Available online at www.sciencedirect.com
ScienceDirect
Journal of Theoretical Biology 242 (2006) 954–961
Journal of Theoretical Biology
www.elsevier.com/locate/yjtbi

Constructal pattern formation in stony corals, bacterial colonies and plant roots under different hydrodynamics conditions

António F. Miguel*

Department of Physics, Rua Romão Ramalho 59, 7000-671 Évora, Portugal

Received 14 March 2006; received in revised form 12 April 2006; accepted 12 May 2006
Available online 19 May 2006

Abstract

This paper explores a new application of the constructal theory, namely in describing and predicting the formation of dissimilar patterns inside elements of the same species under different hydrodynamics conditions. Our study proposes an explanation for the differences found in morphology of stony corals, bacterial colonies and plant roots. It specially provides an answer to the following question: have their shapes (architecture) been developed by chance, or do they represent the optimum structure serving their ultimate purpose? We show that in order to persist in time, these systems must evolve in such a way that an easy access to nutrients is ensured: their shapes develop in such a way as to minimize the time to reach the nutrient source. Moreover, it is also shown that it is the combination of a dispersive (diffusive) and a convective mechanism that allows for the maximization of nutrient transfer through use of the best of these mechanisms at a specific time.

In the light of this outcome, it is straightforward to conclude why the existence of an optimal architecture makes sense: it is because there is an overriding natural tendency and because the system has the freedom to morph its shape in the search for an optimal attainment of this goal within a set of constraints imposed by the situation.

Keywords: Design in nature; Dissimilar patterns; Stony corals; Bacterial colonies; Plant roots; Nutrient transport; Optimal shape; Constructal theory

1. Introduction

The multitude of patterns and shapes present in nature remains a troublesome question for scientists conducting research in the areas of life sciences. Among all the phenomena of formation and development of complex structures involving living organisms, the emergence of different patterns inside elements of the same specie has attracted the attention of scientists in recent years. In bacterial colonies growing within agar plates a variety of shapes which may be circular or branched, can be often observed depending on their environment (Shapiro, 1986; Fujikawa and Matsushita, 1991; Ben-Jacob et al., 1995; Shapiro and Dworkin, 1997). Colonies that have to cope with hostile environmental conditions have more branched growth forms than colonies of the same species from environments more rich in nutrient (Ben-Jacob et al., 1995). Additionally, it seems that the hydrodynamic motion of the environment can also affect colony growth and colony morphology (Lega and Passot, 2003).

The coral growth process also generates a wide range of morphologies. These morphologies are species specific, but can also present a high intraspecific variability (Merks et al, 2003), apparently due to variability of environmental parameters (Darke and Barnes, 1993; Anthony, 1999; Merks et al, 2003). In stony corals and other organisms with a relatively weakly developed transport system, the amount of nutrients arriving at a certain site in the tissue, and the local deposition speed of the skeleton material, is limited both by the locally available suspended material and the local amount of contact with the environment (Sebens et al., 1997; Anthony, 1999). It is known that stony corals collected from exposed growth sites, where higher water currents are found, present more spherical and compact shape, while corals of same species from sheltered sites have thin-branched morphologies (Kaandorp and Sloot, 2001; Merks et al, 2003).

---

*Tel.: +351266745372.
E-mail address: afm@uevora.pt.

0022-5193/$ - see front matter © 2006 Elsevier Ltd. All rights reserved.
doi:10.1016/j.jtbi.2006.05.010

Nomenclature

D	nutrient diffusion coefficient
L^*	transition length from dispersive to convective driven transport
l_{br}	characteristic length of bacteria population or root tips
l_c	characteristic coral length
L_{conv}	characteristic length corresponding to nutrient convective driven transport
L_{disp}	characteristic length corresponding to nutrient dispersive driven transport
n	concentration of nutrients
r	nutrient particles radius
T	absolute temperature
t	time
t^*	transition time from dispersive to convective driven transport
t_{conv}	characteristic time that correspond to nutrient convective driven transport
t_{disp}	characteristic time that correspond to nutrient dispersive driven transport
t_{lL}	critical time
u	average fluid velocity
v_c	average growth speed
w	width of the branch/needle
θ	consumption of nutrient
κ	Boltzmann's constant
γ	Cunningham slip correction factor
μ	fluid viscosity
λ	growth coefficient

Root systems constantly provide plants with water and dissolved minerals for their survival. Consequently, plants produce new roots to maximize nutrient absorption and continue to grow. The growth of root system may show intraspecific variability caused by the soil environment, mainly by the availability and distribution of nutrients (Thaler and Pages, 1998). The root systems seem to be able to respond to localized regions of high nutrient supply by proliferating or elongating root branches into these nutrient-rich patches (Robinson, 1994; Hodge et al., 1999). Plants in soil have more open and more thinly branched roots than specimens of the same species which are growing under hydroponics regime (Howard, 1994). In hydroponics, nutrients are always made readily available to the plant, and roots do not need to seek for nutrients as plants in soil do. It seems that there is a strong influence of availability of nutrient on the overall degree of compactness of the root system.

Much effort has been devoted to the search for the basic principles governing pattern formation in these living organisms. Since the pioneering work of Alan Turing (1952), several attempts have been made to provide patterns in nature with a mathematical and physical description. The development of patterns is very often approached by models of Laplacian growth (Barra et al., 2002), diffusion-limited aggregation (Witten and Sander, 1981) or the closely related Meakin (1986) and Eden models (Dahmen et al., 1998). Very often there are similarities between growth patterns that arise from these model approaches and the patterns developed by corals and bacterial colonies in nature (Lacasta et al., 1999; Kaandorp and Sloot, 2001; Merks et al, 2003; Chavarría-Krauser and Schurr, 2004). A comprehensive review of the literature on this topic can be found in Miguel (2004).

Bejan's constructal theory (Bejan, 1996, 2000; Bejan et al., 2004; Bejan and Lorente, 2005) is a hierarchical way of thinking that accounts for organization, complexity and diversity of man-made systems but also of systems that occur in nature. The principle that generates geometric structure, called constructal principle, is the search of an objective subject to specified constraints (e.g., availability of nutrient, space, etc.). This principle was enounced by Bejan (1997a) as follows: "For a finite-size system to persist in time (to live), it must evolve in such a way that it provides easier access to the imposed currents that flow through it". This is the principle of configuration generation, or the principle of design. The geometry of the system is free to change while its global performance is being maximized. The morphing of structure is the result of the conflict between the global objective and the global constraints. In other words, the resulting constructal configuration is the means by which the system achieves its global objective under the constraints.

The rapid development of constructal theory has been reviewed in several books (Bejan, 2000, 2004; Bejan et al., 2004; Rosa et al., 2004; Bejan and Lorente, 2005) and articles (Poirier, 2003; Lewins, 2003; Torre, 2004; Bejan, 2005; Reis, 2006). Specifically, biology-inspired studies are also available in the literature. Based on the argument of minimum power expenditure, Bejan (1997b, 2000) addressed some pulsating physiological processes that occur in mammalian, by relating them with body size. Bejan (2001, 2005) gave also theoretical background to the allometric laws such in order to relate body heat loss to body size (Kleiber's law). Respiratory activity has been assessed via the constructal law by Reis et al. (2004). This study describes how the best oxygen access to the alveolar tissues is provided by a flow structure composed of ducts with 23 levels of bifurcation that ends with alveolar sacs from where oxygen diffuses into the tissues. The dimensions of the alveolar sac, the total length of the airways, the total alveolar surface area, and the total resistance to oxygen transport in the respiratory tree were also obtained. Moreover, the study also reports the existence a length defined by the ratio of the square of the first airway diameter to its length that is constant for all individuals of