

SGP Council 2009-2010

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Graham Ellis-Davies
Mt. Sinai School of Medicine

Meeting Site Information

Registration: Meeting registration takes place on the first floor of the Swope Center from 2:00 to 10:00 p.m. on Wednesday, September 8; and from 8:00 a.m. to noon on Thursday, September 9. Check-in is at the main desk in Swope Lobby (opposite the door) and your registration packets are at the first table on your left. If you arrive during the night, instructions are posted at Swope Center on how to contact the watchman who will have your room key.

Mail/Messages/Faxes: Private phones are available in nearly all guest rooms. Messages can be left at 508-548-3705 24 hours a day and are available for pickup at the front desk of Swope Center (phones in rooms do not have voice mail). Packages and mail should be addressed to **your name**, *Society of General Physiologists, Marine Biological Laboratory, 7 MBL Street, Woods Hole, MA 02543-1015*. There is a fax machine in the Copy Center of the MBL Library on the second floor of the Lillie Building. It is available weekdays only, 8:00 a.m. to 5:00 p.m. The fax number is 508-540-6902 and there is a user's fee; payment must be made *in cash at the time of sending or retrieving*. Please be sure that all incoming correspondence is addressed to your name, SOCIETY OF GENERAL PHYSIOLOGISTS, care of MBL, etc.

Library Usage: The MBL Library has a world-renowned collection, and visitors are welcome at all times. The Library is staffed Monday through Friday, 8:00 a.m. to 5:00 p.m. After-hours access is provided via your MBL ID card.

Internet Access: MBL has wireless internet service throughout its campus. To use the system simply browse for wireless networks on any wireless enabled device and select "MBL-Guest". Open a web browser and you will be automatically redirected to a login page. Enter the login credentials: user name = mblguest, password = mblguest. In addition, there are 6 terminals from which you can check your email or do a web search in Swope Center. For other computer activity, the Computer Room is located in the MBL Library, Lillie 204.

Poster Instructions: Poster boards are located on the second floor of Swope Center. Posters may be up to 42 inches wide and 5 feet high. Thumbtacks are provided. Poster numbers and titles are listed in the abstracts section of this program.

MBL's Security System: The MBL has a new security system in all buildings. Every participant is issued an MBL ID card (proximity card) at registration. This card, to be kept with you at all times, will provide 24-hour access to the Lillie Library and Swope, the dormitory building. The main change is that many buildings, including the dormitories, have automatically locking doors. Although Swope will be open until 10 p.m., other buildings will always be locked and you will need your proximity card to gain access. If you should have any questions, both MBL and SGP personnel will be available to answer them during the course of the meeting.

Travel Information

Plane: Boston (Logan Airport) has the advantage of regular, direct bus service between Logan and Woods Hole. Boarding for the Peter Pan/Bonanza bus to Woods Hole is just outside the baggage claim area. Providence (T.F. Green Airport) also offers bus service to Woods Hole, but not directly from the airport. Be sure to check bus options online at www.peterpanbus.com/tickets/fares. If you are planning to rent a car, Green is probably the airport of choice. We suggest you don't fly into Hyannis, as local transportation between Hyannis and Woods Hole is not readily available.

Bus: Round-trip bus fare from Logan Airport to Woods Hole is \$55.00; easiest is to purchase online. You can get the current bus schedule (and purchase tickets) from the Peter Pan/Bonanza website at www.peterpanbus.com/tickets/fares. The bus stop in Woods Hole, a 10-minute walk from Swope Center, is in the Steamship Authority parking lot. Walk the 100 yards or so up Luskombe Avenue to Water Street, turn left and cross the drawbridge, continue another several hundred yards and turn right on MBL Street. (Lillie Building will be on your right.) Swope is straight ahead on the Eel Pond.

Car: The meeting site is about a two-hour drive from Boston (a bit less if you're lucky), and an hour and a half from Green Airport in Providence. If you come down Route 3 and cross the Sagamore Bridge, take the first exit and follow signs for Falmouth (you will turn left at the light and follow the canal west). At the Bourne Rotary, go three-quarters of the way around and go south on Route 28. If you come down I-495, continue to the Bourne Bridge and follow Route 28 south to Falmouth. Woods Hole is about 5 miles from Falmouth, and the road is clearly marked by signs to Woods Hole and Martha's Vineyard. On arrival in Woods Hole, cross over the drawbridge and turn right onto MBL Street. Swope Center is straight ahead at the bend in the road.

Parking: If you drive to Woods Hole, remember that *parking is by permit only*. You must obtain a parking permit at the registration desk and **park ONLY at the Bar Neck parking lot**. Directions will be given to you at the registration desk. Do NOT park in any of the other MBL lots or on the street—towing is a local recreation.

64th Annual Meeting and Symposium of the Society of General Physiologists

Marine Biological Laboratory, Woods Hole, Massachusetts

September 8–12, 2010

NEW OPTICAL METHODS IN CELL PHYSIOLOGY

Organized by Graham Ellis-Davies

SCHEDULE OF EVENTS

Wednesday, September 8

2:00 – 10:00 **Registration and Room Assignments (Swope Center, 1st Floor)**

6:00 – 7:30 **Buffet Dinner (Swope Center, Meigs Room)**

7:30 – 7:45 **Opening Remarks (Lillie Auditorium)**
 Gary Borisy, Director (Marine Biological Laboratory)
 Kenton Swartz, President (Society of General Physiologists)
 Graham Ellis-Davies, Organizer

Session I KEYNOTE ADDRESS

7:45 **Roger Tsien** – HHMI, UC San Diego
 Breeding and building molecules to spy on cells in health and disease

9:00 – 11:00 **Mixer (Swope Center, Meigs Room)**

Thursday, September 9

- 7:15 – 8:45 **Breakfast**
- 8:45 – 12:00** **Session II NEW MICROSCOPES: Minski never dreamt of this**
- 8:45 – 9:30 **Oliver Griesbeck** – MPI Neurobiology, Munich
Biophysics and biocompatibility of troponin C-based calcium indicator
- 9:30 – 10:15 **Fritjof Helmchen** – University of Zurich
Extending two-photon calcium imaging of neuronal activity to short and long time scales
- 10:15 – 10:45 **Break**
- 10:45 – 11:10 **Short talk 1 – Na Ji** – HHMI, Janelia Farm Research Campus
Adaptive optics for high-resolution imaging in brains
- 11:10 – 11:30 **Cranefield awardee Xiaodong Zhang** – UC Davis
Blockade of CLC-0 pore-open mutants by amphiphilic blockers
- 11:30 – 11:50 **Cranefield awardee Jill Jensen** – University of Washington
FRET reveals kinetic steps of a GPCR signaling cascade in living cells
- 12:00 – 1:30 **Lunch**
- 2:00 – 5:00 **Poster Session 1**
Posters may be displayed after 8:00 a.m. on Thursday, and may stay up until Saturday evening
- 1:30 – 3:30 **Authors at Posters** for discussion with attendees and judging for the poster competition (for those who applied to compete)
- 1:45 – 2:15 **SGP Annual Business Meeting**
- 5:30 – 7:00 **Dinner**
- 7:00 – 8:55** **Session III IN VIVO IMAGING: Cajal dreamt of this**
- 7:00 – 7:45 **Josh Sanes** – Harvard
Visualizing circuits in the visual system
- 7:45 – 8:30 **Brian Bacskai** – Harvard/MGH
A window into the Alzheimer brain: In vivo optical imaging of structure and function

8:30 – 8:55 **Short talk 2 – Elizabeth Hillman** – Columbia
Imaging everything: Harnessing endogenous and exogenous contrast in vivo

9:00 – 11:00 **Mixer (Swope Center, Meigs Room)**

Friday, September 10

7:00 – 8:30 **Breakfast (Swope Center, Dining Room)**

8:30 – 12:00 **Session IV PHOTOCHEMICAL ACTUATION: Did Jack know what he started?**

8:30 – 9:15 **Eduardo Rios** – Rush University School of Medicine
Probing excitation-contraction coupling with artificial calcium sparks

9:15 – 10:00 **Gero Miesenbock** – Oxford
Lighting up the brain: Imaging and control of genetically targeted neural circuits

10:00 – 10:30 **Break**

10:30 – 11:15 **Bernardo Sabatini** – HHMI, Harvard
Optical studies of neuromodulatory action in the mammalian brain

11:15 – 12:00 **Ryohei Yasuda** – HHMI, Duke
Imaging signal transduction in single dendritic spines during synaptic plasticity

12:00 – 1:30 **Lunch**

Afternoon free Harbor cruises in local waters

5:15 – 6:45 **Dinner (Swope Center, Dining Room)**

6:45 – 9:00 **Session V PHOTOCHEMICAL ACTUATION: Part Deux.**

6:45 – 7:30 **Ernst Bamberg** – Max Planck Institut Biophysik
Molecular properties and new developments of channelrhodopsins as optogenetic tools

7:30 - 8:15 **Karl Deisseroth** – Stanford
Optogenetics

8:15 – 9:00 **Ehud Isacoff** – Berkeley
Engineering light into glutamate receptors

9:00 – 11:00 **Mixer (Swope Center, Meigs Room)**

Saturday, September 11th

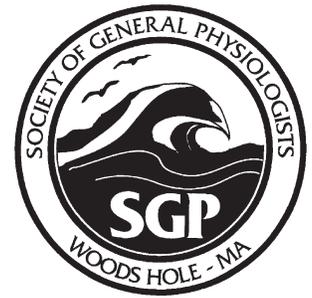
- 7:00 – 8:30 **Breakfast (Swope Center, Dining Room)**
- 8:30 – 11:55 **Session VI: SUPER RESOLUTION IMAGING: Abbe is dead, long live acronyms**
- 8:30 – 9:20 **Stefan Hell** – MPI Gottingen
Nanoscopy with focused light
- 9:20 – 10:10 **Xiaowei Zhuang** – HHMI, Harvard
Super-resolution imaging with STORM
- 10:10 – 10:40 **Break**
- 10:40 – 11:30 **Yale Goldman** – University of Pennsylvania
Single molecule imaging methods for molecular motor and protein synthesis research
- 11:30 – 11:55 **Short Talk 3 Liang Gao** – HHMI, Janelia Farm Research Campus
Bessel beam plane illumination microscopy
- 12:00 – 1:30 **Lunch**
- 2:00 – 5:00 **Poster Session II**
- 5:00 – 6:00 **KEYNOTE 2: (N.B.: this will be held in the Meigs Room, mixer to follow)**
Karel Svoboda – HHMI, Janelia Farm Research Campus
Optical dissection of the cortical circuits underlying somatosensation
- 7:00 – 8:30 **Clambake & Awards Ceremony (Swope Center, Dining Room)**
- 8:30 – 10:30 **Mixer (Swope Center, Meigs Room)**

Sunday, September 12th

- 7:00 – 8:30 **Breakfast (Swope Center, Dining Room)**
- 10:00 **Checkout deadline.** Participants may pick up a box lunch after checkout.

ABSTRACTS OF PAPERS AT THE SIXTY-FOURTH
ANNUAL MEETING OF THE SOCIETY
OF GENERAL PHYSIOLOGISTS

New optical methods in cell physiology



Marine Biological Laboratory
Woods Hole, Massachusetts
8–12 September 2010

Organized by
GRAHAM ELLIS-DAVIES

1. Laser-Scanning Intersecting Plane Tomography for High Speed, Translationless 3-D Microscopy. MATTHEW B. BOUCHARD and ELIZABETH M.C. HILLMAN, *Laboratory for Functional Optical Imaging, Department of Biomedical Engineering, Columbia University, New York, NY 10027*

Well-established imaging techniques, such as confocal or multiphoton microscopy, can provide exquisite three-dimensional (3D) images of biological tissues using absorption and fluorescence contrast. However, they acquire data via illumination point scanning, which provides limited 3-D scan rates, increased rates of photobleaching and photodamage, and an inability to perform real-time volumetric imaging of samples in vivo. Several new volumetric optical imaging techniques have been developed to overcome these limitations. Selective plane illumination microscopy (SPIM), ultramicroscopy, objective-coupled planar illumination microscopy, and oblique plane microscopy utilize the concept of light sheet imaging to image fluorescence contrast and can provide diffraction-limited resolution across 3-D volumes (Dodt, H.U., U. Leischner, A. Schierloh, N. Jährling, C.P. Mauch, K. Deininger, J.M. Deussing, M. Eder, W. Ziegglänsberger, and K. Becker. 2007. *Nat. Meth.* 4:331–336; Dunsby, C. 2008. *Opt. Exp.* 16:20306–20316; Holekamp, T.F., D. Turaga, and T.E. Holy. 2008. *Neuron.* 57:661–672; Huisken, J., and D.Y. Stainier. 2009. *Development.* 136:1963–1975). Optical projection tomography (OPT) is a visible light analogue to x-ray computed tomography (CT), which acquires projection images and uses a modified back-projection algorithm to generate 3-D images of absorbing and/or fluorescent contrast (Sharpe, J., U. Ahlgren, P. Perry, B. Hill, A. Ross, J. Hecksher-Sørensen, R. Baldock, and D. Davidson. 2002. *Science.* 296:541–545). OPT and SPIM-type imaging techniques are limited to minimally or nonscattering samples, or larger ex vivo, chemically cleared samples. Additionally, the need for precise sample translation and/or rotation for OPT and SPIM significantly limits their volumetric scan rates. Here, we describe a new imaging technique: laser-scanning intersecting plane tomography (L-SIPT) (Bouchard, M.B., L. Grosberg, S.A. Burgess, and E.M. Hillman. 2010. *OSA Biomed. BTuE7*), which utilizes a non-contact imaging geometry similar to a confocal theta microscope and an off-axis detection geometry to provide high speed volumetric imaging of non- to minimally scattering tissues. The volume swept by L-SIPT can be scaled from micro- to macro-scales through the choice of an appropriate set of lenses. Here, we describe L-SIPT's imaging geometry and image reconstruction procedure, demonstrate how

it can image microscale samples in 3-D and in real time, and show phantom results.

2. Two-Photon Microscopy of Neurovascular Dynamics In Vivo. BRENDA R. CHEN, ADDASON F.H. MCCASLIN, BARBARA L'HEUREUX, MATTHEW B. BOUCHARD, and ELIZABETH M.C. HILLMAN, *Laboratory for Functional Optical Imaging, Department of Biomedical Engineering, Columbia University, New York, NY 10027*

A regulated and localized change in blood flow dynamics accompanies almost all neuronal activity in the brain and is essential for normal brain function. Although this phenomenon, termed neurovascular coupling, forms the basis for commonly used functional brain imaging modalities such as fMRI, the mechanisms underlying the local hemodynamic response to brain activation remain poorly understood and widely debated. The lack of a cohesive model of neurovascular coupling is largely due to the difficulties associated with observing all of the different neuronal and vascular components involved, simultaneously in vivo.

To overcome this hurdle, we are using custom-designed optical imaging techniques, in conjunction with fluorescent dyes, to selectively visualize both vascular dynamics and the activity of major cell types in rodent cortex. Our high-speed multispectral two-photon microscopy system allows us to visualize the cellular activity, morphology, and interconnectivity of cortical neurons, astrocytes, pericytes, and interneurons, as well as blood flow and vasomotion in the vascular network. These can be imaged simultaneously using cell-specific fluorescent protein labeling, active dyes such as calcium-sensitive dyes, intrinsic fluorescence, and intravascular tracers. Supplementing these studies, our wider-field camera-based optical imaging system allows us to take high-speed multispectral images of cortical surface vessels with sufficient resolution to quantify changes in vessel diameters, blood flow, and blood oxygenation across the entire field of view. We are using both of these techniques to explore neurovascular coupling on multiple length scales in an effort to portray a complete picture of the cellular components and processes involved. We will present an overview of our imaging systems as well as our latest imaging results and a demonstration of the quantitative information that can be extracted from them.

3. An In Vivo Covalent TMP-Tag for Cell Imaging. SARAH S. GALLAGHER,¹ ZHIXING CHEN,¹ MICHAEL P. SHEETZ,² and VIRGINIA W. CORNISH,¹ ¹*Department of Chemistry and* ²*Department of Biological Sciences, Columbia University, New York, NY 10027*

Chemical tags for live cell imaging are emerging as viable alternatives to the fluorescent proteins for labeling proteins with small molecule probes. Among reported chemical tags, trimethoprim (TMP)-tag stands out for having sufficient cell permeability and selectivity to allow imaging of intracellular proteins. TMP-tag provides a noncovalent label in which the protein of interest is fused to *Escherichia coli* dihydrofolate reductase (DHFR) and then labeled with a cell-permeable TMP-probe heterodimer. To complement the utility of the noncovalent TMP-tag, we sought to render the TMP-tag covalent for applications such as single-molecule tracking and pulse-chase labeling that would benefit from a more permanent modification. On the basis of the long-standing use of proximity-induced reactivity for irreversible inhibitor design and its more recent application to in vitro chemical biology tools, we designed an eDHFR variant with a unique cysteine residue positioned to react with an acrylamide electrophile installed on the TMP-probe label. In vitro experiments show that the eDHFR:L28C nucleophile reacts rapidly and quantitatively with the TMP-acrylamide-probe. By tuning the distance between the TMP and the acrylamide, the time required for 50% alkylation of eDHFR:L28C was optimized to be 7 min. Most significantly, the balance in reactivity provided by the acrylamide electrophile allows intracellular proteins tagged with eDHFR:L28C to be labeled with a TMP-acrylamide-fluorescein heterotrimer in live cells with minimal background. Thus, proximity-induced reactivity is shown to be sufficiently selective for use in a living cell, suggesting a general approach for the development of orthogonal covalent chemical tags from existing noncovalent ligand-protein pairs. Moreover, the TMP electrophile described here can be used immediately as a covalent chemical tag in live cells, particularly in the field of in vivo cell imaging.

4. The Potential for Molecular Characterization of the Calcium-activated Potassium Channel in the Skate Electroreceptor. WILLIAM T. CLUSIN, *Cardiology Division, Stanford Medical Center, Stanford, CA, 94305*

Existence of distinct calcium-activated potassium channels was first proposed in 1974 based on voltage clamp experiments in the skate electroreceptor epithelium (Clusin, W.T., D.C. Spray, and M.V.L. Bennett. 1974. *Biol. Bull.* 147:472). The luminal surface of the electroreceptor epithelium (ampulla of Lorenzini) was shown to generate a potassium current that did not occur in the absence of calcium entry into the cells. The receptor cells are hair cells with a cilium on the luminal aspect and ribbon synapses on the basal aspect, which modulate the activity of afferent nerve fibers. Recent research has shown that calcium-activated potassium channels, called BK channels, are present at the apex of vertebrate hair cells and concentrated near the cilium.

The BK channel has been cloned and sequenced in many species, and a partial sequence for *Raja erinacea* (617 bases) was recently published (GenBank accession no. FJ25726.1; Rohmann, K.N., D.L. Deitcher, and A.H. Bass. 2009. *Mol. Biol. Evol.* 26:1509–1521). This sequence includes the pore region and also S6.

BK channels are typically activated by both calcium and voltage. The calcium-activated potassium current in skate electroreceptor is unique because it cannot be activated by depolarization alone if calcium entry is blocked. This suggests a defect in the voltage sensor portion of the BK channel in skate electroreceptor, which could be due to a deletion or point mutation. The voltage sensor is normally on S4 of the BK channel. It is not certain if the BK channel nucleic acid sequence in the electroreceptor is identical to the sequence in whole brain, which was used to obtain the published sequence. Calcium-activated potassium channels are known to undergo alternative splicing, and it is possible that the channel in the electroreceptor contains a loss of function mutation in the voltage sensor region, which is not present elsewhere.

It is proposed that sequencing of messenger RNA from the skate electroreceptor epithelium could establish not only the presence of BK channels in the ampulla of Lorenzini, but also the reason for the apparent absence of activation by voltage.

5. Fluorescence Measurements to Examine the Conformational Dynamics of the Na,K-ATPase. ROBERT E. DEMPSKI,¹ STEFAN GEYS,² and ERNST BAMBERG,² ¹*Department of Chemistry and Biochemistry, Worcester Polytechnic Institute, Worcester, MA 01609;* ²*Department of Biophysical Chemistry, Max Planck Institute of Biophysics, 60438 Frankfurt am Main, Germany*

The Na,K-ATPase is a critical protein for cellular homeostasis. It transports three sodium ions for two potassium ions across the plasma membrane and uses the energy from ATP hydrolysis to transport these cations against the concentration gradient. To correlate conformational changes with cation transport, we have combined fluorescence and electrophysiology methods to measure the conformational dynamics of the holoenzyme and to determine distance constraints between subunits of the enzyme. Furthermore, we have expanded these experiments to monitor conformational changes associated with electrogenic partial reactions of the Na,K-ATPase after changes in the concentration of internal sodium or external potassium. To probe the effects of the internal sodium concentration on the sodium branch of the Na,K-ATPase, oocytes were depleted of sodium and then loaded with sodium using the amiloride-sensitive epithelial sodium channel. The potassium branch of the Na,K-ATPase was studied by exposing the oocytes to different potassium concentra-

tions in the presence and absence of internal sodium to obtain information on the apparent affinity for external potassium. Our results provide evidence on the relationship between lowering the internal concentration of sodium and increasing the amount of external potassium. Using fluorescence-based techniques, in combination with functional measurements, these experiments demonstrate that it is possible to examine how external and internal ligands affect the conformational equilibrium of the ion pump on the surface of intact cells and have the potential to be expanded to a wide variety of membrane proteins.

6. Structural Rearrangements of the BK Channel Gating Ring Revealed by Patch Clamp Fluorometry. PABLO MIRANDA,¹ DIANA WESCH,¹ JORGE CONTRERAS,² MIGUEL HOLMGREN,² FRED SIGWORTH,³ and TERESA GIRALDEZ,¹ ¹Unidad de Investigacion, Hospital Universitario Ntra Sra de Candelaria, 38010 Sta Cruz de Tenerife, Spain; ²NINDS/National Institutes of Health, Bethesda, MD 20892; ³Yale University School of Medicine, New Haven, CT 06510

The large conductance voltage- and calcium-activated potassium channel (BK) is regulated by membrane voltage and intracellular calcium concentration. The calcium sensitivity of this channel is conferred by a large cytosolic domain. When calcium binds to this region, less energy is required to open the channel, but the exact mechanism underlying this process is not clear. The structure of MthK, a prokaryotic, calcium-activated potassium channel suggests that its intracellular calcium sensor domains (RCK) form a ring structure (the “gating ring”). Calcium binding could induce expansion of the gating ring, thus making the channel opening more energetically favorable by applying a force on the channel gate. Because BK cytosolic domain shares some homology with the calcium binding domain of MthK, it has been proposed that they function with similar calcium-sensing mechanisms. This idea is further supported by a BK structural model recently obtained by RSC cryo-EM (Wang, L., and F.J. Sigworth. 2009. *Nature*. 461:292–295). We have measured movements within the putative BK gating ring domain using FRET. BK heterotetramers containing both CFP- and YFP-tagged RCK domains have been formed. We have used patch clamp fluorometry to obtain fluorescence spectra of excised oocyte membrane patches expressing such heterotetramers with insertions in different sites along the gating ring region, including the linker between RCK1 and RCK2 domains, RCK2, the calcium bowl, and the rest of the C-terminal region. Depending on the site that is tagged, we detect changes in FRET due to changes in voltage or in calcium concentration. No changes are observed when the probe is inserted in the calcium bowl or the C-terminal region. These results are consistent

with the model where a gating ring expands in response to increased calcium concentrations and suggest that only part of the C-terminal region forms this gating ring in BK.

7. Role of Intracellular Calcium Mobilization in Melanopsin-mediated Light Signalling in *Amphioxus*. JUAN MANUEL ANGUEYRA,¹ CAMILA PULIDO,² GERARDO MALAGÓN,² ENRICO NASI,^{3,4} and MARÍA DEL PILAR GOMEZ,^{2,4} ¹Department of Physiology and Biophysics, University of Washington, Seattle, WA 98105; ²Departamento de Biología and ³Instituto de Genética, Universidad Nacional de Colombia, Bogotá; ⁴Marine Biological Laboratory, Woods Hole, MA 02543

The discovery of unconventional, nonvisual photoreceptors in the retina of mammals has challenged the dogma that lipid signaling for light transduction is a prerogative of microvillar cells of invertebrate eyes. Melanopsin, the photopigment of vertebrate “circadian” photoreceptors, is homologous to the rhodopsins of rhabdomic photoreceptors, and mounting evidence indicates that it also signals through G_q and PLC. The nature of the downstream effectors, however, remains elusive. Pigmented ocelli and Joseph cells in the neural tube of *Amphioxus*, the most basal chordate, are microvilli-bearing primary photoreceptors that express melanopsin; because they are unambiguously identifiable and amenable to isolation and single-cell physiological assays, they provide a powerful model system to investigate melanopsin-mediated phototransduction mechanisms and their evolutionary history. We previously demonstrated in both cell types light-induced Ca mobilization from internal stores and dramatic attenuation of the photocurrent by intracellular Ca chelators. In the present study, pharmacological manipulations and whole cell patch clamp recording were used to assess the role of the IP₃ receptors. 2-APB and low molecular weight heparin were administered by local rapid superfusion and by intracellular dialysis, respectively, while cells were subjected to photostimulation. Both antagonists of the IP₃R caused a reduction of the photocurrent; however, the kinetics of activation remained extremely fast, manifesting none of the dramatic slow down that occurs in rhabdomic photoreceptors. Concurrently, we failed to observe activation of a membrane conductance by administration of surrogates of diacylglycerol (DAG), such as the alkaloid (–) indolactam V or the phorbol ester PMA. The results are consistent with the notion that calcium released from the ER via IP₃-sensitive channels may fulfill a key role in conveying the light signal to the photoconductance, directly or indirectly, rather than serving as a modulatory side branch of the cascade that controls the kinetics of the enzymatic reactions.

Supported by National Science Foundation grant 0918930.

8. Molecular Identification of Two Isoforms of Arrestin in the Retina of *Pecten*: Role in Light Response Termination in Ciliary Invertebrate Photoreceptors. LADY ESPINOSA,¹ NELSON RAMIREZ,² MARIA DEL PILAR GOMEZ,^{3,5} and ENRICO NASI,^{4,5} ¹Graduate Program in Microbiology, ²Graduate Program in Neuroscience, ³Department of Biology, and ⁴Instituto de Genética, Universidad Nacional de Colombia; ⁵Marine Biological Laboratory, Woods Hole, MA 02543

The two canonical classes of visual receptors, rods, and cones and invertebrate microvillar photoreceptors diverge greatly in terms of downstream light-signaling mechanisms, but follow a similar general blueprint for the early steps of transduction and deactivation. Ciliary hyperpolarizing photoreceptors of mollusks have emerged as a third lineage in vision, with unique mechanisms of excitation and adaptation, but nothing was known about the turn-off of the activated photopigment. We used degenerate-primer PCR in *Pecten* retina cDNA to obtain two 600-bp amplicons highly homologous to arrestin, but differing in a stretch of 71 contiguous nucleotides. The diverging portion was exploited in nested RACE reactions to retrieve the full-length clones, and confirm that separate arrestin isoforms, dubbed Arr12 and Arr23, are expressed. The translated ORFs predict proteins with 425 and 416 amino acids, respectively, and molecular masses of 47 and 46 kD. The canonical N and C arrestin domains are present in both cases. Both isoforms are more homologous to β arrestins than visual arrestins, but lack the clathrin interaction motif in the carboxy tail, and are thus expected to quench metarhodopsin activity without promoting its endocytosis. The sequence identity of Arr12 and Arr23 is 81%, precluding differential localization in ciliary versus microvillar photoreceptors via in situ hybridization. Nonetheless, batteries of antibodies against vertebrate arrestins, previously screened in Western blots, show that for some of them, the immunoreactivity is confined to the distal retina, where ciliary photoreceptors are located. Intracellular dialysis and patch clamp recording indicate that anti-arrestin antibodies interfere with photocurrent shut-off and promote prolonged aftercurrents, even with chromatic stimulation designed not to cause the accumulation of large amounts of metarhodopsin. This novel lineage of light-sensing cells, therefore, uses canonical photopigment deactivation mechanisms, thus strengthening the case for a monophyletic evolutionary origin of visual mechanisms across metazoan.

Supported by National Science Foundation grant 0639774.

9. On the Transduction Gain of Melanopsin-mediated Light Signalling in *Amphioxus*: Single-Photon, Unitary, and Early Receptor Currents. MARÍA DEL PILAR GOMEZ^{1,3} and ENRICO NASI,^{2,3} ¹Departamento de Biología and ²Instituto de Genética, Universidad Nacional de Colombia, Bogotá; ³Marine Biological Laboratory, Woods Hole, MA 02543

Melanopsin, an ancient photopigment related to the rhodopsin of microvillar visual receptors in present-day invertebrates, has evolved in vertebrate organisms to subserve nonvisual light-sensing functions, like controlling the pupillary reflex and entraining the circadian rhythm. Compared to their counterparts in arthropods and mollusks, circadian receptors in the vertebrate retina present no hint of a microvillar specialization and display an extremely reduced light sensitivity and uncommonly sluggish kinetics. Recently, bona fide melanopsin-expressing photoreceptors presumably ancestral to those of vertebrates have been characterized in the neural tube of *Amphioxus*, the most basal chordate. Known as Joseph and Hesse cells, they bridge the evolutionary gap between the photoreceptors of invertebrates and the circadian receptors of vertebrates. We used patch clamp recording to dissect the gain stage of the light transduction process. Dim illumination evoked distinct current fluctuations with a mean amplitude of 2–3 pA at –50 mV and a rapid time course (≈ 3 ms), attributable to melanopsin isomerizations produced by individual photons. Cell-attached recordings with stronger illumination revealed single-channel currents activated by light; the fast kinetics poses a challenge for accurate resolution, but the unitary amplitude is clearly in the 1-pA range, like those of invertebrate microvillar receptors. The gain can therefore be estimated to be substantially lower than in most rhabdomic receptors, where 10^2 – 10^3 channels are recruited per photoisomerized rhodopsin. In contrast, high-speed measurements of responses to bright lights show fast transients, called early receptor currents (or ERCs), that precede the activation of the photoconductance and reflect the charge displacement upon the photo-induced conformational transition of melanopsin. The ERC density in *Amphioxus* is comparable to invertebrate rhabdomic receptors; as a consequence, a reduction in the photopigment-to-channel coupling efficiency appears to be the primary cause underlying the low photosensitivity of melanopsin-utilizing light receptors in vertebrates.

Supported by National Science Foundation grant 0918930.

10. Characterization of Intrinsic Contrast in Intact Tissues Using Hyperspectral Two-Photon Microscopy. LAUREN E. GROSBERG, ANDREW J. RADOSEVICH, MATTHEW B. BOUCHARD, and ELIZABETH M.C. HILLMAN, Laboratory for Functional Optical Imaging, De-

partment of Biomedical Engineering and Department of Radiology, Columbia University, New York, NY 10027

For most fluorescence microscopy techniques, contrast comes from exogenous dyes and autofluorescence must be minimized. However, removing intrinsic signals throws away valuable, readily available information about the chemical makeup of the specimen. Furthermore, exploiting intrinsic contrast allows repeatable imaging of a wide range of 3-D structures in intact fresh or even living tissue, without the need for histological processing, fixing, slicing, or staining.

Our hyperspectral two-photon microscopy technique allows detailed characterization of the two-photon excitation and emission spectrum of every voxel within a sample. This approach is particularly valuable for intrinsic contrast imaging because it readily allows identification and segmentation of a wide range of tissue types, while also providing the possibility for quantitative analysis of the constituents of each tissue type (including NADH, FAD, elastin, collagen, keratin, etc.) (Radosevich, A.J., M.B. Bouchard, S.A. Burgess, B.R. Chen, and E.M. Hillman. 2008. *Opt. Lett.* 33:2164–2166).

We have used hyperspectral two-photon microscopy to image a range of murine tissues either in vivo or perimortem. These samples include tissue from the colon, small intestine, kidney, spleen, skin, and pancreas. We showed that in all of these tissues, intrinsic contrast revealed detailed 3-D morphology to depths of up to 500 microns without sectioning artifacts or the need for computational co-registration. Comparative histology of the same samples revealed good agreement between the structures visualized between the two techniques.

Beyond morphology, we are now validating the ability of hyperspectral two-photon microscopy to enable identification and quantification of specific intrinsic fluorophores. This will allow blind determination of tissue type, while also reporting the behavior of key endogenous fluorophores such as NADH and FAD in their native environment.

Our results suggest that hyperspectral two-photon microscopy could provide an alternative to conventional histology, particularly in settings where speed is important (such as during lesion excision or biopsy) or when there can be a benefit from visualizing key structures in 3-D. The method also has the potential for clinical translation for endoscopic applications.

11. Targeting Cyclic AMP Microdomains in Living Cells. KONSTANTINOS LEFKIMMIATIS, DANIELA LERONNI, SILVANA CURCI, and ALDEBARAN M. HOFER, *Department of Surgery, Harvard Medical School, VA Boston Healthcare System, and Brigham and Women's Hospital, West Roxbury, MA 02132; D. Leronna's present address is Dept. of Genetics and Microbiology, University of Bari, 70100 Bari, Italy*

The advent of FRET-based cAMP sensors has made possible the visualization of cAMP microdomains in living cells (Zaccolo, M., and T. Pozzan. 2002. *Science*. 295:1711–1715). However, the lack of available tools to perturb the cAMP microdomains in situ constitutes a major roadblock toward understanding the specific information potentially encoded by localized cAMP signals. Previously, we developed a genetically encoded mCherry-tagged cAMP buffer (cAMP sponge) (Lefkimmiatis, K., M.P. Moyer, S. Curci, and A.M. Hofer. 2009. *PLoS ONE*. 4:e7649). This cytosolic construct was able to bind up cAMP and block the activation of its major effector, protein kinase A. Here, we propose that localized versions of our cAMP sponge can be used to selectively perturb cAMP microdomains, and we focus on the examples of the nuclear and mitochondrial compartments (Zippin, J.H., J. Farrell, D. Huron, M. Kamenetsky, K.C. Hess, D.A. Fischman, L.R. Levin, and J. Buck. 2004. *J. Cell. Biol.* 164:527–534; Acin-Perez, R., E. Salazar, M. Kamenetsky, J. Buck, L.R. Levin, and G. Manfredi. 2010. *Cell Metab.* 9:265–276). To achieve nuclear or mitochondrial targeting of our sponge, we used two tandem nuclear localization sequences and four mitochondrial localization signals, respectively. Confocal microscopy demonstrated that both constructs were highly expressed and efficiently localized in >90% of the transfected cells. To estimate the affinity and specificity our targeted buffers, we performed pull down assays using agarose beads coated with a cAMP analog (Sp-2-AEA-cAMPS) as bait. Increasing doses of exogenous cAMP or high doses of cGMP were used to compete with Sp-2-AEA-cAMPS. Subsequent western blotting using specific antibodies showed that the nuclear and mitochondrial sponges bind cAMP specifically with roughly sub-micromolar affinity. Moreover, the introduction of point mutations in the cAMP binding domains rendered these constructs cAMP insensitive and provided an important negative control. Due to their high affinity, our targeted cAMP sponges promise to efficiently dampen local agonist-induced cAMP elevations, as well as putative constitutive signaling “micro-events,” unveiling the physiological roles of localized cAMP signals in resting and stimulated cells.

12. Benzodiazepines Modulate GABA-A Receptor Surface Levels and Synaptic Inhibition. T.C. JACOB,¹ G. MICHELS,² and S.J. MOSS,¹ *¹Department of Neuroscience, Tufts University, Boston, MA 02111; ²Internal Medicine Clinic III, University of Cologne, 50937 Cologne, Germany*

Benzodiazepines potentiate the activity of gamma-aminobutyric acid receptors (GABA-ARs) and are widely used to treat anxiety, insomnia, and seizure disorders. However, the use of these therapeutic compounds is severely limited due to the development of tolerance. The molecular mechanism underlying benzodiazepine (BZ)

tolerance is unknown. It is increasingly evident that BZ preferentially enhances the activity of synaptic GABA-AR subtypes that are largely composed of $\alpha 1$ -3, $\beta 3$, and $\gamma 2$ subunits. To directly address the role of BZ in regulating GABA-AR cell surface stability, we performed live imaging studies of pH-sensitive, GFP-tagged GABA-AR $\alpha 1$ ($\alpha 1$ -pHGFP) and $\alpha 2$ ($\alpha 2$ -pHGFP) subunits in hippocampal neurons to visualize the behavior of cell surface receptor populations. 24-hour treatment with the classical BZ flurazepam dramatically decreased α subunit cell surface levels. We measured total $\alpha 2$ subunit levels by revealing pHGFP-tagged GABA-ARs inside the cell with NH₄Cl. These live confocal studies showed that total neuronal $\alpha 2$ subunit levels were lowered by BZs. These data suggest that BZs promote GABA-AR degradation, likely due to increased lysosomal degradation of endocytosed receptors or increased endoplasmic reticulum-associated protein degradation via the proteasome. Next, we tested if the observed effect on BZ-sensitive GABA-AR surface levels is specifically induced by BZ binding. 1-hour treatment with the BZ antagonist flumazenil restored the BZ-lowered GABA-AR surface levels to control levels. The rapid time scale of flumazenil action is consistent with BZ-induced changes affecting receptor insertion and/or endocytosis rather than protein synthesis. Finally, we compared mIPSC properties in control neurons and those pretreated with flurazepam for 24 hours before recording. BZ treatment resulted in a decrease in mIPSC amplitude. Collectively, these data suggest that BZ treatment promotes the removal of $\alpha 2$ subunit-containing GABA-ARs from the plasma membrane and their subsequent degradation, leading to a reduction in inhibitory synapse size and number, along with a decrease in the efficacy of synaptic inhibition.

13. Trimethoprim-based Chemical Tag for In Vivo Protein Labeling and Live Cell Imaging. CHAORAN JING, SARAH S. GALLAGHER, and VIRGINIA W. CORNISH, *Department of Chemistry, Columbia University, New York, NY 10027*

Over the past decade, chemical tags have emerged as viable tools to selectively label proteins in living cells. Combining the selectivity provided by genetic encoding and a modular small molecule fluorophore, chemical tags have been demonstrated to complement the utility of fluorescent proteins and facilitate demanding biophysical measurements in live cells. However, although it is now relatively straightforward to label cell surface proteins using chemical tags, developing a cell-permeable fluorescent probe with high signal-to-noise remains a challenging task. We previously demonstrated that the high-affinity interaction between *Escherichia coli* dihydrofolate reductase and trimethoprim (TMP) can be used to selectively label proteins with fluorescent tags inside

living cells. Here, we present a TMP-based chemical tag with a modular organic fluorophore for two-photon live cell imaging. This TMP-fluorophore conjugate is shown to have appreciable two-photon excited fluorescence intensity and high cell permeability to allow efficient, high-resolution live cell imaging. We also present progress toward a TMP-based fluorogenic chemical tag aimed at enabling high signal-to-noise live cell super-resolution imaging. Collectively, our TMP-based chemical tags expand the tool kit available for labeling and visualizing intracellular proteins.

14. Altered Calcium Signaling in PMCA2^{+/-} Mice: Implications for Purkinje Cell and Cerebellar Function. AMANDA K. FAKIRA,^{1,2} LAWRENCE D. GASPERS,³ ANDREW P. THOMAS,³ and STELLA ELKABES,^{2,4} *¹Integrative Neurosciences, UMDNJ-Graduate School of Biomedical Sciences, ²Department of Neurology and Neurosciences, ³Department of Pharmacology and Physiology, and ⁴Department of Neurosurgery and the Tim Reynolds Family Spine Research Laboratory, UMDNJ-New Jersey Medical School, Newark, NJ 07103*

Plasma membrane Ca²⁺ ATPase isoform 2 (PMCA2), a pump required for Ca²⁺ extrusion from the cytosol, is most abundantly expressed in cerebellar Purkinje cells (PCs). We have previously reported that PMCA2 forms a complex with synaptic proteins and glutamate receptors mGluR1, GluR δ 2, and the AMPA receptor subunits GluR2/3. Fura-2 Ca²⁺ imaging on cultured PMCA2^{+/+} and PMCA2^{+/-} PCs was used to determine how PMCA2 may contribute to AMPA receptor signaling. Our results indicate that the amplitude of AMPA receptor-mediated Ca²⁺ transients are increased in PMCA2^{+/-} PCs compared with PMCA2^{+/+}. This is likely due to increased Ca²⁺ influx, as expression of P/Q-type voltage-gated Ca²⁺ channels (VGCC) is increased in PCs of the PMCA2^{+/-} mice in vitro. We also examined the expression of P/Q-type VGCC in PCs of the 3-week-old mouse cerebellum, as the maturity of the PCs at this age corresponds to that of PCs in vitro. In accordance, we found higher P/Q-type VGCC expression in 3-week-old PMCA2^{+/-} cerebella as compared with the PMCA2^{+/+}. In contrast, alterations in other mechanisms, such as sequestration into the endoplasmic reticulum or intracellular Ca²⁺ buffering, did not appear to contribute to higher amplitude.

In addition, we determined whether reduced PMCA2 expression affects the expression of glutamate receptors in the complex. We did not find any significant differences between PMCA2^{+/+} and PMCA2^{+/-} mice at 3 weeks. However, a significant decrease in GluR2/3 and mGluR1 levels was observed by 8 weeks of age. This was followed by a small but significant reduction in the number of PCs by 20 weeks of age. Thus, early abnormalities in Ca²⁺ influx and the subsequent aberrance in

glutamate receptor expression could lead to delayed PC dysfunction and loss in the PMCA2^{+/-} mice.

15. Does a Specific Isoform of Adenylyl Cyclase Mediate Store-operated Cyclic AMP Signaling? ISABELLA MAIELLARO, KONSTANTINOS LEFKIMMIATIS, SILVANA CURCI, and ALDEBARAN M. HOFER, *Department of Surgery, Harvard Medical School, VA Boston Healthcare System, and Brigham and Women's Hospital, West Roxbury, MA 02132*

The various isoforms of adenylyl cyclase (AC1-AC9), the enzymes that generate cAMP, are differentially regulated and have been implicated in specific pathophysiological processes. For example, knocking down AC3 in mouse induces an obese phenotype (Wang, Z., V. Li, G.C. Chan, T. Phan, A.S. Nudelman, Z. Xia, and D.R. Storm. 2009. *PLoS One*. 4:e6979), whereas knockdown of AC5 prolongs lifespan and protects against stress (Yan, L., D.E. Vatner, J.P. O'Connor, A. Ivessa, H. Ge, W. Chen, S. Hirotsu, Y. Ishikawa, J. Sadoshima, and S.F. Vatner. 2007. *Cell*. 130:247–258). Our lab recently discovered a new pathway in which Ca²⁺ depletion from the endoplasmic reticulum (ER) causes cAMP to increase through activation of one or more isoforms of conventional AC in colonic epithelial cells. This “store-operated” process is independent of cytosolic [Ca²⁺] and requires the ER transmembrane protein, STIM1 (Lefkimmatis, K., M. Srikanthan, I. Maiellaro, M.P. Moyer, S. Curci, and A.M. Hofer. 2009. *Nat. Cell Biol.* 11:433–442). Here, we asked whether there is a unique AC isoform involved in store-operated cAMP production. Ca²⁺ stores were released using 5 μM ionomycin in a Ca²⁺-free solution, resulting in a significant increase in cAMP, as measured using a FRET-based cAMP reporter in single colonic epithelial-derived cells. Transient overexpression of AC3 resulted in a statistically significant increase in cAMP production induced by ionomycin (59.25 ± 3.60% of the maximal response; *n* = 32 cells), compared with control (52.91 ± 3.53%; *n* = 32; *P* < 0.05). In contrast, overexpression of AC5, AC6, or AC7 resulted in a statistically insignificant increase in cAMP production (AC5, *n* = 13 cells; AC6, *n* = 12 cells; AC7, *n* = 15 cells). Knockdown of AC3 using siRNA inhibited the ionomycin-induced elevation of cAMP (41.40 ± 2.28%; *n* = 60 cells; *P* < 0.05), whereas silencing of AC5 (*n* = 68 cells) or AC6 (*n* = 91 cells) had no effect. Thus far, our data indicate that AC3 may be specifically involved in cAMP production elicited by ER store depletion. This information may ultimately provide clues about the physiological function of store-operated cAMP signaling, and it may help to identify other components of this unusual signaling pathway.

16. Super-Resolution Imaging of Cardiac Signaling Microdomains by STED Microscopy. T. KOHL,¹ M.A.

LAUTERBACH,² E. WAGNER,¹ V. WESTPHAL,² B. HAGEN,³ W.J. LEDERER,³ S.W. HELL,² and S.E. LEHNART,^{1,3} ¹*Heart Research Center Göttingen, Department of Cardiology and Pulmonology, University Medical Center, Göttingen, Germany;* ²*Department of Nanobiophotonics, Max Planck Institute for Biophysical Chemistry, 37077 Göttingen, Germany;* ³*Center for Biomedical Engineering and Technology, University of Maryland, Baltimore, MD 20742*

Structures for intracellular signaling in heart cells are compartmentalized within specialized microdomains, which are believed to be crucial for physiological function. However, these microdomains typically have dimensions that are below the resolution limit of conventional light microscopy; therefore, their structure and function are not well understood.

Methods. To overcome these limitations, we have examined two principal components of intracellular calcium release units (CRUs) by stimulated emission depletion (STED) microscopy: supramolecular clusters of intracellular Ca²⁺ release channel/ryanodine receptors (RyR2s) and transverse tubules (TTs). Peripheral, immunolabeled CRUs near the plasma membrane of mouse cardiomyocytes were analyzed for RyR2 cluster size and structure. TTs were stained with the lipophilic dye di-8-ANEPPS in living cells to characterize their structure and diameters.

Results. Peripheral RyR2 clusters are often arranged in double rows centered on Z-lines. Within individual RyR2 clusters, by STED microscopy we readily identified substructures below the optical resolution limit of confocal imaging. RyR2 cluster shapes ranged from circular to asymmetric elongated. Clusters sometimes showed periodic substructures of yet unknown physiological relevance. RyR2 cluster sizes analyzed after image segmentation appear to show an exponential distribution. STED imaging in live cells resolved circular TT sections and TT network organization, while conventional confocal imaging could not resolve true TT structure. Accordingly, the average TT diameter (full width at half-maximum) determined by a 2-D Gaussian fit was in confocal images 262 ± 26 nm versus 233 ± 37 nm in STED images (mean ± SD; *n* = 391; *P* < 0.05). Additionally, optical cross-sections of presumptive TTs showed a 1-peak intensity distribution in confocal images, whereas in STED images hollow structures could be resolved, consistent with morphometric identification of real tubular cross-sections.

Conclusions. STED microscopy optically resolves two major CRU domains in cells, RyR2 clusters, and TTs. This progress opens new windows to the study of complex signaling domains in heart cells and especially their dynamic reorganization in normal and diseased heart states.

17. Co-Stimulation through VLA-4 Inhibits Microcluster Movement by Resisting Myosin-dependent Contraction within the Synapse. ALENKA LOVY-WHEELER,¹ NICHOLAS R. SYLVAIN,² ROSEMARY R. BREWKA,² JON DEGNORE,³ and STEPHEN C. BUNNELL,⁴ ¹Center for Neuroscience Research, ²Program in Immunology, ³Tufts Imaging Facility, and ⁴Department of Pathology, Tufts University School of Medicine, Boston, MA 02111

Antigen receptors assemble signaling microclusters that contain the adapter SLP-76 and are transported toward the center of the immune synapse. These structures are essential for T cell activation; however, no clear rationale has been provided for their movement. Progress in this regard has been hindered by the obscurity of the mechanisms governing microcluster movement. Recently, we determined that the engagement of the $\alpha 4\beta 1$ integrin (VLA-4) by immobilized counter-ligands greatly reduces the mobility of TCR-induced SLP-76 microclusters (SLP-MCs), and that this effect is associated with increased T cell activation. To test the hypothesis that microcluster immobilization promotes T cell activation by enabling more sustained and more productive interactions between the TCR and SLP-MCs, we wished to identify and perturb the systems driving SLP-MC movement. Because our previous data suggested that SLP-MCs are intimately associated with adhesive structures and with the insoluble actin cytoskeleton, we developed a mechanical isolation procedure that allowed us to obtain highly purified TCR- and SLP-MCs, which were analyzed by LC/MS/MS. We find that myosin IIA is associated with SLP-MCs and plays a critical role in MC translocation. Rho kinase (ROCK)-activated myosin II is required to generate contractile, centralizing forces within the synapse; these forces are resisted after VLA-4 ligation, most likely through the engagement of a “molecular clutch” linking VLA-4 to the actin cytoskeleton. Importantly, SLP-MCs immobilized after the inactivation of myosin II do not contribute to T cell activation. Therefore, we propose that T cells are co-stimulated in response to the intracellular tension generated by the opposing activities of myosin II and VLA-4.

18. Optical Assays of Innate Immunity: *Pseudomonas aeruginosa* Homoserine Lactone Activates Store-operated cAMP and CFTR-dependent Cl Secretion by Human Airway Epithelia. S. WONG,¹ J. SHI,¹ E. MATTHES,¹ B. ILLEK,² J.P. IANOWSKI,³ R.J. ARANT,¹ E. ISACOFF,¹ H. VAIS,⁴ J.K. FOSKETT,⁴ I. MAIELLARO,⁵ A.M. HOFER,⁵ and T.E. MACHEN,¹ ¹Department of Molecular and Cell Biology, University of California, Berkeley, Berkeley, CA 94720; ²Children’s Hospital Oakland Research Institute, Oakland, CA 94609; ³Department of Physiology, University of Saskatchewan, Saskatoon SK S7N 5E5, Canada; ⁴Department of Physiology, University of Pennsylvania Medical School, Philadelphia, PA 19104; ⁵Department of Surgery, Brigham and

Women’s Hospital, Harvard Medical School, West Roxbury, MA 02132

The bacterium *Pseudomonas aeruginosa*, bacteria that commonly infect the lungs of cystic fibrosis (CF) patients, secrete *N*-(3-oxo-dodecanoyl)-S-homoserine lactone (3O-C12) to regulate bacterial gene expression. 3O-C12 also affects functions of eukaryotic cells. Trans-epithelial electrophysiology in Ussing chambers showed that 10–100 μM 3O-C12 increased Cl^- secretion (I_{Cl}) in CFTR-expressing airway epithelial cell lines, but not in CF cells. Bright field observations of “bubble” formation in oil-covered pig tracheas showed that 3O-C12 also increased fluid secretion by glands in non-CF pig trachea. Fura-2 imaging showed that 3O-C12 increased cytosolic $[\text{Ca}^{2+}]$, Ca_{cyto} , similarly in Ca^{2+} -containing and Ca^{2+} -free solutions, indicating that Ca was being released from the endoplasmic reticulum. FRET imaging of cameleon D1-transfected cells confirmed that 3O-C12 reduced $[\text{Ca}^{2+}]$ in the endoplasmic reticulum (Ca_{ER}). The Ca^{2+} -ATPase inhibitor thapsigargin (tg) also increased I_{Cl} and Ca_{cyto} , and decreased Ca_{ER} , and 3O-C12 had no effect in cells treated with tg. Patch clamp measurements on isolated nuclei from $\text{IP}_3\text{R1}$ -expressing DT40 cells showed that 3O-C12 also activated $\text{IP}_3\text{R1}$. TIRF imaging showed that 3O-C12 and tg both activated STIM1, an ER protein that regulates plasma membrane proteins. FRET imaging of Epac H30-transfected cells showed that 3O-C12 increased cytosolic $[\text{cAMP}]$ ($\text{cAMP}_{\text{cyto}}$). 3O-C12-stimulated I_{Cl} was inhibited by a cAMP antagonist and increased by a phosphodiesterase inhibitor. The high K_d Ca^{2+} chelator TPEN, which lowers Ca_{ER} without increasing Ca_{cyto} in other cells, increased $\text{cAMP}_{\text{cyto}}$ and I_{Cl} , similar to 3O-C12. It is concluded that 3O-C12 stimulates CFTR-dependent Cl^- and fluid secretion in airway epithelial cells by directly activating IP_3R , lowering Ca_{ER} , and activating STIM1 and store-operated cAMP production. In CF airways, 3O-C12 will alter Ca and cAMP signaling but will not increase Cl^- and fluid secretion.

19. Measurement of Cell Volume and Membrane Integrity in Adherent Cells. JENNIFER L. GREGG,¹ SAHIL M. PANDYA,² and MICHAEL A. MODEL,² ¹School of Biomedical Sciences and ²Department of Biological Sciences, Kent State University, Kent, OH 44023

Cell volume is one of the basic characteristics of a cell and is being extensively studied in relationship to diverse biological processes. At the same time, a simple microscopic technique for its measurement is lacking. The method we propose uses negative transmission contrast rendered to cells by a strongly absorbing dye present in the medium. Cells are placed in a perfusion chamber with a shallow (0.03-mm) channel, and a non-toxic dye, such as Acid Blue 9, is added to the medium. Transmission images are collected at the wavelength of

maximum dye absorption (630 nm). Where the cells displace the dye, the thickness of the absorbing layer is reduced; thus, an increase in cell thickness produces brighter images, and vice versa. The results are unaffected by possible fluctuations in the light source, and a high S/N ratio can be achieved. Because cells in this method are only exposed to low-intensity light, the method is well suited for time-lapse experiments. To demonstrate the utility of this method, we investigated the volume response of T24 cells to a hypotonic buffer and to apoptosis-inducing chemicals staurosporine and ionomycin.

From the known absorption coefficient of the dye, the image contrast can be converted into the absolute values for cell thickness and volume. However, quantitative interpretation of the images relies on the assumption that the cell membrane is impermeable to the external dye. To test for possible membrane leakage caused by treatment with apoptotic agents, we labeled the cytoplasm with the red fluorescent probe CellTracker Orange. If the external dye penetrates the plasma membrane, it quenches CellTracker fluorescence, and from the extent of quenching the intracellular concentration of Acid Blue 9 can be determined. In our experiments, partial loss of membrane integrity was indeed detected after treatment of cells with high concentrations of ionomycin.

20. Monitoring Protein Misfolding and Calcium Signaling during the Unfolded Protein Response (UPR). R. MADELAINE PAREDES,¹ and JAMES D. LECHLEITER,^{1,2} ¹*Department of Cellular and Structural Biology and* ²*Department of Physiology, University of Texas Health Science Center at San Antonio, San Antonio, TX 78229*

The endoplasmic reticulum (ER) is the main intracellular organelle for Ca²⁺ storage (Berridge, 2002). The ER is also the location where proteins destined to be secreted are synthesized, folded, and processed (Helenius, 1994; Parodi, 2000). It is well known that defects in the protein synthesis machinery or in the environment of the ER induce ER stress, which activates a mechanism called the unfolded protein response (UPR) that helps to restore ER homeostasis (Kaufman, 1999; Harding et al., 2002). If ER homeostasis cannot be restored by the UPR, a program of cell death is activated (Nakagawa et al., 2000; Scorrano et al., 2003; Hitomi et al., 2004; Li et al., 2006). In many conditions where protein misfolding occurs, there is a noticeable dysregulation in ER Ca²⁺ homeostasis (Haughey et al., 1999; Hetz et al., 2003; Benali-Furet et al., 2005; Tu et al., 2006). However, it has not been established whether ER Ca²⁺ dysregulation is a cause or a consequence of misfolding. Here, we have developed imaging techniques to monitor the impact of ER Ca²⁺ depletion on protein processing and the effect that protein misfolding may have on ER Ca²⁺. For this

purpose, we partially depleted the ER stores using thapsigargin (Tg) on *Xenopus* oocytes expressing a model secreted protein carboxypeptidase Y (CPY-wt) (Finger et al., 1993). A mutant form of CPY that is known to be retained within the ER (CPY-G255R) was used as a control (Finger et al., 1993; Mancini et al., 2003). Both the wild-type and mutant forms of CPY were labeled with variants of the green fluorescent protein to directly visualize their retention in the ER by confocal microscopy. We found that partial depletion of ER Ca²⁺ with either 50 or 100 nM Tg for 48 hours induced significant induction of the UPR, as monitored by the phosphorylation of eIF2 α (P-eIF2 α), and induced ER retention and accumulation of CPY-wt. Partial depletion had no effect on ER retention of the mutant CPY (CPY-G255R). We also tested whether an accumulation of misfolded proteins in the ER induced ER Ca²⁺ loss. We found that overexpression of the mutant misfolded protein (CPY-G255R) did not significantly affect ER Ca²⁺ levels (DIER) or induce ER stress (P-eIF2 α) in *Xenopus* oocytes. However, inhibition of protein glycosylation by tunicamycin rapidly induced a Ca²⁺ leak from the ER within 5 minutes of treatment. In summary, partial Ca²⁺ depletion of the ER stores is sufficient to induce accumulation of a normally secreted protein. Induction of significant protein misfolding also appears to induce ER Ca²⁺ loss. We suggest that Ca²⁺ may be both a cause and a consequence on the folding/misfolding process under the UPR.

21. Artificial Ca²⁺ Sparks in a Dual Confocal Scanner. A Rich Man's Stopped Flow for the Characterization of Ca²⁺-reactive Molecules and Biosensors. LOURDES FIGUEROA,¹ JINGSONG ZHOU,¹ VYACHESLAV SHKRYL,¹ YAN LI,¹ JIANXUN YI,¹ ATSUYA MOMOTAKE,² LOTHAR BLATTER,¹ GRAHAM ELLIS-DAVIES,³ GUSTAVO BRUM,⁴ and EDUARDO RÍOS,¹ ¹*Rush University, Chicago, IL 60612;* ²*Tsukuba University, 305-8577 Ibaraki, Japan;* ³*Drexel University, Philadelphia, PA 19104;* ⁴*Universidad de la República, Montevideo, Uruguay*

Control of calcium signaling in striated muscle relies on concurrent actions of calcium ions to promote and inhibit release channel opening. As quantifiable local probes of these actions, we developed artificial Ca²⁺ sparks, which are generated by 2-photon (2P) release from various "cages." A "dual scanner" (510 LIVE Duo; Carl Zeiss, Inc.) delivers IR laser flashes to a diffraction-limited region through an LSM 510 scanner, while rapidly imaging fluorescence of a [Ca²⁺] monitor via a slit scanner (5-LIVE; ~100 μ s/line). Ca²⁺ sparks of 0.1–10 μ M are elicited after microseconds of 2P irradiation at 720 nm and imaged with the low affinity dye fluo 4FF. Reaction-diffusion analysis (Ríos, E., M.D. Stern, A. González, G. Pizarro, and N. Shirokova. 1999. *J. Gen. Physiol.* 114:31–48) yields the flux of Ca²⁺ photorelease.

This flux, which initially may reach several hundred mM/s, decays with τ of 2–3 ms when the cage is DM-nitrophen or 5–8 ms when the cage is the much more efficient NDBF-EGTA (Momotake, A., N. Lindegger, E. Niggli, R.J. Barsotti, and G.C. Ellis-Davies. 2006. *Nat. Methods*. 3:35–40). The kinetics of decay after the photolysing IR flash serves to quantify intrinsic photochemical properties of the cages. The technique was also used to quantify the response of the Ca^{2+} biosensors YC3.6 and D4, as well as the properties of calcium buffers used in intracellular solutions, including sulfate and glutamate. It is currently being explored as a tool to derive diffusion coefficients of sensors and buffers.

In sum, while the original goal was to use artificial sparks to quantitatively characterize calcium control in cells (a goal that is actively pursued in our laboratory), the technique was also found to provide a means to characterize photochemistry and physical chemistry of Ca^{2+} -reactive molecules.

The instrument was purchased with an S10 NCRR award and Hasterlik Family matching funds. Supported by Conicyt Uruguay, NIAMS, NHLBI, and MDA.

22. Combined Phosphoinositide and Ca^{2+} Signals Mediating Intracellular Receptor Specificity toward Neuronal Ion Channels. OLEG ZAIKA and MARK S. SHAPIRO, *Department of Physiology, University of Texas Health Science Center at San Antonio, San Antonio, TX 78229*

Phosphatidylinositol (PI) 4,5-bisphosphate (PIP_2) regulates a plethora of ion channels and transporters, including voltage-gated N- and P/Q-type Ca^{2+} (I_{Ca}) and M-type K^+ currents in neurons. Of four $G_{q/11}$ -coupled, PLC-linked receptors in superior cervical ganglion (SCG) sympathetic neurons, the M_1 muscarinic and AT_1 angiotensin II types do not elicit Ca^{2+} signals and suppress both types of currents via depletion of PIP_2 , whereas the B_2 bradykinin and P2Y purinergic types elicit robust IP_3 -mediated $[\text{Ca}^{2+}]_i$ rises, do not deplete PIP_2 nor inhibit I_{Ca} , and suppress M current via Ca^{2+} /calmodulin action. We have suggested that this receptor specificity toward the channels arises from differential Ca^{2+} signals, underlying receptor-specific stimulation of PIP_2 synthesis by PI 4 kinase. Here, we inquire more deeply into these phenomena, asking which PI 4 kinase isoform underlies this signal, whether stimulation of PI(4) 5 kinase is also required to maintain PIP_2 levels during PLC activity, and the origin of receptor specificity in Ca^{2+} signals. We used recordings of endogenous I_{Ca} as a “biosensor” of PIP_2 levels from SCG cells treated with pertussis toxin to isolate $G_{q/11}$ -mediated signaling. In control neurons, stimulation of M_1 receptors with 10 μM oxotremorine methiodide (oxo-M) robustly suppressed I_{Ca} , but the application of 250 nM bradykinin or 10 μM of the P2Y agonist, uridine 5'-triphosphate (UTP)

had little effect on I_{Ca} , reporting that only M_1 receptor stimulation depletes PIP_2 levels. However, when cells were pretreated with the specific PI 4 kinase III β inhibitor PIK93 (0.3 μM ; 7 min) or with DAG kinase inhibitor II (R59949; 20 μM , 1 h), all three agonists suppressed I_{Ca} to varying degrees, and the two drugs together did not have a greater effect. Because DAG kinase converts DAG into phosphatidic acid (PA), which is known to stimulate PI(4) 5 kinase, these data suggest that stimulation of PI 4 kinase III β and PI(4) 5 kinase is required to prevent PIP_2 depletion by receptors. PI(4) 5 kinase is also thought to be stimulated by RhoA and its effector, Rho kinase. Indeed, when endogenous Rho activity was blocked by transfection of dominant-negative RhoA T19N, or when Rho kinase was blocked by pretreatment of cells with 1 μM Y27632 (40 min), UTP, BK, and oxo-M all suppressed I_{Ca} to varying degrees. Transfection of RhoA T19N also reduced tonic I_{Ca} amplitudes. Localization of certain $G_{q/11}$ -coupled receptors with IP_3 receptors has been postulated to explain receptor-specific Ca^{2+} signals. As a test, we compared agonist-induced $[\text{Ca}^{2+}]_i$ rises in neurons transfected with EGFP only or together with exogenous M_1 receptors. The former responded to UTP and BK, but not oxo-M, with robust Ca^{2+} signals, whereas in the latter, the response to oxo-M was large, suggesting that microdomain organization plays a strong role. We also tested the part played by an endogenous inhibitory protein of IP_3 receptors, IRBIT, which we found localizes to SCG neurons by immunostaining. Over-expression of wild-type IRBIT decreased the percentage of SCG cells responding to BK or UTP with Ca^{2+} signals, but it only slightly affected the amplitude of the evoked $[\text{Ca}^{2+}]_i$ rises. Over-expression of dominant-negative IRBIT S68A had little effect on the responses to BK or UTP, but it greatly increased the percentage of cells responding to oxo-M with Ca^{2+} signals. We conclude that overlaid on microdomain organization is IRBIT activity, which sets a “threshold” for $[\text{IP}_3]$ for opening in the vicinity of the IP_3 receptor, assisting in the fidelity of receptor specificity in intracellular Ca^{2+} signaling, downstream agonist-specific depletion of PIP_2 and consequential receptor-specific depression of I_{Ca} and other PIP_2 -sensitive conductances in neurons.

Supported by National Institutes of Health grants R01 NS43394 and ARRA-R01 NS065138 to M.S. Shapiro.

23. Protein Localization Using Correlative Super Resolution Fluorescence Microscopy and Electron Microscopy. SHIGEKI WATANABE,¹ ANNE DORE PUNGE,² GUNTHER HOLLOPETER,¹ ROBERT JOHN HOBSON,¹ M. WAYNE DAVIS,¹ STEFAN W. HELL,² and ERIK M. JORGENSEN,¹ ¹*Department of Biology and Howard Hughes Medical Institute, University of Utah, Salt Lake City, UT 84112;* ²*Department of NanoBiophotonics, Max*

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To fully understand the cell biology of synapses, the location of proteins relative to features such as the active zone and synaptic vesicles needs to be revealed. Immunofluorescence or genetically encoded fluorescent proteins have been used extensively to identify subcellular localization of proteins. However, the resolution of fluorescence microscopy is limited to around 200 nm by the diffraction of light (Born, M., and E. Wolf. 2002. *Principles of Optics*. Cambridge University Press, Cambridge)—a resolution that is not useful given the size of structures at synapses. Recently, several microscopy techniques, namely STED (Hell, S.W., and J. Wichmann. 1994. *Opt. Lett.* 19:780–782) and PALM (Betzig, E., G.H. Patterson, R. Sougrat, O.W. Lindwasser, S. Olenych, J.S. Bonifacino, M.W. Davidson, J. Lippincott-Schwartz, and H.F. Hess. 2006. *Science*. 313:1642–1645) or STORM (Rust, M.J., M. Bates, and X. Zhuang. 2006. *Nat. Methods* 3:793–795), have been developed to overcome this resolution limit. Proteins can be localized at 20-nm resolution. One drawback of fluorescence-based approaches is that the cellular context is often absent from the image. On the other hand, immuno-electron microscopy (immuno-EM) depicts subcellular structure, but protein localization in electron micrograph is limited by sample preparation and availability of antibodies (Roth, J., M. Bendayan, E. Carlemalm, W. Villiger, and M. Garavito. 1981. *J. Histochem. Cytochem.* 29:663–671). Combining the super-resolution microscopy techniques with electron microscopy could merge the protein localization advantages of fluorescence microscopy with the structural information of electron microscopy. Thus, we have developed techniques to localize fluorescently tagged proteins in tissue samples that are compatible with electron microscopy. Fusion proteins tagged with Citrine or tEos were preserved during specimen fixation and embedding. Fluorescence localizations revealed by STED or PALM were correlated with organelles imaged in electron micrographs from the same sections. This correlative method will be used to localize synaptic proteins within *Caenorhabditis elegans* synapses.

Sponsored by funding awarded to E.M. Jorgensen.

24. Label-free Cellular Imaging by Wide-Field Surface Plasmon Resonance Microscopy. KEVIN F. WEBB and NOAH A. RUSSELL, *Institute of Biophysics, Imaging and Optical Science, School of Electrical and Electronic Engineering, University of Nottingham, Nottingham NG7 2, England, UK*

Long-term observation of cell behavior is crucial to the investigation of many physiological processes. Exposure to transmitted incident light is directly detrimental to cell health and excites and bleaches fluorophores throughout the cell. Evanescent field methods such as

TIRF use very high angles of illumination to produce total internal reflection at the coverslip interface. An evanescent field extends ~100 nm into the preparation, restricting excitation to within this restricted volume. Surface plasmon resonance (SPR) microscopy involves the incorporation of a 50-nm gold layer at the coverslip surface, upon which cells are cultured attached to an aminothioli self-assembled monolayer. By adjusting the angle of illumination at the back aperture of a high-NA objective lens, plasmon resonance is evoked whereby incident photons excite plasmons in the metal electrons and very little light is reflected. The resonant angle is very sensitive to the refractive properties of material within the evanescent field, providing high contrast in reflectance mode. The evanescent field is amplified at the surface by SPR, allowing TIRF-like studies at lower illumination intensities. An imaging system has been constructed incorporating a 1.49-NA objective for TIRF/TIRM/SPR, in addition to transmitted, reflectance, and epifluorescent imaging from above. High resolution in XY and very high contrast is achieved over a field of ~300 μm . Primary neurons, cardiac myocytes, and fibroblast cell lines have been cultured on SPR surfaces and imaged over periods of hours. Dynamic cell events such as cytoplasmic extension, membrane process formation, and movement, etc., can be followed over long periods, with appropriate homeostasis being maintained. The sensitivity of SPR also allows surface layers, such as self-assembled monolayers, extracellular matrix, or cell adhesion deposits to be detected. Long-term, label-free live cell imaging by wide-field SPR microscopy thus offers a minimally invasive, highly flexible modality that may be of considerable use in cellular physiology.

25. Visualization of Repeated Synaptic Vesicle Recycling. BENJAMIN G. WILHELM^{1,2} and SILVIO O. RIZZOLI,¹ *¹European Neuroscience Institute, 37077 Göttingen, Germany; ²International Max Planck Research School Neuroscience, 37077 Göttingen, Germany*

Synaptic transmission at chemical synapses relies on the release of neurotransmitters via synaptic vesicle exocytosis. Two modes of release have been described: spontaneous (at rest) and active (during stimulation). It has been thought for decades that the vesicles releasing actively or spontaneously are identical, especially as they contain precisely identical levels of neurotransmitter. However, several recent studies on hippocampal cultured neurons suggested that the two release modes are supported by distinct synaptic vesicle populations. This notion is currently a highly contested one, and so far based exclusively on cultured synapses. To test this hypothesis, we investigated the release of FM 1-43 (which is directly proportional to the rates of exocytosis) in several preparations. Presynaptic vesicles were loaded with FM 1-43 by active or spontaneous exo-endocytosis, and

were subsequently unloaded either actively or spontaneously. If different vesicles maintain active and spontaneous release, the FM dye loaded by one paradigm would only be released by the same paradigm. This was not the case in hippocampal neurons, and neither in three mature neuromuscular synapses (from mouse, frog, and *Drosophila*): vesicles were released equally well spontaneously or actively, regardless of the loading procedure. To further confirm the FM-derived results in hippocampal neurons, we used a novel assay in which recycling vesicles were labeled in a first round (either actively or spontaneously) with antibodies against the vesicle marker synaptotagmin, followed by secondary detection of the antibody in a following round (again, actively or spontaneously). All labeling combinations provided the same levels of fluorescence, again suggesting that the same vesicles can be released both spontaneously and actively. We therefore conclude that synaptic vesicles recycled at rest and during synaptic activity are identical. (Prof. Dr. Erwin Neher)

26. Mapping the Structure of CLC-1 Using Fluorescence Resonance Energy Transfer. YAWEI YU, XIAODONG ZHANG, WELPING YU, and TSUNG-YU CHEN, *Center for Neuroscience and Department of Neurology, University of California, Davis, Davis, CA 95618*

CLC-1, a member of the CLC channel/transporter family expressed on the cell membrane of skeletal muscles, contributes to >50% of the resting membrane conductance of the skeletal muscle. Although the crystal structure of bacterial CLC as well as the cytoplasmic domain of various mammalian CLC molecules has been solved (Dutzler, R., E.B. Campbell, and R. MacKinnon. 2003. *Science*. 300:108–112; Meyer, S., and R. Dutzler. 2006. *Structure*. 14:299–307; Markovic, S., and R. Dutzler. 2007. *Structure*. 15:715–725; Meyer et al., 2007), the high-resolution structure of CLC-1 remains elusive. In this study, we use the fluorescence resonance energy transfer (FRET) technique to map the general structure of CLC-1 and study its structure–function relationship. We conducted FRET experiments by tagging CFP and YFP to different positions of CLC-1. By tagging N terminus and C terminus of CLC-1 with CFP and YFP simultaneously, a low FRET efficiency of merely ~5% was detected. However, with only about 100 amino acids truncated from the C terminus, the FRET efficiency dramatically increased to about 22%. Using this approach, we are able to compare the structure of CLC-1 with CLC-0 and other members of the CLC chloride channel/transporter family. The results suggest a structural architecture consistent with various high resolution structures from other CLC family members.

27. Two-Photon Imaging of Phototransduction Proteins in Living Mouse Rods. DELAINE LARSEN, NATHAN MELLING, MARIE BURNS, and EDWARD N.

PUGH JR., *Center for Neuroscience, University of California, Davis, Davis, CA 95618*

Background. Arrestin1 (Arr1) is a 48-kD protein essential for the normal deactivation of photoactivated rhodopsin in rod photoreceptors during phototransduction, and is the second most abundant protein in rods after rhodopsin. In the dark-adapted rod, Arr1 is primarily excluded from the outer segment, where it interacts with rhodopsin; this has been shown using immunohistochemical techniques in several species, serial cryosectioning with Western blotting in mice and confocal imaging of an Arr1-eGFP fusion protein in *Xenopus*. After exposure to steady light, the subcellular distribution of Arr1 changes, with a dramatic translocation to the outer segment. Investigations of the physiological consequences of Arr1 translocation in living rods has been impeded by the fact that standard imaging techniques used to image Arr1 also induce its translocation. To overcome this impediment and lay the grounds for electrophysiological characterization of single rods with measured quantities of Arr1 in the outer segment, we have used two-photon (2p) imaging of a tdTomato-Arr1 (tdTom-Arr1) fusion protein expressed in mouse rods to measure its translocation in living retinal slices under conditions amenable to electrophysiology.

Methods. TdTom-Arr1 fusion protein was expressed in c57B/6 mouse rods under the rhodopsin promoter using neonatal electroporation. Small retinal slices were dissected under infrared (IR) viewing and loaded into a flow chamber on the stage of an inverted microscope. Rapid rastering of the chamber viewfield using transmitted IR viewing allowed selection of properly oriented slices for 2p imaging. TdTom fluorescence was excited with a Ti-sapphire laser (Coherent Ultra II) tuned to 920 nm focused to its diffraction limit, and collected with photon-counting photodiodes, with 3-D scanning under control of a customized LabView interface (Calvert, P.D., W.E. Schiesser, and E.N. Pugh Jr. 2010. *J. Gen. Physiol.* 135:173–196). Laser exposure was kept to the minimum required to reliably observe tdTom fluorescence, as confirmed with emission spectra analysis.

Results. Overall expression of tdTom-Arr1 varied from cell to cell, but the normalized distribution of the protein was highly consistent. Calibration of tdTom fluorescence using purified recombinant proteins was made using the known extinction coefficients, and revealed the fusion protein to be at 50–300 μ M, ~1/60th to 1/10th the endogenous level of Arr1. The vast majority of tdTom-Arr1 was located in the inner segment and synaptic regions of dark-adapted rods. After a strong light exposure, most of the tdTom-Arr1 translocated from the inner segment to the outer segment over a time course of several minutes.

Conclusions. We have used 2p imaging to measure the translocation of an Arr1 fusion protein in living mouse

retinal rods at high temporal and spatial resolution. The preliminary data show that the method sufficiently minimizes effective visible light exposure to capture sequential images of tdTom-Arr1 localization in its dark-adapted distribution. The ability to use 2p imaging to

measure the concentration of Arr1 in outer segments without strongly driving phototransduction will be pivotal in future studies determining how Arr1 levels affect the gain and kinetics of the rod's electrical photoresponse.

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ADDITIONAL ABSTRACTS

28. Single molecule myosin V dynamics using high time resolution polarized TIRF. JOHN F. BEAUSANG¹, PHILIP C. NELSON¹, and YALE E. GOLDMAN² ¹Department of Physics, University of Pennsylvania, Philadelphia PA 19104, ²Department of Physiology, University of Pennsylvania and Pennsylvania Muscle Institute, Philadelphia PA 19104

Translocation of the molecular motor myosin along its actin filament track was studied using polarized total internal reflection (polTIRF) microscopy, a technique that determines the 3D orientation and dynamic wobble of single fluorophores. The maximum time resolution of the experimental setup was increased 50-fold by cycling 8 different input laser polarizations in ~ 1 ms. The arrival time and polarization state of each photon was recorded using a modified time-correlated single photon counting device. A new analysis, the Multiple Channel Change Point algorithm, was developed to detect changes in molecular orientation and wobble using the raw time-stamped data with no user-defined bins or thresholds. The analysis objectively identified changes in orientation and wobble of each fluorophore with a time resolution limited only by the photon counting rate. The polarized fluorescence from single rhodamine probes bi-functionally attached to one of the calmodulins on the myosin lever arm was recorded as the motor translocated along a fixed actin filament in the presence of ATP. Long duration intervals, corresponding to stable orientations of the lever arm, were routinely observed between the rapid tilting motions that occurred with each step of the myosin. Occasionally, short duration substeps of increased probe wobble between these long dwells were detected, possibly corresponding to the putative diffusive search of the detached head for its next actin binding site. Periods of large wobble were also detected at the end of many runs and when molecules were attached to actin in the absence of ATP. In both of situations motors are probably bound to actin by only one head. Motility experiments in the presence of the myosin inhibitor BDM were performed to test whether the substeps would be detected more readily if they were prolonged. This work was supported by NSF grants DMR-0832802, EF-0928048, IGERT DGE02-21664 and NIH grant GM-086352.

29. *In vivo* Quantitative Analysis of Retinal Ganglion Cell Dendrites in Mouse Retina. LING CHEN and NING TIAN *Department of Ophthalmology and*

Visual Science, University of Utah School of Medicine, Salt Lake City, UT 84132, USA

To determine whether *in vivo* confocal scanning laser microscopy can be used to quantitatively analyze the dendrites of retinal ganglion cells (RGCs) in developing and degenerative retina. Transgenic mice with Yellow Fluorescent Protein (YFP) expressed in a small fraction of RGCs are used in this study. Fluorescent images of individual YFP⁺ RGCs were obtained *in vivo* and *in vitro* using a confocal scanning laser microscope at different developmental ages and under pathological conditions. The dendrites of *in vivo* and *in vitro* images of YFP⁺ RGCs were quantitatively analyzed. The dendrites of YFP⁺ RGCs can be clearly visualized and quantified from *in vivo* images. Using this quantitative measurement, we found that the size of RGC dendritic field continues to increase after P23 due to a selective elongation of terminal dendrites. In addition, we demonstrated that RGC dendritic changes could be observed much earlier than the time of RGC death in the NMDA-induced retinal toxicity and after optic nerve crush. Furthermore, high intensity laser with long exposure time could also damage RGCs. RGCs with laser-induced damage show dendritic degeneration several days before cell death. *In vivo* confocal scanning laser microscopy provides a reliable and sensitive approach to detect dendritic changes of RGCs during postnatal development and under pathological conditions.

30. Longitudinal two-photon microscopy of a fluorescent version of the 5xFAD mouse model of Alzheimer's disease. SARAH E CROWE, YOSSIE BUSKILA, AND GRAHAM C.R. ELLIS-DAVIES *Mount Sinai School of Medicine, New York, NY*

Finding a cure for Alzheimer's disease (AD) presents a great challenge, as the etiology of the disease is unknown. One consequence of this is a true mouse model of AD is not possible. However, familial AD (FAD) is genetic, so several transgenic mice have been made using mutant human APP and/or PS1 to yield "plaque" models. Most plaque mice (e.g. the Tg2576 and PDAPP models) do not show much neuronal loss or atrophy, unlike AD sufferers. Recently new mice have been made that express high levels of Abeta42 and have significant neuronal atrophy of pyramidal neurons in the hippocampus and/or neocortex. We have taken one of these models (called 5xFAD) and crossed it with a well-studied transgenically fluorescent H-line YFP mouse, to yield a 29. Genetic deletion of *trkB.T1* increases muscle specific

fluorescent FAD mouse that enables 2-photon imaging of spines in layer 5. Long-term, intraviral 2-photon microscopy of fluorescent mice by several labs has established that the dendritic tree of pyramidal neurons is extremely stable. In contrast, we find the neocortex shrinks by 20-50% and layer 5 neurons undergo profound atrophy over time. End stage AD sufferers also have severely shrunken brains. Longitudinal 2-photon imaging of young fluorescent 5xFAD mice revealed the first stage of neuronal decay was localized axonal dystrophy. In vitro electrophysiology of layer 5 pyramidal neurons was consistent with this structural change as the rheobase was significantly higher than age-matched controls. The Abeta hypothesis is the dominant theory in the AD field and it suggests that overproduction of Abeta42 leads to toxic oligomers that initially cause synaptic failure in the dendritic compartment, before neuronal decay and/or death. Our data suggest that synaptic failure does indeed occur early on in FAD but that the first stage in the concomitant structural decay of neurons involves axons not spines or dendrites.

31. Microfluidic Technology for Red Fluorescent Protein Evolution. KEVIN M. DEAN¹, JENNIFER L. LUBBECK², RALPH JIMENEZ², and AMY E. PALMER¹, ¹*Department of Chemistry & Biochemistry, University of Colorado at Boulder, USA. 80309.* ²*JILA, University of Colorado Boulder and National Institute of Standards and Technology, USA. 80309.*

Next-generation single-molecule imaging necessitates fluorescent markers with superior brightness and photostability. Unfortunately, genetically encodable fluorescent proteins (FPs), which offer unparalleled labeling specificity in vivo, suffer from complex photophysical processes and emit 10-100x less photons than their small-molecule counterparts. To address these shortcomings, we have developed a microfluidic platform that couples flow cytometry with laser-based photobleaching assays on single mammalian cells in a high-throughput fashion (>20 cells/s). Flexible operating parameters allow one to control the duration and intensity of the photobleaching beam, thereby providing the opportunity to study photobleaching processes under different excitation regimes. As a result, our microfluidic photobleaching platform successfully differentiated a mixture of four RFPs (mOrange2, mCherry, TagRFP, and TagRFP-T) based upon their propensity to undergo laser-induced photobleaching. Importantly, reversible and irreversible contributions to photobleaching were identified and isolated using

different screening geometries. Current emphasis includes library construction, implementation of an optical based sorting method, and an improved molecular understanding of photobleaching in RFPs. Ultimately, given our microfluidic platforms capacity for carrying out versatile and quantitative photobleaching assays, we envision vastly improved photon output in future generations of fluorescent protein variants.

32. Time-resolved microscopy for imaging lanthanide luminescence in living cells. NIVRITI GAHLA-LAUT and LAWRENCE W. MILLER *University of Illinois at Chicago, Department of Chemistry.*

Time-resolved luminescence (TRL) measurements can detect signals from lanthanide coordination complexes or other probes with long emission lifetimes while simultaneously eliminating short-lifetime (<100 ns) autofluorescence background inherent in biological specimens. Potentially, TRL detection offers substantial advantages in sensitivity for cellular microscopy applications that are particularly sensitive to high background, such as fluorescence resonance energy transfer (FRET) measurements or single molecule imaging. However, lanthanide complexes emit far fewer photons per unit time than conventional fluorescent probes, making it difficult to rapidly acquire high quality images at probe concentrations that are relevant to live cell experiments. Here we present data showing the feasibility of rapid, high resolution cellular imaging with a TRL microscope. We describe the development and characterization of a TRL microscope that employs a light-emitting diode (LED, $\lambda_{em} = 365$ nm) for pulsed epi-illumination and an intensified charge-coupled device (ICCD) camera for gated, widefield detection. Europium chelate-impregnated microspheres were used to evaluate instrument performance in terms of short-lifetime fluorescence background rejection, photon collection efficiency, image contrast and signal-to-noise ratio (SNR). 200 nm microspheres were imaged within the time resolution limit of the ICCD (66.7 ms) with complete autofluorescence suppression. 40 nm microspheres containing ~400 chelate molecules were detected within ~1 s acquisition times. A luminescent terbium complex, Lumi4-Tb[®], was introduced into the cytoplasm of cultured cells at an estimated concentration of 300 nM by the method of osmotic lysis of pinocytotic vesicles. Time-resolved images of the living, terbium complex-loaded cells were acquired within acquisition times as short as 333 ms, and the effects

of increased exposure time and frame summing on image contrast and SNR were evaluated. The performance analyses show that TRL microscopy is sufficiently sensitive and precise to allow high-resolution, quantitative imaging of lanthanide luminescence in living cells under physiologically relevant experimental conditions.

33. Bessel Beam Plane Illumination Microscopy. LIANG GAO, THOMAS PLANCHON, and ERIC BETZIG *Janelia Farm Research Campus, Howard Hughes Medical Institute, 19700 Helix Drive, Ashburn, VA 20147*

Plane illumination microscopy represents an attractive approach for *in vivo* volumetric fluorescence imaging due to its optical sectioning capability, high imaging speed and low photobleaching rate. However, the diffraction of Gaussian beams dictates a tradeoff between the excitation sheet thickness and the field of view within the specimen: over cellular dimensions (~50 μm), sheets several μm thick are required. Therefore, subcellular studies have rarely benefited from plane illumination microscopy.

In the Bessel beam plane illumination microscope, Bessel beams are used instead to create the excitation light sheet. Due to their ability to propagate over long distances with minimal spreading, they produce sub- μm thick light sheets yielding isotropic, diffraction limited resolution (~0.4 μm) and high speed (10 ms/plane) subcellular volumetric imaging were realized over cellular-sized fields of view (50 x 50 x 80 μm), all with >10x slower photobleaching than in confocal microscopy.

As demonstrated in multicolor images of fixed cells, and high speed two-photon imaging of live cells over hundreds of image volumes, Bessel beams facilitate the extension of plane illumination microscopy from the multicellular, micron-level domain to the subcellular, nanometric-level one.

34. Arrays of nanoapertures for examining membrane organization and dynamics. CHRISTOPHER V. KELLY, DAVID HOLOWKA, BARBARA BAIRD, and HAROLD G. CRAIGHEAD *Chemistry and Chemical Biology Department, School of Applied and Engineering Physics, Cornell University, Ithaca, NY*

Nanoscale domains in the plasma membrane may be responsible for a variety cellular signaling processes via membrane receptor clustering and lipid

phase partitioning. However, current experimental approaches are limited in spatial and/or temporal resolution to address many membrane domain hypotheses. We have developed a new approach utilizing an array of nanoapertures to examine membrane organization and dynamics with near-field optical fluorescent microscopy without incorporating a scanning probe or disturbing the membrane. These nanoapertures are glass-filled, cylindrical pores (≥ 50 nm diameter) in a thin aluminum film on a fused silica support, and they provide a planar surface for unperturbed cell growth. A nanoaperture confines the transmitted excitation light to a sub-diffraction limited spot directly above aperture, providing a 40-fold decrease in the illuminated area versus diffraction-limited illumination of the plasma membrane. Otherwise conventional microscopy excitation sources and fluorescent probes are used to enable fluorescence correlation spectroscopy (FCS) with 50 nanometer and 1 microsecond resolution. Further, these apertures provide two key benefits for FCS in addition to improved resolution: assured alignment of numerous illumination spots for cross-correlations and assured focusing of illumination on the cellular membrane as opposed to focusing within the cytoplasm. Chromatic aberrations and slight laser misalignment that may complicate far-field, two-color FCS are not of concern here since the illumination profile is determined by the aperture directly. The illumination is confined both laterally and vertically over each aperture and, consequently, fluorescence from within the cytoplasm is diminished and there is no need for z-scanning to ensure proper focusing on the membrane. This technique has been applied to both model and living cell membranes to examine the correlated diffusion of lipids and proteins. In particular, results will be presented demonstrating the effectiveness of this technique to observe induced cross-correlation of membrane proteins and lipids in varying phases.

35. Synaptic Depression and Recovery at the *C. elegans* Neuromuscular Junction. QIANG LIU, GUNTHER HOLLOPETER, and ERIK JORGENSEN *Howard Hughes Medical Institute, Department of Biology, University of Utah, Salt Lake City, UT*

C. elegans neuromuscular junctions manifest short term depression upon high frequency stimulation. The mechanisms of the synaptic depression at this model synapse are unknown. Here we induce depression with channelrhodopsin-2 variant ChIEF at acetylcho-

line neuromuscular junctions and dissect the depression process into multiple components to analyze its molecular mechanisms. ChIEF has less inactivation than channelrhodopsin-2 and a conditioning light pulse stimulation completely eliminates the remaining inactivation resulting in train stimuli with uniform strength. Postsynaptic nicotine acetylcholine receptor desensitization partially contributes to synaptic depression. *Punc-17::ChIEF* was crossed into *acr-16* background and repetitive stimulation reveals presynaptic depression. Under such conditions, acetylcholine currents evoked by a train of 10Hz stimulation depress exponentially with two time constants. The fast time constant of ~73 msec could potentially be due to voltage-gated calcium channel inactivation or depletion of readily releasable pool. The slow time constant of ~18.4 sec may reflect the depletion of reserve pool. After synaptic depression induced by 10Hz stimulation for 30 sec, acetylcholine current recovers following a two-order exponential time course. Surprisingly, loss of function of either clathrin heavy chain or dynamin-1 by temperature-sensitive mutation does not eliminate the recovery from depression. However, dynamin-1 ts mutation slows down the recovery time course, and reduces mini frequency but increases the percentage of large minis. The exact mechanisms remain to be uncovered. Furthermore, spontaneous release is not depressed by high frequency stimulation, but potentiated following hyperpolyrization by halorhodopsin, suggesting there might be two independent pools of vesicles at the synapse. In summary, our preliminary results demonstrate that synaptic depression and recovery at the *C. elegans* acetylcholine neuromuscular junction are complex multi-components process. Further in-depth genetic and electrophysiological studies are required to dissect out all the individual cellular and molecular steps.

36. X-ray structure of a blue-light dependent DNA binding protein. HARTMUT LUECKE, *University of California at Irvine*

Environmental sensory proteins play a crucial function for cellular adaptation in response to changing conditions. These proteins frequently contain effector (e.g. catalytic) domains whose activity is regulated by specialized sensory domains that detect alterations in local conditions, often utilizing small molecule cofactors to do so. One widely distributed class of such sensory domains is the PAS (Per-

ARNT-Sim) family, whose members typically regulate protein/protein interactions in response to changing environmental conditions. A subset of PAS domains use flavin cofactors to detect changes in blue light intensity or redox state, leading to their naming as the Light-Oxygen-Voltage (LOV) subfamily. These domains are found in proteins that control biological responses as diverse as phototropism, seasonal gene transcription and bacterial stress responses. To do so, LOV domains control a wide range of output domains, including kinases, F-boxes and DNA binding domains. How can one class of small, light-regulated proteins control such a diverse group of outputs?

We obtained a 2.1 Å resolution structure of dark state EL222 using X-ray crystallography. The N-terminal domain adopts the expected mixed a/b LOV domain fold. We observed a single FMN molecule within the core of this domain, oriented such that the Cys75 S_γ atom is only 3.9 Å from the C4a position of the flavin isoalloxazine ring, ready for the photochemical formation of the adduct. Following the LOV domain is a helical linker, as seen with AsLOV2 and YtvA. Interestingly, this helical linker associates more closely with the HTH domain, rather than being docked onto the β-sheet surface as in AsLOV2. This arrangement allows the EL222 LOV β-sheet surface to interact directly with the HTH domain via its 4α helix and loop between the 2α and 3α helices. This interface is analogous to that used by other LOV and PAS domains to bind their respective effectors. This interface combines both hydrophobic interactions between the domains as well as a hydrogen bond between the Arg215(HTH) guanidinium and Ser137(LOV) hydroxyl groups. Hydrophobic interactions between the two domains involve Leu102 and Leu120 on the LOV β-sheet pointing towards the HTH helix 4α residues Val214 and Val218. As in the structures of NarL and DosR, the EL222 regulatory LOV domain contacts the HTH dimerization helix (4α); however, the LOV domain does not contact the DNA-binding recognition helix (3α) directly, as observed with the regulatory domains of these other structures. Such structural comparisons supported our hypothesis that EL222 fails to bind DNA in the dark by a combination of (a) sequestration of the likely dimerization interfaces (LOV β-sheet; HTH 4α helix) and (b) steric interference by the LOV domain with HTH-DNA interactions.

We next employed a series of solution biophysical methods to establish that adduct formation correlated with conformational changes within EL222. Limited chymotrypsin proteolysis provided initial insight based on differential protease accessibility to a susceptible region of the protein. To probe these conformational changes at a higher resolution, we used solution NMR spectroscopy. Using a combination of triple resonance and NOESY data, we assigned 81% (40%) of the protein backbone (side chain) ^{15}N , ^{13}C and ^1H chemical shifts of EL222 in the dark state. These assignments, combined with through-space ^1H - ^1H NOE data, let us confirm that the crystal and solution state samples have similar secondary (and likely tertiary) structures. Upon illumination, we observed many chemical shift and peak intensity changes throughout the length of the protein.

Taken together, our data demonstrate that conformational changes propagate through the LOV domain upon illumination, disrupting inhibitory LOV-HTH interactions mediated by the LOV β -sheet. To test this, we mutated a site predicted to constitutively break the interaction between the LOV and HTH domains in an attempt to generate a mutant locked in the DNA-binding conformation (L120K). Gel shift assays conducted under dark-state conditions demonstrated that EL222 L120K bound DNA similar to wild type under lit-state conditions. Limited proteolysis of L120K using chymotrypsin showed little difference between the protein in the dark or lit state, with both resembling the lit state of wild-type protein.

37. A BioTIFF-based strategy for annotating digital microscopy-based biophysical result in a way that supports large scale indexing and retrieval of specific results from large collections. PETER PENNEFATHER and WEST SUHANIC, *Laboratory for Collaborative Diagnostics, Leslie Dan Faculty of Pharmacy, University of Toronto, 144 College St., Toronto ON, Canada, M5S 3M2*

At the 2010 Biophysical Society meeting we described how BioTIFF code (www.biotiff.org) enables all metadata needed to interpret a given digital image region to be embedded within the same file structure used to store that image. We examined how such a system could be used for creating an atlas for the trillion synapses found in a mouse brain. This metadata can be indexed so that Google-like queries can be performed to explore that petabyte data-set. Since indexing can be done either on a single local set of

BioTIFF images or a distributed set of images using a distributed file server, such a system allows a type of collaborative science that will be needed to make sense of synaptic structure and function. The distributed index enables exploration of image relationships across different subsets of images within large sets. Single cell, or single synapse, or single molecule responses measured using digital microscopy-based biophysical methods, which relate cellular mechanism to light-based surrogate measures, can be linked to a specific cell in a specific field-of-view of a specific sample and compared to abstract models of how that cell should have behaved given the circumstances. The replication of such results over time in the same lab or in a distributed manner by multiple labs can allow for collaborative replicable science to anchor evolution of shared understanding of cell physiology mechanisms. We will demonstrate how the approach can be implemented using a plurality of commodity gear meeting certain minimum standards and open source imaging, indexing and search software. This level of transparency and annotation of experimental detail allows for differences in experimental conditions between experiments and labs to be accommodated in open collaborative interpretation of biophysical data. Some form of BioTIFF-like application will be necessary for application of advanced cellular imaging in addressing general physiology questions.

38. Imaging protein-protein interactions in living cells with time-resolved LRET microscopy. HARSH-SHA E. RAJAPAKSE and LAWRENCE W. MILLER *University of Illinois at Chicago, Department of Chemistry.*

Proteins interact transiently to control nearly all cellular processes. Currently, Förster resonance energy transfer (FRET) microscopy is the only means available to dynamically map the spatio-temporal organization of protein-protein interactions in living cells. Steady-state imaging of intermolecular FRET between two fluorescent protein fusions (the most popular FRET microscopy method) is limited by substantial non-FRET fluorescence background that can obscure small FRET signals. Here we show that time-resolved microscopy of luminescence resonance energy transfer (LRET) can image protein-protein interactions within living cells with 50-fold greater signal-to-background ratio and 5-fold better temporal resolution than conventional FRET methods (Rajapakse, Gahlaut, Mohandessi, Yu, Turner, Miller. 2010. *Proc.*

Natl. Acad. Sci USA 107:13582-13587). A luminescent terbium complex, TMP-Lumi4, was introduced into cultured Madin Darby Canine kidney (MDCK) cells and shown to bind specifically and stably to transgenically-expressed *Escherichia coli* dihydrofolate reductase (eDHFR) fusion proteins. LRET between the eDHFR-bound terbium complex and green fluorescent protein (GFP) was detected as long-lifetime, sensitized GFP emission. Background signals from cellular autofluorescence and directly excited GFP fluorescence were effectively eliminated by imposing a time delay (10 μ s) between excitation and detection. Background elimination made it possible to detect interactions between the first PDZ domain of ZO-1 (fused to eDHFR) and the C-terminal YV motif of claudin-1 (fused to GFP) in single microscope images at sub-second time scales. We observed a highly significant ($P < 10^{-6}$), six-fold difference between the mean, donor-normalized LRET signal from cells expressing interacting fusion proteins and from control cells expressing non-interacting mutants. Ongoing development of this technique will make a greater variety of molecular interactions amenable to real-time visualization within living cells.

39. Hybrid SHG-TPEF Microscope for 3D Sarcomere Imaging. YONGHONG SHAO¹, HONGHAI LIU², RUI WANG², LUCAS SCHMIDT², TOMNG YE³, and BRUCE Z. GAO² ¹*Institute of Optoelectronics, Shenzhen University, Shenzhen, PR China,* ²*Department of Bioengineering, Clemson University, Clemson, SC, USA,* ³*Department of Neurobiology, University of Alabama at Birmingham, Birmingham, AL, USA*

Imaging systems based on Second harmonic generation (SHG) and two-photon excitation fluorescence (TPEF) have the advantages of intrinsic high-resolution and high-contrast for three-dimensional biomedical research. In particular, Since SHG is a coherent nonlinear optical phenomenon that originates from polar molecules organized in noncentrosymmetric structures, such as collagen fibers, microtubules, and contractile proteins of muscle fibrils, the polarization SHG images can show the fine molecular structures of the samples. We have developed a hybrid SHG-TPEF polarization imaging system in which the SHG and TPEF signals from samples are recorded by two PMTs in the forward and backward direction respectively. We report the application of this system to study the myofibrillogenesis in heart muscle cells. Several models of myofibrillogenesis had been proposed in the previous research. Some lipid membrane-embedded proteins, such as integrins, were supposed to be responsible for the beginning of myofibrillogenesis when they received stimulating signals from the environments. Therefore, determining the relationship between the cell membrane and the myofibrillogenetic sites is critical. However the lipid membrane is easily affected in cellular immunofluorescent procedures while the cells are being fixed and stained. Using this newly developed hybrid SHG-TPEF polarization imaging system, we obtained 3D images of the sarcomere via SHG and DiO stained lipid membrane via TPEF simultaneously in live cardiomyocytes isolated from neonatal and adult rat. To increase the axial resolution, temporal focusing mechanisms was employed. The results showed the potential of SHG and TPEF in the research of myofibrillogenesis.