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14. ABSTRACT We trained graduate and undergraduate students by involving them in research elucidating ways in which the structure and the motions of olfactory antennae affect how they encounter the concentration distributions in turbulent odor plumes as they search for the source of an odor in ambient currents or waves. We learned that the designs and motions of olfactory antennules enhance their ability to take pulsatile odor samples that are temporally and spatially discrete from each other. In the turbulent water flow typical of shallow coastal habitats, odor plumes are characterized by complex swirls of narrow filaments of high concentration near the odor source, but wider filaments of lower concentration farther from the source. Antennules only sample					
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FINAL REPORT

GRANT #: N00014-97-1-0726

PRINCIPAL INVESTIGATOR: M. A. R. Koehl

INSTITUTION: University of California at Berkeley

GRANT TITLE: Hydrodynamic Interaction Between Olfactory Antennae and Odor Plumes

AWARD PERIOD: 6/01/97 - 5/31/00

OBJECTIVE: Our objective is to train graduate and undergraduate students by involving them in research elucidating ways in which the structure and the motions of olfactory antennae affect how they encounter the concentration distributions in turbulent odor plumes as they search for the source of an odor in ambient currents or waves.

APPROACH: We have been comparing the flow through and molecule capture by arrays of chemosensory hairs on olfactory antennules from diverse marine crustaceans (lobsters, crabs, mantis shrimp). We use particle-image velocimetry to measure velocity profiles around dynamically-scaled physical models to study effects of antennule morphology and kinematics on flow near sensor surfaces. We determine how these flow fields affect the spatial and temporal patterns of molecule diffusion to the surfaces of the sensory hairs using a mathematical model. The parameters used to build our models are based on our morphometric (using SEM, TEM, light microscopy) and kinematic (using high-speed video) analyses of the antennules. We measure water velocity profiles and turbulence in the animals' habitats using acoustic doppler velocimetry; these field data are used by our collaborators at Stanford (J. Koseff) to design flow regimes in their flume that are relevant to real biosensors in coastal environments. Planar laser induced fluorescence is used to study the spatial and temporal distribution of concentration filaments in dye plumes in their flume. We place models of animals in these plumes to measure effects of flicking and distance from source on the spatio-temporal patterns of concentration encountered by antennules.

ACCOMPLISHMENTS:

Educational Accomplishments: The AASERT provided stipend for a number of graduate students who learned research approaches and techniques required for their dissertation research by working as assistants on the olfaction project. This grant provided equipment and software for the olfaction research that was also available for student use in their dissertation projects. Of the six graduate students involved in AASERT work, four have already completed their Ph.D.'s, one completed a Masters degree, and the youngest is progressing well towards her Ph.D. Undergraduate students (majoring in biology, engineering, or physics) were hired using funds from the parent grant and AASERT to participate in research in my laboratory. So far, six of these students have gone on to graduate school.

Scientific Accomplishments: We conducted kinematic and morphometric analyses of antennules of spiny lobsters (whose long antennules bear a complex, dense array of guard and sensory hairs), mantis shrimp (whose antennules bear a simple, sparse array of sensory hairs), and blue crabs

(whose short antennules bear a dense brush of sensory hairs). We have used these data to construct dynamically-scaled physical models of the antennules of all these species and have used particle image velocimetry to determine that waater only flows through the arrays of sensory hairs on these olfactory sensors during the rapid downstroke portion of the flick. We have developed a reaction-diffusion model to calculate molecule arrival at the sensory hairs on antennules. Water flow measurements have been made at a variety of shallow coastal habitats and our collaborators at Stanford have used these data to design flow regimes in their flume (see Koseff's progress reports for details of their accomplishments in producing and quantifying chemical plumes in their flume). We conducted experiments in the Stanford flume using model organisms flicking antennules in plumes in which we simultaneously measured plume structure and the spatio-temporal pattern of molecule arrival within the array of chemosensory hairs on the flicking antennules.

CONCLUSIONS: The basic design of many antennules used by marine animals to capture odor molecules from the surrounding water is that of a moveable rod supporting an array of chemosensory hairs. These antennules are periodically moved through the water with a rapid flick and slower return stroke. The sensory hairs of some species splay apart during the flick, but not the return. The hairs on antennules from a variety of species operate at Reynolds numbers (Re) of order one. In this Re range, changes in hair speed and spacing have a pronounced effect on whether or not fluid penetrates into the spaces between hairs; increasing fluid penetration raises the rate of molecule arrival at the surfaces of the sensory hairs. The designs and motions of these antennules enhance their ability to take pulsatile odor samples that are temporally and spatially discrete from each other. Such sampling is desirable for olfactory probes used for determining position in an odor plume.

In the turbulent water flow typical of shallow coastal habitats, odor plumes are characterized by complex swirls of narrow filaments of high concentration near the odor source, but wider filaments of lower concentration farther from the source. Near the source, these filaments are so narrow that there can be differences along the length of an antennule in the odor concentrations arriving at sensory hairs, thus the spatial pattern of concentrations along an olfactory probe could be used to assess distance from an odor source. Antennule flicking does not disrupt these filaments upstream of the antennule, but does downstream, thus flicking frequency of an olfactory probe can be tuned to ambient current speed so that the probe can sample ambient filaments (for odor-tracing devices) or can sample well-stirred water (to measure chemical concentrations in the environment).

SIGNIFICANCE: By determining how the flow microenvironments and odorant encounter of olfactory antennules is affected by their structure and behavior in realistic odor plumes, we are discovering ways in which the physical design of an antenna affects how it filters chemical information from the environment. These basic rules provide insights for the design of man-made chemical sensors and also reveal how other filamentous biological devices work that capture molecules or particles from the surrounding fluid (e.g. gills, filter-feeding appendages).

AWARD INFORMATION:

Mimi Koehl (P.I.):

Phi Beta Kappa Visiting Scholar, 1998-1999

Distinguished Alumni Award, Gettysburg College, 1998
President, Western Society of Naturalists, 1999
Featured in: Sherrer, B. & B.S. Sherrer [eds.] (1996) *Notable Women Scientists in the Life Sciences*. Greenwood Pub, Westport, CN.
Koehl research on hydrodynamics of hair-bearing appendages featured in BBC science documentary "Suspension Feeding" (filming done 12/98)
Research Kate Loudon and I did on the fluid dynamics of molecule capture by moth antennae was featured in the "Editor's Choice" section of Science:
(2000) Fanning the Flame. *Science* 289: 2007
Miller Professorship, 2001
Honorific Lectures: Keynote Thursday Night Speaker, Gordon Conference on Theoretical Biology and Biomathematics, 1996
Cruickshank Lecturer, University of Rhode Island, 1997
Keynote Speaker, Engineering Found'n International Symposium, 1998
Plenary Lecturer, Oceanographic Society & IOC Meeting, Paris, 1998
Weise Lecturer, Dauphin Island Marine Laboratory, 1999
Keynote Lecturer, Symposium in Nonlinear Biology, 1999
Illg Memorial Lecturer, Friday Harbor Laboratories, 1999
Ian Morris Scholar, Horn Point Laboratory, University of Maryland
Distinguished Speaker, International Workshop on Biofluidynamics in Memory of Sir James Lighthill, Israel

Marlene Martinez (graduate student):

Outstanding Graduate Student Instructor Award, U.C. Berkeley, 1999

Michael McCay (graduate student):

Dwight Davis Award, Soc. Integrative & Comparative Biology, 1999
Outstanding Graduate Student Instructor Award, U.C. Berkeley, 1999
UC-Berkeley Gompertz Award, 1997
Honorable mention, DOD Graduate Student Fellowship, 1997
Gaige Fund Award, ASIH, 1999.

Matthew McHenry (graduate student):

Outstanding Student Paper Award, Hon. Men., West.Soc.Naturalists, 1997
Graduate Research Fellowship, Division of Evolution, National Science Foundation (1997).
Best Student Paper Award, Soc. Integrative & Comparative Biology, 1998
Adrian Wenner Strong Inference award, Society of Integrative & Comparative Biology, Division of Invertebrate Zoology, 2000

Kimberly Quillin (graduate student):

Best Student Paper Award, Soc. Integrative & Comparative Biology, 1998
Certificate of Recognition from the NASA Inventions and Contributions Board. (1998)

Winnie Lau and Jeff Goldman (undergraduates in Koehl lab):

Graduated with Honors, U.C. Berkeley

PUBLICATIONS AND ABSTRACTS:

Koehl (P.I.): (funded by parent ONR grants, published during dates of AASERT)(Due to page limits, no abstracts are listed):

1. Koehl, M. A. R. (1998) Small-scale hydrodynamics of feeding appendages of marine animals. *Oceanography* 11 : 12 -14.
2. Shimeta, Jeff and M. A. R. Koehl (1997) Mechanisms of particle selection by tentaculate suspension feeders during encounter, retention, and handling. *J. Exp. Mar. Biol. Ecol.* 209: 47-73.

3. Koehl, M .A. R. (1998) Small-scale hydrodynamics of particle and odorant capture by animals. (abstract) *Oceanography* 11: 20.
4. Mead, K. S., M. A. R. Koehl, and M. J. O'Donnell (1999) Stomatopod Sniffing: The scaling of chemosensory sensillae and flicking behavior with body size. *J. Exp. Mar. Biol. Ecol.* 241: 235-261.
5. Koehl, M. A. R. (2000) Consequences of size change during ontogeny and evolution. pp. 67-86 *In* *Scaling in Biology*. J.H.Brown and G. B.West [eds.], Oxford University Press, NY.
6. Dickinson, M.H., Farley, C.T., Full, R.J., Koehl, M.A.R., Kram, R., and Lehman, S. (2000) How Animals Move: An Integrative View. *Science* 288: 100-106
7. Loudon, C. and M. A. R. Koehl (2000) Sniffing by a silkworm moth: Wing fanning enhances air penetration through and pheromone interception by antennae. *J. Exp. Biol.* 203: 2977-2990.
8. Mead, K.S. and M.A.R. Koehl (2000) Stomatopod antennule design: The asymmetry, sampling efficiency, and ontogeny of olfactory flicking. *J.Exp.Biol.* 203: 3795-3808.

Student Papers and Abstracts (Due to page limit, only abstracts published in journals are listed and no "in prep." papers are listed.)

9. Martinez, M., R. Full & M. Koehl (1998) Underwater punting by an intertidal crab: A novel gait revealed by the kinematics of pedestrian locomotion in air vs.water. *J.Exp.Biol.* 201:2609-2623.
10. Martinez, M. M. (2001) Running in the surf: Hydrodynamics of the shore crab *Grapsus tenuicrustatus*. *J.Exp.Biol.* 204: 3097-3112
11. McCay, M. G. (1998) A comparison of the aerodynamic stability of three species of neotropical tree frogs: How does stability change with gliding ability? *Am. Zool.* 38: 150A.
12. McCay, M.G. (1999). A tale of two tree frogs: comparing the habitat and gliding behavior of two species of tree frogs. *Am.Zool.* 39:103A.
13. McCay, M.G. (2000) The effects of aerodynamic stability on the dynamics of tree frog gliding. *Am. Zool.* 40:1122A.
14. McCay, M. G. (2001) Aerodynamic stability and maneuverability of the gliding frog *Polypedates dennysi*. *J.Exp.Biol.* 204: 2817-2826
15. McHenry, M.& E. Azizi (1998) Like fish and flagellates: The 3D kinematics of swimming ascidian larvae. *Am. Zool.*37: 451A.
16. McHenry, M. J.and E.Azizi (1998) Like fish and flagellates: The 3D kinematics of swimming ascidian larvae. *Am. Zool.* 37: 451A.
17. McHenry, M.J. (1999) Mechanisms for helical swimming: Asymmetries in the morphology, mechanics, and movement of ascidian tadpole larvae (*Distaplia occidentalis* *Am.Zool.* 39: 102A.
18. Crenshaw, H.C., Ciampaglio, C.N., & McHenry, M.J. (2000) Analysis of the three-dimensional trajectories of organisms: Estimates of velocity, curvature, and torsion from positional information. *J. Exp. Biol.* 203:961-982.
25. Quillin. K. J. (1998) Ontogenetic scaling of hydrostatic skeletons: Geometric, static, and dynamic stress scaling of the earthworm *Lumbricus terrestris*. *J. Exp. Biol.* 201: 1871-1883.
26. Quillin, K. J. (1999) Kinematic scaling of locomotion by hydrostatic animals: Ontogenetic peristaltic crawling by the earthworm *Lumbricus terrestris*. *J. Exp. Biol.* 202: 661-674
27. Quillin, K.J. (2000) Ontogenetic scaling of burrowing forces in the earthworm *Lumbricus terrestris*. *J. Exp. Biol.* 203: 2757-2770