ABSTRACT

Bacteria navigating in a chemically guided manner are under the impact of noise from at least three sources – inside the cells, at the binding sites between chemoattractants in the environment and corresponding receptors of the cells, and in the environment itself. For Escherichia coli as model system, compounded effects of these sources of noise were investigated recently by using the fractal dimensions of the trajectories of the cells as an index of the nature of population motility. It was observed that environmental noise can drive synchronized movement of a population toward a chemoattractant into stochastic chaos. Those results have been used here to explore the effectiveness of different kinds of noise filters in restoring coherent motion of the cells. An auto-associative neural filter was the best, followed by the extended Kalman filter. The performance of either filter depended on the relative rates of motion of the bacteria and the chemoattractant, and on whether the responses of the cells to fluctuations in the external chemoattractant was non-adaptive or adaptive. The results establish: (a) the validity and usefulness of fractal indexes to characterize noise-affected chemotaxis, (b) the significance of the effect of environmental noise on chemotactic motility, and (c) the effectiveness of a neural filter in rescuing coherent population movement from noise-induced chaos.

Keywords: Bacterial Chemotaxis, Chaotic Motions, Coherent Movement, Environmental Noise, Escherichia Coli, Fractal Dimensions, Intra-Cellular Noise, Noise Filters

INTRODUCTION

Many biological process may be analyzed usefully through fractal measures of the time-domain or spatial profiles of one or more key variables. The systems for which fractal analysis is applicable vary widely, as illustrated by applications to microbial flocs (Li & Leung, 2005), treatment regimens for cancer (Bizzari, Giuliani, Cucunia, Anselmi, Soto, & Sonnenschein, 2011), the dispersal of pathogenic organisms in the atmosphere (Kenkel & Irwin, 2004), and
structure function analysis of complex biological molecules (Mirny, 2011).

Although the applications cited above differ in their scope, their spatial and time domains and in the microorganisms involved, two features are common to most of them. One is the regulated movement of a population of cells (Escherichia coli in this work) in the increasing direction of a chemical stimulant, and the other is the presence of fluctuations in the observed variables due to the impingement of noise from different sources. While these features have been tacitly acknowledged to exist in these examples, other studies have concentrated specifically on the mechanistic and/or quantitative analysis of chemically driven bacterial movement per se. This phenomenon is called chemotaxis, meaning the taxis of a swarm of cells in response to a chemical stimulus. Chemotaxis has been explicitly recognized to have important implications in diverse processes such as wound healing (Agyingi, Maggelakis, & Rose, 2010), the operations of microfluidic reactors (Ahmed, Shimizu, & Stocker, 2010), the diagnosis of Alzheimer’s disease (Magdalena, 2002), and the degradation of harmful chemicals in the soil or in water8. In these and many other situations the cells move toward increasing concentration of a chemical gradient. This observation has two significant features: (a) chemotaxis generally involves cellular movement toward, and not away from, a chemical stimulant and (b) the movement is “uphill” of a gradient, which is against the normal direction of Fickian motion. Thus, most useful examples of chemotaxis have chemoattractants, and gradient sensing is a critical feature that determines population movement.

Fluctuations (or “noise”) are a ubiquitous feature of many real biological processes, including bacterial chemotaxis. The noise may emanate either from within the cells or from outside. Intra-cellular noise has received greater attention in research studies, both for its mechanisms; Rao, Wolf, & Arkin, 2002; Shibata & Ueda, 2008; Patnaik, 2012a) and for certain quantitative effects (Paulsson, 2004; Swain, Elowitz, & Siggia, 2002; Elmonet & Cluzel, 2008), than noise from two other main sources. One of these is at the sites of binding of the ligands of the chemoattractant molecules to compatible sensory receptors attached to the cells. The other source is in the extra cellular environment, whose myriad disturbances are manifested in fluctuations in the concentration of the chemoattractant. Despite having fewer quantitative analyses than intra-cellular noise, results from models of ligand-receptor binding noise (Andrews, Yi, & Iglesias, 2006; Patnaik, 2010; Sartori & Yu, 2011) and environment noise (Patnaik, 2007b; Xu & Tao, 2006) provide persuasive arguments that their permeation into chemically motile cells and subsequent interaction with intra-cellular noise can significantly distort the chemotactic behavior of a bacterial population, even driving the ensemble to stochastic chaos.

The possibility of noise-induced chaos was the subject of a recent analysis (Patnaik, 2013), and the present study extends that work to investigate whether acceptably coherent chemotactic movement can be recovered by filtering out the noise from a chaotic population of cells. In that analysis fractal dimensions were computed from the time-domain trajectories of a population of cells of the bacterium Escherichia coli moving toward a chemoattractant and subject to genetic noise within the cells, noise associated with the binding of chemical ligands to corresponding cellular receptors, and noise present in the ambient chemoattractant itself. Since it is diffident to identify separately the contributions of different sources of noise to the observed fluctuations in the chemotaxis paths, the overall fluctuations were considered as a lumped composite effect of all perturbations. Individual effects were, however, considered for each of four parameters in a recent model describing the chemotaxis of E. coli. The physical problem, the model and the computation of fractal dimensions are described below, followed by the application of noise filters to situations where cellular motility becomes chaotic under the influence of noise.
Noise-Induced Stability Analysis of a Capillary Flow Microreactor with Mixing by Radial Diffusion of Laminar Flow Profiles
