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**DEVELOPMENT OF MORE EFFICACIOUS Tc-99m ORGAN IMAGING AGENTS
FOR USE IN NUCLEAR MEDICINE BY CHARACTERIZATION OF
RADIOPHARMACEUTICALS**

Final Report

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William R. Heineman

Carl J. Seliskar

Department of Chemistry

University of Cincinnati

P.O. Box 210172

Cincinnati, OH 45221-0172

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I. Goals

The primary goals of the project during this funding period were twofold:

- (1) Development of a microsensor that would demonstrate the capability for *in vivo* monitoring of a radiopharmaceutical after its injection into a test animal.
- (2) Exploration of capillary electrophoresis (CE) as a separation technique for the analysis of radiopharmaceuticals that are mixtures of different compounds.

The combination of *in vivo* sensors for real-time monitoring of specific chemical states of a radiopharmaceutical in individual organs and CE for analysis of radiopharmaceuticals prior to injection would provide valuable information regarding the fate of an imaging agent after administration. Such information should give insight into strategies for the development of more efficacious radiopharmaceuticals.

II. Summary of Technical Results

A. Sensors for *In Vivo* Monitoring of Radiopharmaceuticals

Model Compound. $[\text{Re}^{\text{I}}(\text{DMPE})_3]^+$, where DMPE is 1,2-bis(dimethylphosphino)ethane, was chosen as the model compound for the development of the microsensor because it exhibits uptake in the heart, possesses appropriate electrochemical and optical properties with respect to sensor requirements, and can be obtained in nonradioactive form to facilitate experimentation. Both electrochemical and optical sensors for this imaging agent were initially pursued because it was not apparent at the beginning of the project which sensor type would be best.

As a prelude to sensor development, the electrochemical and spectroscopic properties of $[\text{Re}^{\text{I}}(\text{DMPE})_3]^+$ and other candidate model compounds were examined in aqueous solutions. Cyclic voltammograms at gold, platinum, and glassy carbon electrodes showed a well defined, 1-electron, reversible voltammogram for the $[\text{Re}^{\text{I}}(\text{DMPE})_3]^+ / [\text{Re}^{\text{II}}(\text{DMPE})_3]^{2+}$ redox couple that provided the basis for an electrochemical sensor. Examination of the spectroscopic properties of $[\text{Re}^{\text{I}}(\text{DMPE})_3]^+$ showed an absorbance wave at 530 nm that could be the basis for an absorbance-based optical sensor. No fluorescence was observed. Thus, $[\text{Re}^{\text{I}}(\text{DMPE})_3]^+$ served as the model compound for development of both an electrochemical and optical sensors.

Polymer Coatings. The main difficulty in developing a sensor for *in vivo* monitoring is achieving the selectivity to detect $[\text{Re}^{\text{I}}(\text{DMPE})_3]^+$ at the required concentration level in the presence of other electroactive or light absorbing species that exist in organs and tissues. Both detection limit and selectivity can be improved by taking advantage of the positive charge and the lipophilicity of $[\text{Re}^{\text{I}}(\text{DMPE})_3]^+$. The sensor surface can be modified with a thin film of polymeric membrane into which $[\text{Re}^{\text{I}}(\text{DMPE})_3]^+$ preferentially extracts from the aqueous environment of the organ tissue, thereby preconcentrating it at the sensor surface for detection. The polymer can also act as a barrier to certain interferents. Numerous polymers were evaluated in conjunction with $[\text{Re}^{\text{I}}(\text{DMPE})_3]^+$. The polymer with the best characteristics was found to be the sulfonated fluorocarbon polymer Nafion, which is a cation exchange polymer, and Nafion gel which is prepared by mixing Nafion with tri-*n*-butyl phosphate. Both electrochemical and spectroscopic experiments showed strong partitioning of $[\text{Re}^{\text{I}}(\text{DMPE})_3]^+$ into films of these two materials.

Electrochemical Sensor. The electrochemical sensor was planned to be a carbon fiber microelectrode coated with a thin film of Nafion or Nafion gel. Concentration studies were performed to evaluate the ability to detect $[\text{Re}^{\text{I}}(\text{DMPE})_3]^+$ within the concentration range anticipated in vivo, namely 10^{-7} to 10^{-9} M. The detection limits at Nafion-modified electrodes and Nafion gel-modified electrodes were 10^{-9} M and 10^{-8} M, respectively. Thus, sensors with adequate sensitivity for in vivo monitoring by electrochemistry could be made. Selectivity against a number of compounds that are present in heart tissue that are electroactive in approximately the same potential range as $[\text{Re}^{\text{I}}(\text{DMPE})_3]^+$ was found to be adequate. We then demonstrated that a Nafion gel modified microelectrode sensor constructed from a 32 μm carbon fiber can detect $[\text{Re}(\text{DMPE})_3]^+$ in vivo. Substantial electrochemical signals for $[\text{Re}(\text{DMPE})_3]^+$ were obtained at sensors inserted both in excised organs (heart, lung, muscle, kidney, and liver) and blood and in the beating heart of test rats following intravenous injection.

These experiments demonstrated that sensors of this type provide a new analytical tool for studying electroactive radiopharmaceuticals. The possibility now exists to monitor in vivo an imaging agent in real time as it distributes into different organs after its injection. Simultaneous monitoring in different organs could be accomplished by using an array of microsensors.

Fiber Optic Sensor. The fiber optic absorbance sensor which was designed and developed had these main features: (1) the incorporation of a chromatically-tuned fiber/GRIN lens couple for efficient light coupling within the sample cavity; (2) an analyte optical cavity with preconcentration polymer which can be fixed at a variety of long pathlengths; (3) an end mirror of a diameter no larger than the GRIN lens; and, (4) a rigid perforated outer jacket in which all the sensor optics are assembled and held in a fixed concentric linear arrangement. Evaluations of sensors showed that the current usable lower limit of such sensors is as low as 0.001 absorbance units. The diameter of the sensor is scalable to small sizes and a 500 μm sensor was developed. However, midway into the project, it became apparent that much smaller electrochemical sensors with better detection limits that were easier to construct could be fabricated. Consequently, work on the spectroscopic approach was discontinued and all effort was concentrated on the electrochemical sensor.

B. Capillary Electrophoresis as Applied to Nuclear Medicine

Capillary electrophoresis (CE), a relatively new technique in the field of separation science, has the potential to be a valuable separation technique for the characterization and development of improved radiopharmaceuticals, some of which are complicated mixtures, and in the detection of metabolites in biological samples. This capability was demonstrated with the separation of diphosphonate skeletal imaging agents using Re-HEDP, where HEDP = hydroxyethylidene diphosphonate, as a model system. These radiopharmaceuticals are complicated mixtures of Re-HEDP complexes and excess reducing agent and antioxidant. The effects of buffer pH, additives such as cyclodextrins and excess HEDP, and gels on the quality of the separation were studied. Proton induced X-ray emission was used as a detection technique to determine which eluting peaks contained Re.

III. Publications Resulting From This Project

(Reprints are appended) —

Reprints removed for separate processing

Chemical Sensors for Radiopharmaceuticals, W. R. Heineman, B. H. Swaile, E. A. Blubaugh, D. A. Landis, C. J. Seliskar and E. Deutsch. *Radiochim Acta*, **63**, 199-203 (1993).

Fiber Optic GRIN Lens Absorbance Sensor with Wavelength Scanning Capability, D. A. Landis, C. J. Seliskar and W. R. Heineman. *Appl. Optics* **33**, 3432-3439 (1994). (Note: This paper resulted in our design being featured on the cover of a special issue of *Applied Optics* devoted to graded index optics.)

A Miniature Fiber Optic Absorbance Sensor for 99m-Tc Imaging Agents. D. A. Landis, M. L. Jeng, B. H. Swaile, E. A. Blubaugh, C. J. Seliskar, W. R. Heineman and E. A. Deutsch. *Proc. Second World Congress on Biosensors*, Elsevier, Oxford, pp. 484-491 (1992).

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Sensitive Absorbance Measurements of 99m-Tc Imaging Agents Using a New Fiber Optic Sensor, D. A. Landis, C. J. Seliskar, W. R. Heineman and E. A. Deutsch. *Soc. Photo-opt. Instrum. Eng.* **2136**, 335-343 (1994).

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Thiolato-technetium Complexes. Part 6. Synthesis, Characterization, Electrochemical Properties and Crystal Structure of [Tc(tdt)(dmpe)₂]PF₆ [tdt=3,4-toluenedithiolate, dmpe=1,2-*bis*(dimethylphosphino)ethane], T. Konno, J. R. Kirchhoff, M. J. Heeg, W. R. Heineman and E. Deutsch. *J Chem Soc Dalton Trans*, **1992**, 3069-3075 (1992).

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Preparation, Characterization, Electrochemical Properties and Single-Crystal Structural Analysis of $[\text{Tc}(\text{SCP})_2(\text{DMPE})_2](\text{PF}_6)_3$, Where SCP is the Zwitter-Ionic Ligand - $\text{SCH}_2\text{P}^+(\text{CH}_3)_2(\text{CH}_2)_2\text{P}(\text{S})(\text{CH}_3)_2$ and DMPE is 1,2-bis(Dimethylphosphino)ethane, K. I. Okamoto, J. R. Kirchhoff, W. R. Heineman and E. Deutsch. *Polyhedron*, **12**, 749-757 (1993).

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Electrochemical Behavior of $[\text{Re}(\text{DMPE})_3]^+$, Where DMPE = 1,2Bis(dimethylphosphino)ethane, at Perfluorosulfonated Ionomer-Modified Electrodes, Y. Deng, C. J. Seliskar, W. R. Heineman. *Anal. Chem.*, **69**, 4045-4050 (1997).

Optically Transparent Polyelectrolyte-Silica Composite Materials: Preparation, Characterization and Applications in Optical Chemical Sensing, Y. Shi, C. J. Seliskar. *Chem. Materials*, **9**, 821-829 (1997).

Spectroscopic and Electrochemical Evaluation of Nafion and Nafion Gel as Preconcentrating Medium for $[\text{Re}(\text{DMPE})_3]^+$ where DMPE = 1,2-bis(dimethylphosphino)ethane, B. H. Swaile, E. A. Blubaugh, C. J. Seliskar, W. R. Heineman. Accepted *Anal. Chem.*, 1998.

Evaluation of the Electrochemical Characteristics of a Poly(vinyl alcohol)/poly(acrylic acid) Polymer Blend, C. O. Dasenbrock, T. H. Ridgway, C. J. Seliskar, W. R. Heineman. Accepted *Electrochim. Acta*, 1998.

IV. Papers Presented at Conferences

A Miniature Fiber Optic Absorbance Sensor for Tc-99m Imaging Agents, Biosensors '92, May 20-22, 1992, Geneva, Switzerland. M. L. Jeng, E. Blubaugh, W. R. Heineman, C. J. Seliskar and E. A. Deutsch.

Electrochemical and Spectroscopic Evaluation of Nafion Polymer as a Preconcentrating Medium for Radiopharmaceutical Imaging Agents Using $\text{Re}(\text{DMPE})_3\text{CF}_3\text{SO}_3$ as a Non-Radioactive Model, Pittcon 93, Atlanta, GA, March 8-11, 1993. B. H. Swaile, E. A. Blubaugh, C. J. Seliskar and W. R. Heineman.

Chemical Sensors for Radiopharmaceutical Imaging Agents, Topical Symposium on the Behavior and Utilization of Technetium 93, March 18-20, 1993, Sendai, Japan. W. R. Heineman, B. H. Swaile, E. A. Blubaugh, D. A. Landis, C. J. Seliskar and E. Deutsch.

Electrochemical Sensors for Radiopharmaceutical Imaging Agents: Nafion Gel Modified Electrodes. Symposium on Chemical Sensors, 183rd Meeting of the Electrochemical Society, Honolulu, Hawaii, May 16-21, 1993. W. R. Heineman, B. H. Swaile, E. A. Blubaugh and C. J. Seliskar.

Electrochemical Sensors for Imaging Agents in Nuclear Medicine, Thirty-second Annual Eastern Analytical Symposium, Sommerset, NJ, Nov. 15-19, 1993. W. R. Heineman, B. H. Swaile, E. A. Blubaugh, Y. Deng, B. L. Ramos, C. J. Seliskar and E. A. Deutsch.

A Fiber Optic Absorbance Sensor for 99m-Tc Imaging Agents, 20th Annual Meeting of the Federation of Analytical Chemistry and Spectroscopy Societies, Detroit, MI, October 17-22, 1993. C. J. Seliskar, D. A. Landis and W. R. Heineman.

Electrochemical Sensors for Radiopharmaceutical Imaging Agents: Electrochemical Behavior of $\text{Re}(\text{DMPE})_3\text{CF}_3\text{SO}_3$ at Bare and Nafion Coated Electrodes, 20th Annual Meeting of the Federation of Analytical Chemistry and Spectroscopy Societies, Detroit, MI, October 17-22, 1993. Y. Deng, W. R. Heineman and C. J. Seliskar.

Simulation of Fiber Optic-GRIN Lens Couples for Use in Chemical Spectroscopy, 20th Annual Meeting of the Federation of Analytical Chemistry and Spectroscopy Societies, Detroit, MI, October 17-22, 1993. D. A. Landis and C. J. Seliskar.

A New Small—Diameter Fiber Optic Absorbance Sensor. 20th Annual Meeting of the Federation of Analytical Chemistry and Spectroscopy Societies, Detroit, MI, October 17-22, 1993. D. A. Landis and C. J. Seliskar.

Sensitive Absorbance Measurements of 99m-Tc Imaging Agents Using a New Fiber Optic Sensor, OE/LASE '94, Biomedical Optics Symposium, Los Angeles, CA, Jan 22-29, 1994. D. A. Landis, W. R. Heineman, C. J. Seliskar and E. A. Deutsch.

New Small Diameter Fiber Optic Absorbance Sensor for Continuous Spectral Scanning, OE/LASE '94, Biomedical Optics Symposium, Los Angeles, CA, Jan 22-29, 1994. D. A. Landis and C. J. Seliskar.

Catheter-sized Fiber Optic Absorbance Sensor with Compact Instrumentation, OE/LASE '95, Biomedical Optics Symposium, San Jose, CA, Feb 4-10, 1995. D. A. Landis and C. J. Seliskar.

Gamma Irradiation Induced Grafting of Polymer Films to PTFE Shielded Microelectrodes, B. L. Ramos, E. A. Blubaugh, W. R. Heineman, Pittcon '93, Atlanta, GA, March 8-11, 1993.

Electrochemical Sensors for Radiopharmaceutical Imaging Agents: Nafion Gel Modified Electrodes, W. R. Heineman, B. H. Swaile, E. A. Blubaugh and C. J. Seliskar, Symposium on Chemical Sensors, 183rd Meeting of the Electrochemical Society, Honolulu, Hawaii, May 16-21, 1993.

Gamma Irradiation Induced Grafting of Polymer Films to PTFE Shielded Microelectrodes, B. L. Ramos, E. A. Blubaugh and W. R. Heineman, 1993 International Electroanalytical Symposium, Indianapolis, IN, May, 1993.

Evaluation of Nafion Modified Carbon Microelectrodes as Sensors for Radiopharmaceutical Imaging Agents, B. H. Swaile, E. A. Blubaugh, W. R. Heineman, Pittcon '94, Chicago, IL, February 27-March 4, 1994.

Development of Electrochemical Sensors for Characterization and Determination of Radiopharmaceuticals, Y. Deng, G. Reeder, W. R. Heineman, C. J. Seliskar, Pittcon '94, Chicago, IL, February 27-March 4, 1994.

Polymer Modified Microelectrode as a Sensor for Analogs of TC-Based Radiopharmaceuticals, B. L. Ramos, E. A. Blubaugh, A. J. Horn, W. R. Heineman, Pittcon '94, Chicago, IL, February 27-March 4, 1994.

Investigations of Re-analogues of ^{99m}Tc -Bone Imaging Agents by Capillary Electrophoresis, E. Rohde, W. R. Heineman, J. G. Dorsey, Frederick Conference on Capillary Electrophoresis, October 25-26, 1994.

Investigations of Re-analogues of ^{99m}Tc -Bone Imaging Agents by Capillary Electrophoresis. E. Rohde*, W. R. Heineman, J. G. Dorsey, Frederick Conference on Capillary Electrophoresis, October 25-26, 1994.

Investigations of Re-analogues of ^{99m}Tc -Bone Imaging Agents by Capillary Electrophoresis. E. Rohde*, W. R. Heineman, J. G. Dorsey, Pittcon '95, New Orleans, LA, March 5-10, 1995.

Development of a Nafion Gel-Based Modified Electrode for Detection of Hydrophobic Cations. M. Lee*, E. A. Blubaugh, W. R. Heineman, Pittcon '95, New Orleans, LA, March 5-10, 1995.

Development of a Nafion Modified Electrochemical Sensor for in Vivo Radiopharmaceutical Monitoring. B. H. Swaile*, W. R. Heineman, Pittcon '95, New Orleans, LA, March 5-10, 1995.

Studies of Composite Ion Exchange Membranes Formed from Gamma Radiation Initiated Grafting of Polymers to Modified Expanded Teflon Membranes. E. A. Blubaugh*, B. L. Ramos, W. R. Heineman, Pittcon '95, New Orleans, LA, March 5-10, 1995.

Polymer Modified Electrodes Based on Nafion Gels with Different Tri-Alkyl Phosphate Plasticizers: An Electrochemical Characterization of Several Large Hydrophobic Cations of Environmental Interest. E. A. Blubaugh*, L. R. Shao, B. H. Swaile, M. T. Lee, W. R. Heineman, Pittcon '95, New Orleans, LA, March 5-10, 1995.

Polymer Membranes for Improving Selectivity and Sensitivity of Biosensors. W. R. Heineman, International Conference on Biofunctional Membranes, University of Kentucky, Lexington, KY, April 9-11, 1995. Invited lecture.

Development of a Nafion-modified Microelectrode for in vivo Sensing of Re-based Imaging Agents, M. T. Lee*, C. J. Seliskar, W. H. Heineman, Chicago ACS Meeting, Chicago, IL, August 20-24, 1995. Poster session.

Electrochemical Sensors: Strategies for Improving Selectivity and Sensitivity, W. R. Heineman, International Society of Electrochemistry 46th Annual Meeting, Xiamen, China, August 27-September 1, 1995, Invited keynote lecture.

Characterization of Re- and Tc-Based Radiopharmaceuticals by Capillary Electrophoresis, E. Rohde*, W. R. Heineman, J. G. Dorsey, The 22nd Annual Conference of the Federation of Analytical Chemistry and Spectroscopy Societies (FACSS), Cincinnati, OH, October 15-20, 1995.

Development of a Polymer Modified Microelectrode for *In Vivo* Sensing of Re-Based Imaging Agents, M. T. Lee*, C. J. Seliskar, T. McGoron, W. R. Heineman, The 22nd Annual Conference of the Federation of Analytical Chemistry and Spectroscopy Societies (FACSS), Cincinnati, OH, October 15-20, 1995. Poster session.

Investigation of Electrochemical Properties of a Poly(Vinyl Alcohol)Poly(Acrylic Acid) Polymer Blend, C. O. DeSantis*, C. J. Seliskar, W. R. Heineman, The 22nd Annual Conference of the Federation of Analytical Chemistry and Spectroscopy Societies (FACSS), Cincinnati, OH, October 15-20, 1995. Poster session.

Studies of Composite Ion Exchange Membranes Formed from Gamma Radiation Initiated Grafting of Polymers to Expanded Teflon Membrane, E. A. Blubaugh*, B. L. Ramos, W. R. Heineman, The 22nd Annual Conference of the Federation of Analytical Chemistry and Spectroscopy Societies (FACSS), Cincinnati, OH, October 15-20, 1995.

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Investigation of Nafion Modified Microelectrodes as in vivo Sensors for Re-based Imaging Agents, American Chemical Society Meeting, Chicago, IL, June 21-25, 1995. With M. T. Lee, W. R. Heineman and T. McGoron.

New Smart Optical Materials for Chemical Sensors, FACSS XXII Meeting, Cincinnati, OH, October 15-20, 1995. With L. Gao, C. DeSantis, S. Milstein, S. Lindberg and W. R. Heineman.

Investigation of Nafion-modified Microelectrodes as in vivo Sensors for Re-based Imaging Agents, M. T. Lee*, W. R. Heineman, T. McGoron, C. J. Seliskar, 1995 International Chemical Congress of Pacific Basin Societies (Pacifichem), Honolulu, HI, December 17-22, 1995. Poster session.

Investigations of Different Radiopharmaceuticals by Capillary Electrophoresis. E. Rohde*, W. R. Heineman, Pittcon '96, Chicago, IL, March 3-8, 1996. Poster session.

Microelectrode Sensor for In Vivo Measurement of Heart Imaging Agents. W. R. Heineman*, C. J. Seliskar, M. T. Lee, A. J. McGoron, B. H. Swaile, Y. Deng, Pittcon '96, Chicago, IL, March 3-8, 1996.

Development of Nafion Modified Microelectrodes for In Vivo Sensing of Re-Based Imaging Agents. M. R. Lee*, T. McGoron, C. J. Seliskar, W. R. Heineman, Pittcon '96, Chicago, IL, March 3-8, 1996.

Investigation of Electrochemical Properties of a Poly(Vinyl Alcohol)Poly(Acrylic Acid) Polymer Blend. C. O. Dasenbrock*, C. J. Seliskar, T. H. Ridgway, W. R. Heineman, Pittcon '96, Chicago, IL, March 3-8, 1996.

Detection of Lipophilic Cationic Tracers with Microelectrode Sensors. A. J. McGoron*, M. T. Lee, W. R. Heineman, C. J. Seliskar, Proceedings of the 43rd Annual Meeting, SNM, Reston, VA, June 1996. Poster session.

Effects of Stability and Lipophilicity on Brain Extraction and Retention of 99m-Tc-PAO Complexes, 11th International Symposium on Radiopharmaceutical Chemistry, Vancouver, BC, Canada, 1995. With C. Cutler, Z. Jiang, B. Chen, L. Shao, YP Ding, WR Heineman, T. Maina, F. Tisato and E. Deutsch.

New Transparent Polymer Blends for Optical Sensors, 28th ACS Central Regional Meeting, Dayton, OH, June 9-12, 1996. With L. Gao.

Novel Hybrid Ion-Exchangeable Sol-Gel Materials: Preparation, Characterization and Optical Chemical Sensing Applications, 28th ACS Central Regional Meeting, Dayton, OH, June 9-12, 1996. With Y. Shi.

Electrochemical Sensors for *In Vivo* Monitoring, ACS Spring National Meeting, San Francisco, April 13-17 (1997). With W. R. Heineman, M. T. B. Lee, and A. J. McGoron.

Sensors for Bioanalysis. W. R. Heineman, Gordon Research Conference on Chemical Sensors and Interfacial Design, New London, NH, July 28-August 1, 1996.

Electrochemical Biosensors. W.R. Heineman, 213th ACS National Meeting, San Francisco, CA, April 13-17, 1997 in Symposium on Biosensing and Biosensors: Chemistry, Recognition, and Process Control. Plenary Session II: Topical Reviews.

Microelectrode Sensors for In Vivo Detection of Radiopharmaceuticals. W. R. Heineman*, M. T. Lee-Alvarez, A. J. McGoron, C. J. Seliskar, 191st Electrochemical Society Meeting, May 4-9, 1997, in the Symposium on Immuno and Bio-Sensors, Montreal, Quebec, Canada.

Electrochemical Behavior of Re-DMPE Complex on Polymer-Modified Electrodes, Z. Hu*, W. R. Heineman, C. J. Seliskar, at the 37th ORNL-DOE Conference on Analytical Chemistry in Energy Technology, Gatlinburg, TN, Oct. 7-9, 1997. Poster session.

Electrochemical Sensors: Strategies for Improving Selectivity and Sensitivity, W. R. Heineman*, The Seventh National Symposium on Chemical Sensors, China, October 16-19, 1997. Plenary lecture.

IV. Postdoctoral Assistants, Visiting Scholars, and Students Supported

Postdoctoral Assistants/Visiting Scholars

Dr. Elmo Blubaugh (visiting scholar), Dr. Yingping Deng (postdoctoral assistant), Dr. Hendrik Emons (visiting scholar with Feodor-Lynen Fellowship from Germany, University of Leipzig), Dr. Tafeedah Jarbawi (visiting scholar with Fulbright Fellowship,

Birzeit University), Gunther Wittstock (Visiting Scholar with Humboldt Fellowship from Germany, University of Leipzig), Carla Vogt (visiting scholar with support from University of Leipzig), Hiroki Ohura (visiting scholar with support from Kyushu Sangyo University, Japan).

Graduate Students

Jane Johnson (Ph.D. 1994), Lisa Hayes (M.S. 1992), Brigitte Ramos (Ph.D. 1994), Alicia Wilson (Ph.D. 1996), Ellen Rohde (Ph.D. 1996), Robert Rigney (Ph.D. student), Gregory Reeder (Ph.D. 1996), Dean Peterman (Ph.D.), David Landis (Ph.D. 1994), Cathy Dasenbrock (Ph.D. 1996), Letian Gao (Ph.D. 1998), Zhongmin Hu (Ph.D. 1998), Maria T. Lee (Ph.D. 1998), Hong Shen (Ph.D. 1997), Yining Shi (Ph.D. 1998), Sam Gratz (Ph.D. Student), Wes Johnson (Ph.D. 1997), A. Slaterbeck (Ph.D. 1998).

Undergraduate Students

Angela Horn (B.S. 1993), Mark Nighman (B.S. 1994), Andrew McDonald (B.S. 1994), Seth Lindberg (B.S. 1995), Lisa Milstein (B.S. 1995)