Spiraling insights: Scientists observe mechanical waves in bacterial communities

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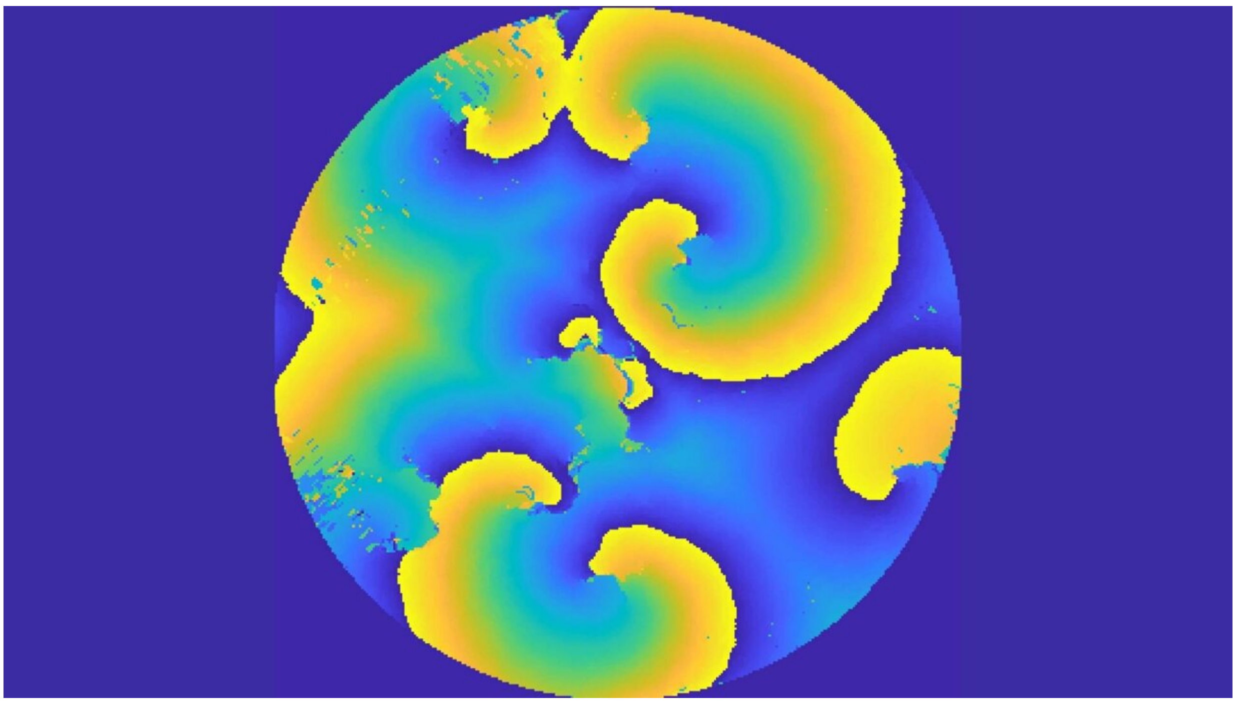

Propagating spiral waves in a bacterial film ~2 mm in diameter. The color map represents the phase angle distribution of the wave pattern. Credit: Dr. Shiqi Liu

A new study by researchers from The Chinese University of Hong Kong has reported the emergence of mechanical spiral waves in bacterial matter.

Spiral waves are commonly seen in artificial and natural systems (such as the heart). These emerge from interactions of neighboring elements, such as cardiac cells in the case of the heart. These spiral waves can have varying effects, sometimes leading to life-threatening conditions like fibrillation in the heart.

The new study, published in *Nature Physics*, explores spiral waves in bacteria—something that has not been observed before. In particular, the researchers' focus was on the species Pseudomonas aeruginosa. These are commonly found in soil and water and are also known to colonize hospitals.

The research is a continuation of their previous work where the authors studied long-range material transport in bacterial communities via open fluid channels.

Co-author of the study, Dr. Shiqi Liu, told Phys.org, "While we studied the development of bacterial canals, we discovered signatures of density waves and were intrigued by this beautiful wave pattern."

Pilus motors

These spiral waves as observed by the researchers in bacteria are an emergent phenomenon. Emergent phenomena are a crucial aspect of complex systems, which are systems where the interaction of individual entities leads to phenomena that otherwise can't be observed.

This means we need to understand what is happening at the level of each entity, which in this case is a Pseudomonas aeruginosa bacterium. These bacteria have pilus motors, which are the key to the spiral waves.

Pilus motors are molecular motors, which are attached to pili—thin, hair-like appendages present on the bacterial cell surface. These motors play an important role in various processes for the bacterium, such as movement and surface attachment.

"The propagating spiral waves resulted from the coordinated activity of the pilus motor, a grappling-hook-like motile organelle found in many bacterial species," explained a co-author of the study, Dr. Yilin Wu.

The mechanical movements of the pilus motors in many bacteria result in these spiral waves, which are like ripples on the bacterial surface.

Protein markers and coupled oscillators

To study the spiral waves, the researchers employed both experimental techniques and mathematical modeling.

The researchers relied on using fluorescent protein as markers. They tracked the movement of individual cells by labeling a small fraction of the population with these fluorescent proteins.

Then, they used a microscope to observe the behavior of individual bacteria and bacterial populations. Researchers also used the markers to track cell densities to visualize the spatial distribution of cells within the bacterial populations.

To further understand the role of pilus motor activity in spiral wave generation, the researchers treated bacterial populations with drugs known to affect pilus motor activity. By observing the effects of these treatments on wave dynamics, they could infer the importance of pilus motors in wave formation.

Finally, the researchers developed a mathematical model based on coupled oscillators, where the movement of one oscillator affects the others and vice versa. The mathematical model was built to simulate the behavior of bacterial populations and to validate their experimental work.

Non-reciprocating interactions and large-scale coordination

The researchers found that the spiral waves resulted from the coordinated activity of pilus motors. They also observed that the waves were self-sustaining and stable, with nearly stationary spiral cores.

This stability is a characteristic shared by certain types of electrical and chemical spiral waves found in other living systems. However, the spiral waves observed in the bacteria are distinct from the other spiral waves.

Dr. Liu explained, "The spiral tension waves we discovered in bacterial populations are due to cyclic mechanical processes at the single-cell level, distinct from the spiral waves in most chemical/biological processes, where the spiral waves are in the form of oscillating chemical concentration."

"Moreover, the spiral tension waves in bacterial populations spontaneously emerge without external stimulation or inhomogeneity, while the spiral waves in many other systems require stimulation or spatial inhomogeneity."

Further, the researchers demonstrated the role of non-reciprocal interactions between bacterial cells on the spiral waves. They found that these interactions (which are asymmetric, meaning that the impact of one cell on another is not mirrored) are essential for the stable formation of spiral waves.

Essentially, this means that these interactions can lead to a form of self-organization (or sustenance) that gives rise to collective behaviors at a large scale or emergent phenomenon, such as the propagation of spiral waves.

Biofilms and dispersal

The findings shed light on bacterial populations and behavior, such as the formation of biofilms.

When bacteria adhere to a surface, it does so by producing extracellular polymeric substances (EPS). This substance forms a structured community known as biofilm, such that the bacteria is embedded in a matrix of EPS, protecting the bacteria from environmental stresses like antibiotics and host immune responses.

This entire process, known as the formation of biofilms, is essential for the survival of bacterial colonies. The opposite of this phenomenon—dispersal—is equally important.

When bacteria within a biofilm detach and spread to new locations, it is known as dispersal. Dispersal can occur in response to environmental cues, nutrient availability, or as part of the life cycle of the bacteria.

This mechanism can help bacteria colonize new surfaces or host environments and can influence the spread of infectious diseases or the formation of microbial communities in various ecosystems.

The researchers believe that the pilus motors not only serve as mechanical actuators but also as sensors. This means that they can detect mechanical stimuli in the environment in the environment, which allows for synchronized movements within bacterial populations.

"We believe that the coordination or coupling of pilus activities allows bacterial populations to control large-scale tension forces and may influence their dispersal," explained Dr. Wu.

Therefore, understanding spiral waves can help to understand the behavior of bacterial species.

Additionally, stationary spiral waves are found in many diverse systems. "The wave pattern in the pilus-powered bacterial matter may, therefore, provide a tractable mechanical analog for investigating the origin and control of stable spiral waves in diverse living systems, such as cardiac tissues," explained Dr. Liu.

For future work, the researchers want to study how spiral waves can be controlled.

"The information may guide the control of stable spiral waves in other living systems. For instance, controlling spiral waves in heart tissues associated with life-threatening cardiac arrhythmia," said Dr. Wu.

More information: Shiqi Liu et al, Emergence of large-scale mechanical spiral waves in bacterial living matter, *Nature Physics* (2024). DOI: 10.1038/s41567-024-02457-5