Our Members!

New members are always welcome to join.

BioInteractions
Advancing Healthcare Through Innovation™

BAUSCH + LOMB

Medtronic

EAG LABORATORIES | WE KNOW HOW™

APS
AMERICAN PRECLINICAL SERVICES

GORE
Carmeda

DSM

PHYSICAL ELECTRONICS
A DIVISION OF ULVAC-PHI

ESS
Experimental Surgical Services
UNIVERSITY OF MINNESOTA
Driven to Discover℠

Boston Scientific

Colorado State University

SurModics

GORE
Creative Technologies Worldwide

AST PRODUCTS, INC

Surface Solutions Laboratories™

INTERFACE BIOLOGICS

PROVISION KINETICS

Abbott

ExThera Medical

ASPEN RESEARCH

Pace Analytical®