Material and structural characterization of mineralized elasmobranch cartilage – lessons in repeated tiling patterns in mechanically loaded 3D objects

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Biological tissues achieve a wide range of properties and function, however with limited components. The organization of these constituent parts is a decisive factor in the impressive properties of biological materials, with tissues often exhibiting complex arrangements of hard and soft materials. The "tessellated" cartilage of the endoskeleton of sharks and rays, for example, is a natural composite of mineralized polygonal tiles (tesserae), collagen fiber bundles, and unmineralized cartilage, resulting in a material that is both flexible and strong, with optimal stiffness. The properties of the materials and the tiling geometry are vital to the growth and mechanics of the system, but had not been investigated due to the technical challenges involved.
We use high-resolution materials characterization techniques (qBEI, µCT) to show that tesserae exhibit great variability in mineral density, supporting theories of accretive growth mechanisms. We present a developmental series of tesserae and outline the development of unique structural features that appear to function in load bearing and energy dissipation, with some structural features far exceeding cortical bone's mineral content and tissue stiffness. To examine interactions among tesserae, we developed an advanced tiling-recognition-algorithm to semi-automatically detect and isolate individual tiles in microCT scans of tesseral mats. The method allows quantification of shape variation across a wide area, allowing localization of regions of high/low reinforcement or flexibility in the skeleton. The combination of our material characterization and visualization techniques allows the first quantitative 3d description of anatomy and material properties of tesserae and the organization of tesseral networks in elasmobranch mineralized cartilage, providing insight into form-function relationships of the repeating tiled pattern. We aim to combine detailed knowledge of intra-tesseral morphology and mineralization to model the relationships of tesseral shapes and skeletal surface curvature, to understand fundamental tiling laws important for complex, mechanically loaded 3d objects.

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