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Published in partnership with: Deutsche Physikalische Gesellschaft and the Institute of Physics

OPEN ACCESS

PUBLISHED
11 April 2019

EDITORIAL

Focus on bacterial mechanics

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All living organisms are subject to mechanical forces, while also generating such forces themselves. These forces shape their behavior on a broad range of length and time scales, from the molecular scale to the scale of whole organisms. Forces are key ingredients to the stepping of molecular motors, the motility of cells, the connectivity of tissues, morphogenesis and differentiation in development, and the activity and material properties of soft and hard tissues [1–6]. With the development of techniques to probe forces and to image deformations on the cellular level, the mechanics of cells has come to center stage over the last 30 years. For eukaryotic cells and tissues, such studies are now well established and form a core area of cellular biophysics.

The mechanical properties of bacteria and multicellular bacterial populations, however, have been studied much less and are much less understood. This discrepancy between our mechanical knowledge about eukaryotic cells and bacteria is mostly based on two interconnected reasons: one is the smaller size of bacteria, about an order of magnitude in linear size or three orders of magnitude in volume. This property meant that until recently, the intracellular structures of bacteria were below the resolution limit of optical microscopy. Related to that inability to observe intracellular structures such as a cytoskeleton or organelles was the widespread belief that such structures were absent in bacterial cells, which were often viewed as 'bags of enzymes'.

This situation has changed dramatically in recent years, as advances in experimental and theoretical approaches have made it possible to explore the role of mechanical forces in bacteria as well as to resolve the underlying subcellular structures [7, 8]. New themes of mechanical research on bacteria have emerged, often in analogy to the corresponding lines of research in the eukaryotic word: Bacteria were found to have abundant subcellular structures ranging from protein complexes via cytoskeletal filaments to the nucleoid and organelles [9–13]. Likewise, a variety of force-generating molecular machinery is characterized including the molecular motors of bacterial motility such as pili and flagella [14, 15], which allow bacteria to move in viscous environments, to swim against fluid flow and to penetrate host tissues in pathogenesis; the machinery of plasmid and chromosome segregation, which works against entropic and steric barriers [16]; and the machinery of cell wall synthesis and remodeling, which can cope with large mechanical stresses in the cell wall [17]. On a multicellular scale, biofilms are now understood as tissue-like multicellular structures [18, 19]. These structures include an extracellular matrix, which is a key determinant of the mechanical properties of the biofilm, and mechanical forces have key roles in its morphogenesis [7].

In general, forces do not only pose barriers, but they also provide the cells mechanisms to sense their environments, their neighboring cells, and quite possibly even their own intracellular organization. For example, magnetotactic bacteria exploit the Earth's magnetic field for navigation [20], biofilm-forming bacteria sense the presence of surfaces to induce biofilm-related genes [21, 22], and differential mechanical stresses in the cell wall lead to changes of cell shape during growth [23].

Throughout these studies, the mechanics of eukaryotic cells has served as crucial inspiration and shaped the way in which bacterial mechanics is approached. Indeed, today we often emphasize the analogies between the mechanics of bacteria and eukaryotes rather than any fundamental differences. However, some differences will likely remain, and a specifically bacterial mechanics of the cell may yet emerge. For example, all eukaryotes base their cytoskeleton on a small set of filament types that are re-used for many functions (often together with associated proteins), while bacteria exhibit a great diversity of filaments (compare the plethora of bacterial actin-related proteins to just actin in eukaryotes) [11].

Overview of the issue

In this 'Focus on bacterial mechanics', we showcase recent advances in different aspects of bacterial life that are influenced by mechanics including intracellular and multicellular organization and patterns, morphogenesis, and motility.

An important example of macroscopic spatial organization of intracellular biomolecules is chromosome segregation. A widespread system for chromosome and plasmid segregation is the ParABS system. A large amount of ParB proteins faithfully bind plasmid DNA close to the origin of replication after nucleating on an array of *parS* sites. Interestingly, the ParB cluster spreads over thousands of basepairs by forming both bonds between adjacent sites on the DNA and between distant sites along the DNA through DNA looping. In the work by Walter *et al* [24], this system is studied in terms of a statistical model of ParB binding, interaction, and DNA loop formation, which accurately predicts ParB binding profiles in agreement with previous experimental CHIP-Seq data. While the ParB cluster on DNA contains almost all ParB proteins in the cell, many membrane-embedded proteins form multiple distinct clusters. Wasnik *et al* [25] describe how multiple clusters can stably persist through constant nucleation of new clusters in the growing cell envelope. This could be highly relevant for the formation of chemoreceptor arrays, which are found periodically along the cell axis. Expansion of the cell surface due to growth might also be the underlying cause for the asymmetric distribution of a bacterial adhesin in the rod-shaped pathogen *Pseudomonas aeruginosa* observed by Cooley *et al* [26]. They found that the adhesin Psl is distributed homogeneously over the cell surface in wildtype cells. However, in the absence of a co-factor Pel, the protein is predominantly localized at the old poles of growing cells. Asymmetric distribution, in turn, lets cells detach from the surface at the old pole, with consequences on colony formation recently also described in work by Duvernoy *et al* [27].

Motility has a significant impact on cellular and multicellular organization. At the multicellular level, *N. gonorrhoeae* form microcolonies consisting of cellular aggregates on surfaces. Pönisch *et al* [28] demonstrated that pili–pili interactions are critical for the self-assembly of microcolonies. Through a computation model, the authors showed that the combination of pilus force generation and the mechanical interaction between pili of neighboring cells gives rise to cell aggregates. In individual cells, flagella enable bacteria to swim through diverse environments. Zhou *et al* [29] investigated the ability of bacteria to swim in an environment that contains a preferred orientation through the use of lyotropic chromonic liquid crystals. Here, *B. subtilis* swimming was guided by the directors that bias the orientation of the cell. The authors found that bacteria in this environment can adopt one of two swimming states: spinning along their long axis and remaining parallel to the director, but not moving in the plane of the cell, or swimming perpendicular to the directors. At the molecular level, the rotation of flagella is regulated by a chemosensory network. If the network is perturbed, Nord *et al* [30] found that the rotation of flagella pauses. In *E. coli* strains lacking the chemosensory component CheY, flagella rotation under low load pauses on average for 5 ms for multiple times per second. These pauses are distinct from the transient pauses with functional chemosensory networks and demonstrate a distinct mechanism of flagellar pausing.

Another class of cellular and multicellular organization is given by dynamic patterns. Probably the best-known system forming such a dynamic pattern is the oscillating Min system, which controls the plane of cell division in many bacteria. Here this system is studied by Kessler and Levine [31] to find generic conditions for the emergence of traveling waves in a system with components that switch between the cytoplasm and the membrane, while their total abundance is conserved, see also the comment by Kruse [32]. Patterns on a multicellular scale are discussed in the contribution by Morris *et al* [33] and Wioland *et al* [34]. In both cases, interactions with walls are crucial and guide the population behavior. In the first example, the interplay of motility, population growth and interaction with funnel-shaped barriers leads to population waves [33]. In the other, interactions with walls influence the spatial organization of a bacterial suspension and result in a directed flow of the cells [34], see also the comment by Giomi [35].

Outlook

Many questions remain and provide ample opportunities for future studies of bacterial mechanics. At the subcellular level, the lack of cytoskeletal motors raises the question how intracellular forces are generated. Is there a specific dedicated mechanism for every process that requires forces or are there generic mechanisms taking the role of the cytoskeletal motors? Does the diversity of cytoskeletal filaments correspond to an equally large diversity of mechanical properties?

At the cellular level, mechanical stimuli, both external and intracellular, have to be integrated with biochemical signaling. How is this accomplished For example, in motility, behavioral responses have to integrate chemical signals (chemotaxis) and mechanical 'signals', where the latter may either be sensed by a

mechano-responsive sensor and transduced into chemical signals in the cell or act directly as an opposing force on the motility apparatus.

Finally, at the multicellular or tissue level, there is interplay of the mechanical properties of colonies and biofilms with their population dynamics, which has not been addressed much (a notable exception is [36]). Moreover, many environmental as well as infection-related scenarios involve the interaction between different variants (mutants or phenotypically different cell types) of one species as well as multiple species (for example a pathogenic bacterium, the cells of its host and the host's microbiome).

We believe these and other questions will provide many opportunities to address the importance of mechanics for the biology of bacteria. The analogy to the more established eukaryotic cell mechanics can provide helpful guidance, but one should also expect surprises. The articles collected in this focus edition provide a window into this fascinating field, which we hope will stimulate the readers to join into our enthusiasm for the mechanics of the bacterial world.

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