DY 47: Focus Session: Nonlinear Dynamics of the Heart I (joint session DY/BP)

Time: Thursday 9:30–12:45 Location: ZEU 118

Invited Talk DY 47.1 Thu 9:30 ZEU 118

Nonlinear dynamics of cardiac arrhythmias in the long QT syndrome — •Alain Karma — Northeastern University, Boston, USA

Long QT syndrome is associated with fatal ventricular arrhythmias promoted by triggered activity in the form of early afterdepolarizations (EADs). This talk will review recent progress to understand the genesis of EADs and associated life-threatening arrhythmias at cellular and tissue scales using a combination of computational and experimental studies. Computational studies make use of a physiologically detailed computational model of calcium (Ca2+) cycling and membrane voltage dynamics that bridges the submicron scale of individual couplons of plasmalemmal L-type Ca2+ channels clusters and sarcoplasmic reticulum (SR) Ca2+ release units (CRUs) and the whole cell. Experimental studies make use of large animal transgenic rabbit models that mimic human mutations associated with most common forms of the long QT syndrome types 1 and 2. The results, obtained by iterations between modeling and experiments spanning ion channels, cellular, and organ scales, highlight the important roles of the coupling between intracellular Ca2+ cycling and voltage dynamics in the genesis of cellular EADs and tissue-scale spatial heterogeneities in the initiation of arrhythmogenic premature ventricular contractions.

DY 47.2 Thu 10:00 ZEU 118

Understanding the origin of line defects in heart tissue. — •Marcel Hörning[1], Alessio Gizzi[2], and Alessandro Loppini[2] — [1]University of Stuttgart, Stuttgat, Germany — [2]University Campus Bio-Medico of Rome, Rome, Italy

Spatiotemporal patterns are observed in a wide range of excitable systems. They have important and diverse regulatory functions, such as regulation of cell migration of Dictyostelium cells, synchronization of electrophysiological dynamics in the cerebral neocortex, and maintenance of the contractility and cardiovascular blood circulation in mammalian hearts. In the heart, excitable waves can form complex oscillatory and chaotic patterns even at an abnormally higher frequency than normal heart beats, which increase the risk of fatal heart conditions by inhibiting normal blood circulation. Previous studies suggested that the occurrence of line defects in alternans play a critical role in the stabilizion of those undesirable patterns. However, this nonlinear phenomenon is still poorly understood. It remains to be elucidated, how nodal lines form, what their origin is, and how they stabilises. Here we show new insights in the stability of those by observing and analysing nodal line dynamics in spiral waves that exhibit stable alternans, and giving first clues on the origin of those.

DY 47.3 Thu 10:15 ZEU 118

Optogenetic Control Spiral Wave Dynamics in Cardiac Tissue — •Sayedeh Hussaini[1,2,4], Rupamanjari Majumder[1,4], Valentin Krinski[1,4], Ulrich Parlitz[1,4], Stefan Luther[1,2,3,4], and Claudia Richter[1,4] — [1]Max Planck Institute for Dynamics and Self-Organization, Goettingen, Germany — [2]Institute for the Dynamics of Complex Systems, Goettingen, Germany — [3]Institute of Pharmacology and Toxicology, Goettingen, Germany — [4]German Center for Cardiovascular Research, Goettingen, Germany

Cardiac optogenetics may be used as a tool to elucidate the mechanisms underlying the dynamics and control of the spiral waves in the heart. Here we present a simulation study based on the ionically realistic Bondarenko model of mouse ventricular cardiomyocytes, coupled to a model for the light-activated protein Channelrhodopsin-2. We show that constant global sub-threshold illumination increases the resting membrane voltage, decreases the amplitude and the conduction velocity of the excitation wave. Periodic global illumination of the two-dimensional domain results in the transition of the spiral wave core of the trajectory from circular to epicycloidal and hypocycloidal. Using structured sub-threshold illumination, we induced spiral drift towards the boundary and subsequent termination. In the presence of an intensity gradient, the spiral wave drifts towards higher intensities.

DY 47.4 Thu 10:30 ZEU 118

Dynamics of scroll waves in a cylinder jacket geometry — Christian Bruns[1] and •Marcus Hauser[2] — [1]Institut für Biometrie und Medizinische Bioinformatik, Universität Magdeburg, Magdeburg, Germany — [2]Insitut für Biologie, Universität Magdeburg, Magdeburg, Germany

The dynamics of scroll waves in a narrow cylinder jacket-shaped reactor is investigated experimentally by optical tomography using a chemical model system. The fate of the scroll waves of excitation in the Belousov-Zhabotinsky reaction depend on the thickness of the cylinder jacket. While at sufficiently wide cylinder jackets vertically oriented scroll waves remain stable, the probability that the filaments of the scrolls hit a lateral wall increase with the shrinking width of the cylinder jacket. This may lead to the rupture of the initial filament and pinning of the filament ends at the lateral walls. Filaments that pin to opposite lateral walls shrink and reorient to a horizontal orientation; such a reorientation corresponds to a transition from an intramural to a transmural scroll wave. The kinetics of the reorientation and shrinkage of the scrolls were studied. Furthermore, we find that no new filaments were generated upon collision of excitation waves at the side of the cylinder jacket opposite to the scroll wave. Thus, under the studied conditions, we do not observe any new generation of filaments due to a phenomenon like reentry.

DY 47.5 Thu 10:45 ZEU 118

Synchronization of viscoelastically coupled cardiomyocytes — •Florian Spreckelsen[1,2,3], Stefan Luther[1,2,3], and Ulrich Parlitz[1,2,3,4] — [1]Max Planck Institute for Dynamics and Self-organization, Göttingen, Germany — [2]University of Göttingen, Institute for the Dynamics of Complex Systems, Göttingen, Germany — [3]DZHK (German Center for Cardiovascular Research), Partner Site Göttingen, Germany — [4]University Medical Center Göttingen (UMG), Institute of Pharmacology and Toxicology, Göttingen, Germany

Periodically beating cardiomyocytes coupled mechanically by a viscoelastic extracellular matrix are modelled as viscoelastically coupled excitable oscillators. Their synchronization dynamics depends on the stiffness of the coupling matrix [1].

Systems of two coupled cells and linear chains are investigated numerically. At high stiffness of the viscoelastic coupling, full in-phase synchronization is found. Partial n:n synchronization is observed in case of intermediate stiffness. In the special case of purely elastic coupling, two cells show antiphase synchronization while antiphase chimera states are found in linear chains.

The conditions necessary for the synchronization of viscoelastically coupled cardiomyocytes may give a mechanistic explanation for the importance of fibroblasts to the engineering of cardiac tissue [2,3].

[1] Spreckelsen, Luther, Parlitz, Phys. Rev. E 100, 2019
[2] Tiburcy et al., Circulation 135, 2017
[3] Schlick et al., Prog Bio Mol Bio 144, 2019

15 min. break.

Invited Talk DY 47.6 Thu 11:15 ZEU 118

Wave-particle duality of dissipative vortices and implications for cardiology — •Irina V. Biktasheva — University of Liverpool, Liverpool, UK

Recent theoretical and experimental advancements in study of dynamics of dissipative vortices (aka spiral waves) brought these studies closer to practical impact and applications than ever before.

A dissipative vortex divides homogeneous system into the core, defined by it's rotation centre, or organising filament, and the periphery synchronised by signals from the core. Perturbed vortex slowly changes frequency and location of the core. Regime synchronises all available space, though it behaves as localised object sensitive only to perturbations affecting the core. The wave-particle duality is due to localisation of vortex's Response Functions (RFs) in immediate vicinity of the core. RFs allow quantitative prediction of drift caused by small perturbations of any nature, which makes RFs as fundamental characteristics for spiral waves as mass is for the matter.

We use cardiac re-entry's RFs to predict iscaemic border zone dynamics, and define basal tissue conditions for re-entry's escape into recovered tissue to either collapse or develop fibrillation. In human atrium, we demonstrate functional effects of anatomical structures on re-entry's spontaneous drift along pectinate muscles (PM) and crista terminalis, anchor to PM-atrial wall junctions or to some locations with no obvious anatomical features. The insights might improve patient specific ablation and low-voltage defibrillation protocols.

DY 47.7 Thu 11:45 ZEU 118

Control and self-termination of spiral wave chaos — •Thomas Lilienkamp[1,2] and Ulrich Parlitz[1,2,3] — [1]Max Planck Institute for Dynamics and Self-Organization, Göttingen, Germany — [2]German Center for Cardiovascular Research (DZHK), Göttingen, Germany — [3]Institut für Dynamik Komplexer Systeme, Georg-August Universität, Göttingen, Germany

During life threatening cardiac arrhythmias like ventricular fibrillation the electrical excitation dynamics inside the heart is governed by chaotic spiral/scroll wave propagation. In experiments, it is frequently observed that the chaotic dynamics can also terminate by itself. This phenomenon can also be reproduced in numerical simulations. We demonstrate in simulations, how a system of chaotic spiral wave dynamics can be controlled using small but finite perturbations which are locallized in space and time, by exploiting the state space structure. With this, we show that a control of such systems can be achieved in principle by a minimal interaction with the system.

DY 47.8 Thu 12:00 ZEU 118

Constitutive modeling for failing heart regeneration — Moritz Kalhöfer-Köchling[1,3], Wolfram Zimmermann[2,3], Eberhard Bodenschatz[1,3], and •Yong Wang[1,3] — [1]MPI for Dynamics and Self-Organization, 37077 Göttingen, Germany — [2]University Medical Center Göttingen, 37075 Göttingen, Germany — [3]German Center for Cardiovascular Research (DZHK), Partner Site Göttingen, Göttingen, Germany

Heart failure is a common, costly, and potentially fatal condition in which the heart cannot pump enough blood to meet the body's needs. It is mainly caused by myocardial infarction, and associated with changes both in structure and function of the heart. Employing nonlinear solid mechanics, constitutive modeling is adopted to study cardiac mechanics and guide new therapy such as tissue engineered heart repair. To simulate the infarcted tissue as well as implanted engineered heart muscle, a novel class of constitutive models is proposed by considering fiber dispersion. Compared with their predecessors, those models improve the numerical stability, compute faster and are easier to implement. We also investigate the mechanical properties of heart muscle experimentally. This work was supported by the Max Planck Society and the German Center for Cardiovascular Research.

DY 47.9 Thu 12:15 ZEU 118

Synchronization-based reconstruction of the electrical dynamics of the heart — •Baltasar Rüchardt[1,3], Jochen Bröcker[4], Stefan Luther[1,2,3], and Ulrich Parlitz[1,2,3] — [1]Max Planck Institute for Dynamics and Self-Organization, Göttingen, Germany — [2]Georg-August-Universität Göttingen, Institute for Nonlinear Dynamics, Göttingen, Germany — [3]German Center for Cardiovascular Research (partnersite Göttingen), Göttingen, Germany — [4]University of Reading, Reading, UK

For more than a century, the electrocardiogram (ECG) is the standard diagnostic tool to assess cardiac electrophysiological function. The relation between the electrical excitation of the heart and the electrical potential on the surface of the body is well understood. The reconstruction of the source distribution on the heart from given ECG measurements is challenging, because information is lost when the electrical signal travels through the body in a diffusion-like process. This problem is called inverse problem of electrocardiography.

The standard methods to handle this loss are regularization methods which impose pre-defined assumptions on the problem until a solution can be found. This can exclude the true solution and, in general, does not rely on information of the underlying dynamical processes. In contrast, we show the reconstruction of the electrical state of the heart from sensor signals with reduced spatial information by means of synchronization, based on a model of the spatial-temporal electrical dynamics. We show this for a 2D excitable media heart tissue model and discuss the application to three dimensions.

DY 47.10 Thu 12:30 ZEU 118

Real-time Processing of Optical Fluorescence Videos showing Contracting Hearts using Neural Networks — •Jan Lebert[1,2,3] and Jan Christoph[1,2,3] — [1]University Medical Center Göttingen, Germany — [2]Max Planck Institute for Dynamics and Self-Organization, Göttingen, Germany — [3]German Center for Cardiovascular Research, Partnersite Göttingen, Germany

Optical mapping is an established fluorescence imaging technique for studying electrophysiological wave phenomena in isolated, intact hearts and cardiac cell cultures. Mechanical contraction of the cardiac tissue, however, can lead to severe motion artifacts in the recorded optical signals. Pharmacological electromechanical uncoupling agents have been used to compensate for these artifacts. However, recently numerical motion tracking and post-processing algorithms were developed to suppress motion artifacts and separate the recorded electrical waves from mechanical contraction.

Here, we present a deep convolutional neural network (CNN) approach for the real-time tracking of contracting and fluorescing hearts in optical mapping videos. Our approach provides a dramatic speedup in the processing of optical mapping data and superior performance over conventional optical flow estimation algorithms, which are sensitive to noise and can be irritated by fluorescence-encoded wave patterns, as they assume brightness consistency. After training the network on various experimental and synthetically generated optical mapping data, we evaluated the network's performance and found it to perform robustly under various conditions.