Universal patterns in bone microstructure, composition, and mechanics: engineering science pervading biology (Keynote lecture in MS127)

***Christian Hellmich[1]**

[1]SVienna University of Technology (TU Wien), Vienna, Austria

*Corresponding author: Christian.hellmich@tuwien .ac.at

According to the eminent Austro-American zoologist Rupert Riedl (1925-2005), "… the living world happens to be crowded by universal patterns of organization …". While Riedl, as "classical" biologist, typically took a descriptive approach to this issue, we ventured, over the last decade and in particular during the last few years, into an engineering science approach of mathematical nature, where we have indeed been successful in identifying „universal" rules/patterns in structural biology and their mechanical consequences. A majority of our investigations concerned mineralized biological tissues such as bones, for which we identified the following mathematically cast rules: (I) In extracellular bone tissues across different organs from different animals/humans at different ages, mineral (hydroxyapatite) and collagen contents are not randomly assgined to each other, but fulfill astonishingly precise bilinear relations[1], which follow from rigorous evaluation of dehydration, demineralization, ashing, and de-organifying test data collected over a time period of more than 80 years of experimental research. Furthermore, (II) the distribution of mineral throughout the extracellular bone matrix or ultrastructure, i.e. its partitioning into the fibrillar and extrafibrillar spaces is governed by the on-average uniformity of hydroxyapatite concentration in the *extracollageneous* space[2], as was evidenced from chemical tests like the ones mentioned before, in combination with transmission electron micrographs. Before mineralization (as well as in unmineralized collageneous tissues such as tendon or cartilage), the fibrillar and extrafibrillar spaces again obey another general rule: (III) Upon hydration, the extrafibrillar space grows propertional to the fibrillar volume gain due to accomodation of water in the intermolecular spaces[3], as evidenced from dehydration and neutron diffraction tests. Finally, (IV) mineralization of such tissues is driven by fluid-to-solid phase transformations in the extracollageneous space under closed thermodynamic conditions[4], predicting precisely the volume losses which the tissues undergo during mineralization. All these compositional and structural rules may serve as ideal input for multiscale mechanics models for the elasticity[5], strength[6], and creep[7] of bone tissues; enabling various clinical applications, such as Computed Tomography (CT)-based Finite Element (FE) analysis for biomaterial design[8].

Keywords: bone, biomechanics, structural biology, engineering science, interdisciplinarity

---

[1] Vuong, Hellmich, *J Theor Biol* 287, 115-130, 2011.
[2] Hellmich, Ulm, *Biomech Model Mechanobiol* 2: 21–36, 2003.
[3] Morin, Hellmich, Henits, *J Theor Biol 317,* 384-393, 2013.
[4] Morin, Hellmich, *J Theor Biol*, under review, 2013.
[5] Fritsch, Hellmich, *J Theor Biol* 244: 597 – 620, 2007.
[6] Fritsch, Hellmich, Dormieux, *J Theor Biol* 260: 230 – 252, 2009.
[7] Eberhardsteiner, Hellmich, Scheiner, *Comp Meth Biomech Biomed Eng* DOI:10.1018/10255842.2012.670227, 2013
[8] Dejaco, Komlev, Jaroszewicz, Swieszkowski, Hellmich. *J Biomech* 45, 1068-1075, 2012.