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A Mathematical Model of the Influence of Hydrodynamics on Quorum Sensing in Bacterial Biofilms

Quorum sensing is the process where bacteria monitor their population density through the release of extra-cellular signalling molecules. The presence of these molecules allows bacteria to coordinate gene expression throughout the population. This process has been studied primarily in planktonic batch cultures where it is characterized primarily by a critical population density at which a quorum is induced.

In nature, bacteria predominantly form biofilms where they have been shown to be physiologically distinct from free swimming bacteria of the same species. Unlike the signal levels in batch cultures, environmental signal levels could be affected by the hydrodynamic environment in several ways. Here, we focus on two main external processes affecting the signal concentration: the diffusion of signal produced within the biofilm into the bulk fluid and the mass transfer of the signal out of the local environment due to the presence of a fluid flow over the biofilm surface.

In this study, the communication within and between bacterial biofilm colonies is the primary concern. While the shape of the biofilm can vary due to many different conditions such as the type and availability of the substrate (carbon source) used to grow the biofilms, we consider two different biofilm shapes: biofilms that have formed into continuous sheets and circular biofilms, which are idealized biofilms with a circular cross-section. We model the interaction between the signal concentration and the hydrodynamic environment using a two-dimensional mathematical model for the production, diffusion, advection, and degradation of the signalling molecule coupled with a laminar fluid flow. This coupled fluid flow/transport equations are solved numerically using finite element methods.

The presence of the hydrodynamic environment has numerous effects on the quorum sensing process. First, the presence of the fluid flow suppresses the maximum signal concentration in the domain, increasing the critical biomass density for a quorum to be induced as the flow rate is increased. This observation is expected and has been confirmed experimentally. Second, the presence of non-uniformity in the biomass density in the domain has a strong effect on the onset of a quorum. The critical signal density can be reached if there is a sufficient biomass concentration in a small region and, coupled with the advection of the signal, this can cause a significant portion of the biofilm to reach a quorum even if the total biomass density is below the critical biomass density observed in a planktonic batch culture. This leads to the observation that the conditions under which the biofilm is developed, which influences the biomass distribution in the film, can influence the experimentally measured critical biomass for a quorum to be reached. Lastly, it is observed that the advection of the signal downstream facilitates communication between isolated colonies over a finite distance that varies with the flow rate, allowing colonies that do not possess sufficient biomass for a quorum to be reached in isolation to reach a quorum due to a signal from an upstream colony.