BP 5: Tissue Mechanics I

Time: Monday 15:00–18:00 Location: H 0110

BP 5.1 Mon 15:00 H 0110

Polydispersity-Mediated Crystallization in the Developing Fruit Fly Wing — •Kartik Chhajed[1], Marko Popović[1], and Frank Jülicher[1,2] — [1]Max-Planck-Institut für Physik komplexer Systeme, Nöthnitzer Straße 38, 01187 Dresden — [2]Center for Systems Biology Dresden, Pfotenhauerstraße 108, 01307 Dresden

During development of the fruit fly wing the cellular packing in the wing epithelium transitions from a disordered packing to an ordered, crystalline packing. We investigate biophysical mechanisms controlling this crystallization process. While previous studies highlight the role of tissue shear flow in establishing the ordered cell packing, we find that in fly wings where tissue flows have been inhibited the cells still transition from disordered to an ordered packing. Instead, we propose that the transition is controlled by the cell size heterogeneity, which is quantified by the cell size polydispersity. We use vertex model of epithelial tissues to show that there is a critical value of cell size polydispersity above which cellular packings are disordered and below which they form a crystalline packing. Furthermore, by analyzing experimental data we find that cell size polydispersity indeed decreases during the fly wing development in the wild-type wings, while in perturbed wings where cells remain heterogenous in size cellular packing remains disordered. Finally, we find that although tissue flows do not control the transition they do significantly enhance the tissue scale order as they help align locally ordered crystallites on the tissue scales.

BP 5.2 Mon 15:15 H 0110

The fluid mechanics of the first folding event of the zebrafish forebrain — Angus Inman[1], Judith E. Lutton[2], Elisabeth Spiritosanto[1], Masazumi Tada[3], Till Bretschneider[2], •Pierre A. Haas[4,5,6], and Michael Smutny[1] — [1]Centre for Mechanochemical Cell Biology and Division of Biomedical Sciences, Warwick Medical School, University of Warwick — [2]Department of Computer Science, University of Warwick — [3]Department of Cell and Developmental Biology, University College London — [4]Max Planck Institute for the Physics of Complex Systems — [5]Max Planck Institute of Molecular Cell Biology and Genetics — [6]Center for Systems Biology Dresden

The formation of complex tissues during development relies on robust spatiotemporal coordination of mechanical forces between different tissues or in complex geometries.

Here, I will show how such inter-tissue forces underpin the first folding event in the developing zebrafish forebrain [bioRxiv:2023.06.21.545965v1]. I will develop a fluid mechanical model of tissue flows during zebrafish gastrulation to identify the minimal set of spatiotemporally varying regularised force singularities required to reproduce the topological features of the observed tissue flows qualitatively. I will then discuss how we have tested these predictions in vitro and in silico: I will show in particular that this minimal set of singularities is also sufficient to reproduce the observed tissue flows quantitatively and I will explain how our combined experimental and theoretical results show that the coordination of different mechanical processes in different tissues is required for correct folding of the zebrafish forebrain.

BP 5.3 Mon 15:30 H 0110

Minimal vertex model explains how the amnioserosa tissue remains solid during Drosophila dorsal closure — •Daniel Haertter[1,2], Indrajit Tah[3], Janice M. Crawford[4], Daniel P. Kiehart[4], Christoph F. Schmidt[2], and Andrea J. Liu[3] — [1]Institute of Pharmacology and Toxicology, University Medical Center Göttingen, Germany — [2]Department of Physics, Duke University, NC, USA — [3]Department of Physics and Astronomy, University of Pennsylvania, PA, USA — [4]Department of Biology, Duke University, NC, USA

Dorsal closure is a process in *Drosophila melanogaster* embryogenesis during which the amnioserosa (AS), a one-cell-thick epithelial tissue that fills the dorsal opening, shrinks as the lateral epidermis sheets converge and eventually fuse. This process results in a significant increase in the aspect ratio of the AS cells. Contrary to predictions of the standard vertex model, which suggests tissue fluidization by cell rearrangement, the AS retains its elastic solid properties without such changes. We introduce a two-dimensional cellular vertex model that accounts for the ability of the AS to sustain this behavior. The model demonstrates that the continuous decrease in preferred cell perimeter and variability in cell perimeter size are key factors in maintaining the solid state of the AS. Our model effectively replicates observed changes in cell shape and orientation and indicates a non-uniform pattern of junctional tension, which we verify through laser ablation experiments.

BP 5.4 Mon 15:45 H 0110

Quantification of Glioblastoma Mechanics in Brain Organoids Using Ferrofluid Droplets — •Michael Frischmann[1,2], Elijah R. Shelton[1], Achim T. Brinkop[1], Sofia Kalpazidou[3], Jovica Ninkovic[3], and Friedhelm Serwane[1,4] — [1]Faculty of Physics and Center for NanoScience, LMU Munich, Germany — [2]Faculty of Medicine, LMU Munich, Germany — [3]Biomedical Center, LMU Munich, Germany — [4]SyNergy and GSN, LMU Munich, Germany

Glioblastoma, a highly malignant brain tumor, has a median patient survival of a few months untreated, due to its rapid, infiltrative and destructive growth. Although its molecular biology is well described, knowledge about the mechanical properties and forces that enable its invasive spread is limited. We used cerebral organoids derived from induced pluripotent stem cells (iPSCs) and implanted with patient-derived glioblastoma cells as an *in vitro* model. To measure its viscoelastic properties, ferrofluid droplets were utilized. The mechanical properties were determined from the droplets' dynamic strain curves via a custom modular analysis pipeline developed in Python. This approach allowed quantifying viscous behavior of the tumor tissue on time scales from seconds to minutes. At short time scales, we determined an elastic modulus of $E = (0.96 \pm 0.27)$ kPa, which is consistent with previous elasticity measurements performed in patient tissue. Moreover, we find a long-term viscosity of $\eta = (17.6 \pm 3.9)$ kPa s in the core tumor. A viscoelastic model of glioblastoma enhances our understanding of how brain tumors mechanically affect their environment, which is crucial for targeting the infiltration mechanism.

BP 5.5 Mon 16:00 H 0110

Poking a very soft elastic shell — •Shiheng Zhao[1,2,3] and Pierre Haas[1,2,3] — [1]Max Planck Institute for the Physics of Complex Systems — [2]Max Planck Institute of Molecular Cell Biology and Genetics — [3]Center for Systems Biology Dresden

Biological tissues are very soft materials: Their linear elastic constants tend to be several orders of magnitude smaller than those of conventional soft materials. At the same time, biological tissues undergo large deformations during development, suggesting that their nonlinear elastic behaviour is much more important than that of conventional soft materials.

Here, we therefore consider the simplest model of an elastic material with zero linear shear modulus, i.e. of a purely nonlinearly elastic material. We extend the paradigmatic "Pogorelov dimple" problem of classical elasticity [1] to this "supersoft" material: An elastic spherical shell is poked by a concentrated, point force. Strikingly, our numerical calculations reveal novel scaling behaviour of the force-displacement relation, with an exponent 3/2 for this "supersoft" material, different from the classical exponent 1/2. We develop an elastic shell theory and a scaling argument to explain this exponent, and we characterise numerically the transition between the two scaling regimes as a small, nonzero linear shear modulus is added. Excitingly, the results suggest that the nonlinear contributions to tissue elasticity can be measured from the scaling behaviour in poking experiments.

[1] A. V. Pogorelov, Bendings of surfaces and stability of shells (American Mathematical Society, Providence, RI, 1988).

15 min. break

Invited Talk BP 5.6 Mon 16:30 H 0110

Sculpting embryos through fluid-to-solid phase transitions — •Otger Campas — Physics of Life Excellence Cluster, TU Dresden, Germany

During embryonic development, cells self-organize to build functional structures, like tissues and organs, and progressively shape the organism. While many key molecular players that orchestrate embryonic development are known, the physical mechanisms underlying embryonic morphogenesis remain unclear. Performing direct measurements of the tissue physical state in situ and in vivo using microdroplet techniques, I will show that embryonic tissues undergo fluid-to-solid (rigidity) tran-

sitions that are controlled in space and time to guide morphogenesis. First, I will discuss body axis elongation in vertebrates and show that posterior tissues are fluid-like at their elongating end and become solid-like as they mature anteriorly through a jamming transition of the cell collective. Beyond axis elongation, I will discuss a new nuclear jamming transition that controls tissue architecture during vertebrate eye and brain organogenesis.

BP 5.7 Mon 17:00 H 0110

Mechanically-driven stem cell separation in tissues caused by progeny outflux — •Johannes C. Krämer[1], Edouard Hannezo[2], Gerhard Gompper[1], and Jens Elgeti[1] — [1]Theoretical Physics of Living Matter (IBI-5/IAS-2), Forschungszentrum Jülich, 52425 Jülich, Germany — [2]Institute of Science and Technology Austria, 3400 Klosterneuburg, Austria

The homeostasis of epithelial tissue relies on a balance between the self-renewal of stem cell populations, cellular differentiation, and loss. We expand the two particle growth model [1,2] to incorporate the text book picture of tissue renewal by stem cells and the corresponding differentiation cascade [3], and find that the model generates unexpected dynamic features: stem cells repel each other in the bulk tissue and are thus found rather isolated, as in a number of in vivo contexts. We demonstrate that this repulsion can be quantitatively described by mapping it to an ensemble of passive Brownian particles with effective repulsive interactions. The effective interaction potential between a pair of stem cells decays exponentially with a characteristic length that spans several cell sizes, corresponding to the outflux volume of differentiated cells generated per stem cell division. By introducing stochastic cell fate decisions we find that tissue pressure controls the stem cell number. Our findings may help understanding the dynamics and evolution of normal and cancerous epithelial tissues.

[1] M. Basan et al 2011 Phys. Biol. 8 026014;
[2] N. Podewitz et al 2015 EPL 109 58005
[3] J. C. Krämer et al 2023 arXiv:2310.04272 [physics.bio-ph]

BP 5.8 Mon 17:15 H 0110

Wrinkling instability in unsupported epithelial sheets — •Urska Andrensek[1,2], Primoz Ziherl[1,2], and Matej Krajnc[1] — [1]Jozef Stefan Institute, Ljubljana, Slovenia — [2]Faculty of Mathematics and Physics, University of Ljubljana, Slovenia

We investigate the elasticity of an unsupported epithelial monolayer and we discover that unlike a thin solid plate, which wrinkles if geometrically incompatible with the underlying substrate, the epithelium may do so even in absence of the substrate. From a cell-based model, we derive an exact elasticity theory and discover wrinkling driven by the differential apico-basal surface tension. Our theory is mapped onto that for supported plates by introducing a phantom substrate whose stiffness is finite beyond a critical differential tension. This suggests a new mechanism for an autonomous control of tissues over the length scale of their surface patterns.

BP 5.9 Mon 17:30 H 0110

A model of epithelial folding through local degradation of an elastic basement membrane plate — •Karla Yanin Guerra Santillan[1,2], Caroline Jantzen[1], Christian Dahmann[1,2], and Elisabeth Fischer-Friedrich[1,2,3] — [1]Cluster of Excellence Physics of Life, Technische Universität Dresden, Dresden, Germany. — [2]School of Science, Technische Universität Dresden, Dresden, Germany. — [3]Biotechnology Center, Technische Universität Dresden, Dresden, Germany.

Epithelia are polarized flat layers of cells that line the surfaces of organs. On the basal side, the epithelial cell layer is supported by a basement membrane - a thin polymeric layer of self-assembled extracellular matrix (ECM) that plays a crucial role in shaping healthy organs during organism morphogenesis. Previous research on the larval wing disc of Drosophila melanogaster notes a connection between localized basement membrane degradation and epithelial folding.

In this study, we introduce a unique approach to understanding epithelial folding by integrating a plate theory model of the basement membrane with experiments. Our theoretical model considers force balance within the basement membrane and interactions with the cell layer, explaining epithelial folding during local plate degradation with a preexisting balance of active and passive mechanical prestress.

To validate our theoretical framework, we conducted experiments exploring the influence of cell-internal hydrostatic pressure and basolateral contractility on fold depth, confirming their pivotal roles in fold shape.

BP 5.10 Mon 17:45 H 0110

The Geometric Basis of Epithelial Convergent Extension — Fridtjof Brauns[1], Nikolas H. Claussen[2], and •Boris I. Shraiman[1,2] — [1]Kavli Institute for Theoretical Physics, University of California Santa Barbara, Santa Barbara, California 93106, USA — [2]Department of Physics, University of California Santa Barbara, Santa Barbara, California 93106, USA

Animal development requires large numbers of cells to choreograph their force generation in order to sculpt tissues and organs. Leveraging the fact that cellular forces equilibrate rapidly compared to the speed of development, we formulate a geometrical model for the network of balanced active tensions in an epithelial sheet. Within this framework, we can investigate how cells remodel the tension network to change tissue shape. A simple "winner-takes-all" mechanical feedback loop can self-organize complex cell movement, matching experimental data on the cell and tissue scale. We find that the ability to self-organize depends on initial order in the cellular packing. Our model explains how genetic patterning, embryo geometry, and cellular packing geometry combine to determine tissue shape change.