ABSTRACT

Bacteria such as Escherichia coli navigating through real environments in response to chemical stimuli are under the continual influence of perturbations (or ‘noise’) from within the cells, at the interface between the cell walls and the chemical ligands, and from the extra-cellular surroundings. These perturbations interact with one another and affect the chemosensory reactions that determine the movements of a population of cells. A recent analysis has shown that the response coefficients of certain key variables describing the chemotaxis of E. coli can vary by several orders of magnitude when the kinetic parameters are disturbed by noise-induced fluctuations, thereby inducing corresponding variations in cellular locomotion. This possibility is explored quantitatively here by using the same mathematical model as in the earlier work. The model considers the cells to be in one of three states: some cells moving toward the chemoattractant, some moving away and others in an intermediate ‘tumbling’ state. The focus was on the tumbling cells since they are the most sensitive to disturbances. Based on previous work, the fractal dimensions of the cells tracked over a length of time were used as indicators of stable or unstable chemotaxis. Results showed that while noise-induced variations in some parameters had only marginal effects on cell motility, other parameters strongly influenced the population movement. In the latter cases the chemically guided movement of the population toward the chemoattractant could, under sufficiently intense noise, become chaotic in certain intervals of time. Significantly, the time intervals for such spontaneous chaos differed from one parameter to another, being contiguous with one another, rather than overlapping. Thus at any point in time there is the likelihood of chaotic instability caused by one or more of the parameters, thereby destabilizing the population as a whole. These observations underscore (a) the importance of analyzing the effects of noise on bacterial chemosensory kinetics, (b) limiting the intensity of noise permeating the cells, and (c) the usefulness of fractal dimensions in aiding such analysis.

Keywords: Chaos, Chemotaxis, Escherichia Coli, Fractal Dimensions, Noise-induced Fluctuations, Population Instability

DOI: 10.4018/IJCCE.2015010104
INTRODUCTION

Bacteria such as Escherichia coli and Bacillus subtilis commonly occur in ecological and biological environments, where they influence the nature and functional processes of their habitats through their movements and metabolic processes. The cells do not move randomly but are guided by chemical stimuli in the environment; bacteria detect and respond to these stimuli. The responses are manifested statistically as the net movement of a population of cells either toward or away from the stimulus. The term net movement is significant because, as the model considered here shows, at any given time some cells are moving toward the stimulus and some are traveling away; however, the overall macroscopic movement of the population, measured in terms of population density, is decidedly biased in one direction. Important natural situations where such guided movements (or chemotaxis) include wound healing (Agyingi et al. 2010), the operations of microfluidic systems sustaining biochemical reactions (Ahmed et al. 2010), and the degradation of undesirable chemicals in the soil or in water (Singh and Olson 2008). These examples indicate the variety of situations in which chemotaxis has a significant role and the fact that most applications involve the movement of cells toward a stimulus, i.e., a chemoattractant.

In a chemoattractant-containing environment, as stated above, at any given time some cells are moving away from the stimulus and some toward it. Even the cells that are swimming toward the attractant do not travel directly in the most favorable direction but somewhat tangentially. Thus, the cells that move in unfavorable directions as well as those moving favorably need to have their directions corrected frequently to maintain them on the right paths. These correctional movements involve reorientations of the cells, and they are called tumbles. The straight line motions between consecutive tumbles are called runs. Runs and tumbles therefore alternate, and their relative durations determine how efficiently a population moves toward a chemoattractant. Details of the mechanisms of runs and tumbles are well known in both E. coli and B. subtilis (Berg 2000; Blake et al. 2006) but they are not relevant to the scope of this study. What is important is to recognize the simultaneous presence of three kinds of cells: those traveling away from the stimulus, those traveling toward it, and cells that are tumbling.

Unlike the carefully controlled conditions of closed vessels used in laboratory-scale experiments, most real environments are perpetually under the influence of fluctuations (or noise). Moreover, the chemoattractant is not present either as a point source or homogenously distributed, as in a well-stirred vessel, but as a mobile distribution that fluctuates under the impact of external noise (Xu and Tao 2006; Patnaik 2007a). These fluctuating molecules bind to the chemoreceptors on the cell surface, where an additional source of noise is present in the binding process itself (Andrews et al. 2006). Both sources of noise together permeate the cells, where they encounter a third source in the genetic processes (Rao et al. 2002; Kaern et al. 2005; Patnaik 2012a). Since binding with the chemoattractant initiates a chain of events in the chemosensory network, the multiple sources of noise inevitably have an impact on the kinetic parameters characterizing the chemosensory reactions.

Previous studies (Shahrezaei and Swain 2008; Shibata and Ueda 2008; Patnaik 2007a) have shown that the impingement of noise on a biochemical network can cause significant changes in cellular behavior, sometimes driving a smooth performance to acyclic or chaotic behavior. Although there are a number of mechanistic studies of noise-induced chemical instability, there are few analyses of the quantitative effects on intra-cellular reactions, particularly with respect to chemotaxis. Nevertheless, some studies of noise-driven cellular reactions (Paulsson and Elf 2006; Patnaik 2007b; Patnaik 2012b) have shown that the effect of interactive multiple sources of noise can be analyzed quantitatively and conveniently through the fractal dimensions of the principal variables. This observation is the basis of the present work, in which the effect...