Surprising spatial profiles in steady flows of living cells which polarize to move

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We study the spatial spreading of living cells in a simple model which contains the following basic ingredients: exclusion (cells cannot penetrate each other), switching between two states, namely polarized and depolarized states, and migration of polarized cells. During the process of polarization, a real cell becomes motile and asymmetric, and its shape becomes elongated. A polarized cell can move, in a direction close to its axis. During the process of depolarization, the ``motor'' of the cell is deconstructed, the cell recovers a round shape, and it looses the capacity to move. For simplicity, we assume that these changes of states are random with fixed time rates, that the shape of cells switches between a circular shape and an elongated shape with fixed aspect ratio, and that the direction of polarization is drawn uniformly at random.

Cell division and cell death are of course essential phenomena in living organisms where cell migration takes place (be it during embryo development, growth, wound healing, cancerous invasion...). But we neglect them for the sake of simplicity, and to focus on the effects on the collective behavior of the cells of the migration mechanism itself. We study the settings where cells exit a spatially localized source and fall into a sink.

Thanks to extensive computer simulations in two space dimensions, we observe that, because of the interplay between cell migration, change of shape, and steric interaction (excluded volume), the steady-state spatial spreading of the cells is nontrivial, much more complicated than in a model which neglects the change of shape of the cells for instance. There is a kind of discontinuity close to the source of cells, and a continuous but highly nonlinear density profile between source and sink.

To quantitatively understand the collective behavior in the low density region close to the sink, we use a mean-field like approximation with space scale separation between short-range ballistic motion and long-range diffusive motion. To understand what happens close to the source, we use an exact solution for the probabilities of the configurations of the interacting cells in the limit of maximum cell density, which we complete with a model for the diffusion of ``holes''. Finally, matching the two regimes (which is possible if the ratio width/length of the space where cells move is not too high, i.e. if the system's shape is not very thin, quasi 1D), we are able to predict the full density profile as a function of the rates of polarization, depolarization and move only.

This study can be easily extended to three space dimensions and we checked that the results do not significantly depend on the lattice geometry one uses. We hope it will help to improve the precision of quantitative models of cell invasion e.g. in diffuse brain tumors.