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PERSPECTIVE

An Emerging Grip on the Growth of Grounded Bacteria

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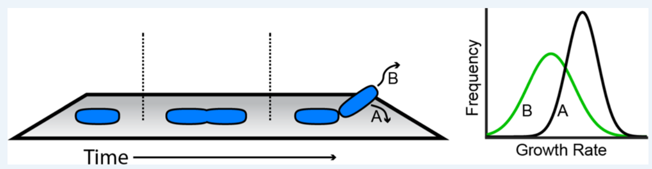
ABSTRACT: Understanding the mechanisms that are involved in determining bacterial growth rates is fundamental to infection biology, yet the factors that influence bacterial growth variation on surfaces are largely unknown. In this issue of *ACS Nano*, Lee *et al.* track individual bacteria on surfaces for several generations to discover systematic differences in growth rate variation between cells that disperse from surfaces and cells that remain attached to surfaces. These growth rate distributions were shown to be strongly influenced by extracellular motility appendages. We provide a perspective on these results and discuss prospects for future work on the interactions between bacteria and surfaces.



The study of unicellular microbes, such as bacteria, has historically been restricted to measurements taken from large populations of cells grown in liquid culture. These measurements of the average behaviors of many cells at once were the substrate for the fundamental advances of early molecular biology. However, biology has gradually been revolutionized over the past two decades by novel techniques for measuring the properties of one cell at a time. One such advance was the application of flow cytometry methods, which permit measurement and separation of single cells from suspensions using fluorescent markers for discrimination and identification. More recently, dramatic advances in microscopy and automated image processing have driven breakthroughs in our ability to measure individual cell behavior.[1−4] These single-cell techniques are currently transforming biology into a quantitative science that is more amenable to comparisons with predictive models.[5−8] In addition, single-cell measurements have compelled us to change our conceptualization of microbial behavior as the output of single-celled organisms that vary widely from one to another, rather than as the averages of large populations.

> In this issue of *ACS Nano*, Lee *et al.* show that bacteria departing from a surface-bound population vary more widely in their rate of growth than bacteria that remain attached to the surface.

Critical questions opened by these new methods include how bacteria individually vary in growth rate, and what controls their growth rate.[9,10] It has often been implicitly assumed that bacteria evolve simply to grow as quickly as possible, yet investigations of bacterial growth at the single-cell level have revealed that bacterial populations can develop a bimodal distribution of growth rates, with some cells becoming metabolically dormant, while others continue to grow.[10] Dormant cells become highly tolerant to exogenous stress, including antibiotic exposure, while the fast-growing subpopulation remains susceptible to killing.[2] These findings have motivated the idea that heterogeneity in bacterial growth rate may serve as a risk management ('bet-hedging') strategy at the clonal population level, optimizing survival in the face of different potential future environments.

How heterogeneity in bacterial growth rate arises, particularly in environments that are natural for bacteria, is an important open question. Over the past 15 years, it has become apparent that, in their natural environments and in clinical settings, many bacteria interact extensively with surfaces.[11−14] The basic patterns and underlying mechanisms by which growth rate variation arises for surface-associated bacteria are largely unknown. This topic relates to the fundamental biology of microbes, how they control surface coverage, how they transition from two-dimensional (2D) surface-attached populations to three-dimensional (3D) biofilm communities,[3,4] and how they may be exploited for technological applications including bioremediation and electricity generation.[15,16] In this issue of *ACS Nano*, Lee *et al.*[17] show that bacteria departing from a surface-bound population vary more widely in their rate of growth than bacteria that remain attached to the surface. This discovery was made possible by the development of innovative imaging methods that allowed Lee *et al.* to track bacteria over multiple generations while bound to surfaces.

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The results obtained by Lee *et al.* also implicate the involvement of extracellular motility appendages in mechanically sensing the environments and in feeding into the regulation of growth rate. These observations reinforce a new understanding that extracellular motility appendages are not, in fact, only present for the sake of motility. This conclusion is an important connection to the emerging and vibrant field of microbial mechanosensing, which includes recent discoveries of bacterial virulence regulation in response to the detection of mechanical forces by pili or flagella.[12,18,19] This field stands to gain tremendously from new and exciting techniques for labeling extracellular bacterial appendages and tracking their behavior in conjunction with new methods in single-cell resolution time-lapse imaging, such as those developed by Lee *et al.* in this issue of *ACS Nano*.

The work of Lee *et al.* may contribute to our understanding of a broad range of phenomena, for which the behavior of bacteria on interfaces is often a central component. The observation that bacteria that depart to the planktonic phase from a surface are more variable in growth rate begs the question, from an ecological and evolutionary perspective, of whether they have evolved a bet-hedging strategy in the face of uncertain resource availability after departing from a surface. The balance of growth, deposition of new cells on surfaces, and cell departure are also key parameters governing the speed and architectural pattern of 3D biofilm formation,[4,14] which are implicated widely in microbial ecology and pathogenesis.[11,20] Controlling the rate of surface occupation *versus* dispersal also has applications in bioreactor design in wastewater treatment[16] and the development of efficient extracellular electron transfer.[15] Unraveling the genetic circuitry and molecular mechanisms that translate mechanical signals into growth rate variation and understanding the evolutionary forces that selected for this behavior are exciting directions for future work on the interface of physics, chemistry, microbiology, and engineering.

> Heterogeneity in bacterial growth rate may serve as a risk management ('bet-hedging') strategy at the clonal population level, optimizing survival in the face of different potential future environments.

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Notes

The authors declare no competing financial interest.

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