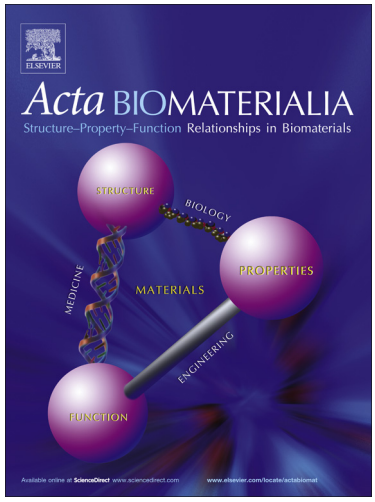

Protective Role of *Arapaima gigas* Fish Scales: Structure and Mechanical Behavior

Wen Yang, Vincent Sherman, Bernd Gludovatz, Mason Mackey, Elizabeth A. Zimmermann, Edwin H. Chang, Eric Schaible, Zhao Qin, Markus J. Buehler, Robert O. Ritchie, Marc A. Meyers

PII: S1742-7061(14)00166-4
DOI: http://dx.doi.org/10.1016/j.actbio.2014.04.009
Reference: ACTBIO 3197

To appear in: *Acta Biomaterialia*

Received Date: 20 December 2013
Revised Date: 12 March 2014
Accepted Date: 8 April 2014

Please cite this article as: Yang, W., Sherman, V., Gludovatz, B., Mackey, M., Zimmermann, E.A., Chang, E.H., Schaible, E., Qin, Z., Buehler, M.J., Ritchie, R.O., Meyers, M.A., Protective Role of *Arapaima gigas* Fish Scales: Structure and Mechanical Behavior, *Acta Biomaterialia* (2014), doi: http://dx.doi.org/10.1016/j.actbio.2014.04.009

Protective Role of *Arapaima gigas* Fish Scales: Structure and Mechanical Behavior

Wen Yang[a], Vincent Sherman[a], Bernd Gludovatz[b], Mason Mackey[c], Elizabeth A. Zimmermann[b*], Edwin H. Chang[b], Eric Schaible[b], Zhao Qin[d], Markus J. Buehler[d], Robert O. Ritchie[b,e,**], Marc A. Meyers[a,f,g,**]

[a] Materials Science & Engineering Program, University of California, San Diego, La Jolla, CA 92093, USA
[b] Materials Sciences Division, Lawrence Berkeley National Laboratory, Berkeley, CA 94720, USA
[c.] National Center for Microscope and Imaging Research Facility, University of California, San Diego, La Jolla, CA 92093, USA
[d] Department of Civil & Environmental Engineering, Massachusetts Institute of Technology, Cambridge, MA 02139, USA
[e] Department of Materials Science & Engineering, University of California, Berkeley, CA 94720, USA
[f] Department of Mechanical & Aerospace Engineering, University of California, San Diego, La Jolla, CA 92093, USA
[g] Department of NanoEngineering, University of California, San Diego, La Jolla, CA 92093, USA

Abstract

The scales of the Arapaima (*Arapaima gigas*), one of the largest freshwater fish in the world, can serve as inspiration for flexible dermal armor. Each scale is composed of two layers: a laminate composite of parallel collagen fibrils and a hard, highly mineralized surface layer. We review the structure of the Arapaima (*Arapaima gigas*) scales and examine the functions of the different layers, focusing on the mechanical behavior including tension and penetration of the scales with and without the highly mineralized outer layer. We show that the fracture of the mineral and the stretching, rotation, and delamination of collagen fibrils dissipate a significant amount of energy prior to catastrophic failure, providing high toughness and resistance to penetration by predator teeth. We show that the Arapaima's scale has evolved to minimize damage from penetration by predator teeth through a Bouligand-like arrangement of successive layers consisting each of parallel collagen fibrils with different orientations. This inhibits crack propagation and restricts damage to an area adjoining the penetration. The flexibility of the lamellae is instrumental to the redistribution of the compressive stresses in the underlying tissue, decreasing the severity of the concentrated load produced by the action of a tooth. The experimental results, combined with small angle x-ray scattering characterization and molecular dynamics simulations, provide a complete picture of the mechanisms of deformation, delamination and rotation of the lamellae during tensile extension of the scale.

Keywords: Arapaima; fish scales; armor, collagen; delamination; strength; toughness

[*] currently at Department of Osteology & Biomechanics, University Medical Center Hamburg-Eppendorf, 22529 Hamburg, Germany.
[**] corresponding authors: Robert O. Ritchie (roritchie@lbl.gov), Marc A. Meyers (mameyers@eng.ucsd.edu)