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LIQUID CRYSTAL STRUCTURE OF WATER AS KEY TO PERMEABILITY OF TRABECULAR BONE

T. Abdalrahman[1], S. Scheiner[1] and C. Hellmich[1]

[1]Vienna University of Technology, Institute for Mechanics of Materials and Structures, Karlsplatz 13/202, A-1040 Vienna, Austria

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At least since the days of the 1937 Nobel laureate Szent-Györgyi [1], it is well-known in cell biology that the structuring of water, i.e. specific liquid crystal-type states of water with physical properties far from those of bulk water (with totally randomly oriented molecules), is central to various physiological processes [2]. The latter are often related to transport properties of the gel-type water found in cells. Evidence has emerged that this effect might reach well beyond the constraints of single cells, playing also a role in various problems beyond the living state [3], comprising even cementitious materials [4]. Motivated by these impressive insights, we here investigate whether the consideration of structured water might also help to resolve the long-lasting enigma behind seemingly too large variations of permeabilities observed in trabecularbones [5,6]. Bone permeability is key to important physiological processes (such as bone remodelling and fracture healing, or transport of metabolites), to the design of tissue engineering scaffolds or of surgical techniques such as vertebroplasty, as well as to deeper understanding of diagnostic tools like ultrasonics.

The starting point of our considerations is that structured water exhibits around seven times the viscosity of bulk water. This higher viscosity slows down the flow in the vascular pores, and hence, the overall bone permeability. However, determination of the latter poses significant challenges, i.e. CFD simulations require high computational cost and very precise geometrical descriptions (e.g. from costly and sometimes not feasible Computer Micro-Tomographs). As a remedy, we here develop a continuum micromechanics-inspired homogenization scheme for estimation of the macroscopic permeability of trabecular bone, based on Poiseuille flow in its vascular pore space. Accordingly, a boundary value problem is formulated for pressure gradients. The underlying representative volume element (RVE)of the macroscopic bone material contains two types of phases: a spherical, impermeable extracellular bone matrix phase interacts with interpenetrating cylindrical pore channel phases that are oriented in all different space directions. This type of interaction is modelled by means of a self-consistent homogenization scheme. While the permeability of the bone matrix equals to zero,the permeability of the pore spaces is found through expressing the classical Hagen-Poiseuille law [7,8] for lamellar flow in the format of a“micro-Darcy law”[9]. The resultingupscaling scheme contains pore size and porosity as geometrical input variables; however, they can be related to each other, based on well-known relations between porosity and specific pore surface [10], see Figure 1 for respective mean and upper/lower bound values.Model-predicted, porosity-dependent macroscopic permeabilitiescompare very well to corresponding experimental results [5,6,11], see Figure 1.Conclusively, layered water-enhanced viscosity, analytical fluid mechanics, and filtration physics, altogether cast into the

framework ofrandom homogenization, have unveiled the enigma of bone permeability: Particularly, the extreme "scattering" around porosities of 0.9 -0.95 is just an expression of a mechano-physical porosity-permeabiltiyrelationship with a very steep "slope" at high porosities.

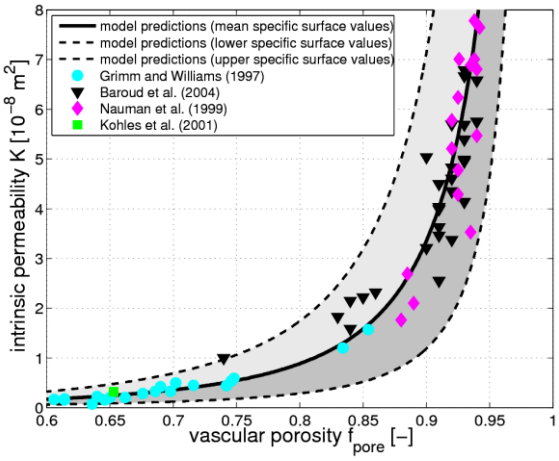

Figure 1: Experimental validation of bonepermeabilityupscalingtheory

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