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Chapter 8

Microvascular transport

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Abstract

Embedded microvascular networks and fluid transport through these pathways enable unique fluid-mediated functionalities within composite structures. Biological inspiration for synthetic microvascular analogs guides the design of vascular networks and systems tailored for specific structures and subcomponents, and which are subject to competing physical constraints and functional objectives. Non-structural functionalities enabled by microvascular fluid transport include self-healing of repetitive fracture damage, thermal regulation of temperature-sensitive regions, structural health monitoring, structural fluid storage, and recovery of macroscale material loss.

8.1 Introduction

Microvascular materials, which are inspired by the fluid transport functionality of biological systems, are engineered analogs to vascularized biological organisms that aim to mimic their multifunctional capabilities. The goal of this chapter is to provide the reader a guide to the microvascular material engineering design, manufacturing, and testing process. In brief, key characteristics from vascularized biological organisms form the basis of analytical or numerical models to produce relevant designs, which are subsequently fabricated and tested for their intended fluid-mediated performance. Engineered microvascular systems are inspired by their biological counterparts, in which nature has evolved complex fluid-vascular systems to perform healing, thermal, and sensing functions via fluid transport. The engineering design of microvascular materials requires a systems-level approach, in which pumping, fluid routing, manufacturability, mechanical effects, and reliability are inter-related, key design decisions. The broad design parameter space is composed of frequently conflicting objectives, which benefits from computational and analytical approaches to narrow the set of optimal solutions. Microvascular materials are fabricated with an increasingly sophisticated set of subtractive and additive manufacturing techniques to translate optimal computed structures into physical instantiations of the designs. The primary structural emphasis to date has led to heavy investigation of the impacts of vascularization on mechanical performance for a range of mechanical loading conditions, including quasi-static, fatigue, and impact loading. These microvascular networks are being implemented to achieve a broad range of functions, including the autonomic restoration of mechanical properties, the regulation of thermal energy, structural health monitoring, integrated fluid storage and recovery, and material growth and recovery. Future expansion of microvascular capabilities will be inspired by the diverse, synergistic functions of natural vascularized materials and will achieve greater mass savings.

8.2 Biological inspiration

The field of engineered microvascular materials is inspired by the diversity of microvasculature evolved in a preponderance of species in the animalia and plantae kingdoms. This sub-section introduces the sub-components that comprise a functioning microvascular system. Vascularized biological structures, specifically cortical bone, dentin, and wood, are examined as a means to inspire synthetic multifunctional composite analogs.

8.2.1 System approach to microvascular transport

Vascularized biological organisms depend on the coordination of multiple sub-systems to successfully circulate life-sustaining fluids. The multi-functional performance mediated by this fluid circulation includes nutrient delivery and chemical waste removal, thermoregulation, delivery of chemical energy, and restoration of damaged tissues. The basic components of this fluid circulatory system are: a circulatory pathway, a circulatory fluid, and a circulatory driving force.

Vasculature defines the physical boundaries of fluid transport. The vascular network geometry can become exquisitely intricate. The network is typically hierarchical, such that the highest order channels i.e., aorta, venae cavae are the fewest in number and the largest in diameter (1-3 cm), and then furcate into more numerous channels with smaller diameters: arteries and veins, arterioles and venules, and then finally into capillaries (5-10 μm in diameter) [1]. The vascular structure dynamically restructures on multiple timescales. The long-term remodeling of the network arises from vasculogenesis (de novo vessels) and angiogenesis (existing vessel growth). By contrast, short-term vasoconstriction or vasodilation adapts the diameter of existing channels to modify the local hydraulic resistance to adjust flow routing.

The circulating fluid(s) can be similarly complex. Blood, for instance, contains plasma (i.e., proteins, hormones, glucose, minerals, carbon dioxide), erythrocytes (i.e., red blood cells), and leukocytes and platelets (i.e., white blood cells). Intricate signaling systems are triggered, for instance, by an injury that recruits cells and proteins to add mass to the damaged region. This temporary repair is subsequently remodeled to remove excess mass and form a permanently healed tissue.

Finally, a driving force exerted on the fluid induces fluid circulation. This driving force can be active pumping or passive flow. An active pump (e.g., the heart) is typical of the animalia kingdom, in which the heart consumes metabolic energy to drive a muscle contraction, resulting in a pulsatile blood flow through the network. By contrast, the plantae kingdom relies on physical phenomena for passive fluid circulation. Typically, transpiration-driven capillarity draws water from the roots toward the canopy. Flows can also be passively driven by thermal cycling (e.g., springtime Maple sap flow).

8.2.2 Structural biocomposites with embedded microvasculature

Structural biocomposites that are vascularized offer inspiration for engineering solutions applicable to structural composite systems. Three widely investigated vascular biocomposites are bone, dentin, and wood. Cortical bone is a load-bearing osseous tissue that comprises the exterior layer of human skeletal bones. The microstructure is build from the fundamental unit of the osteon, which is a series of concentric lamellae surrounding a core Haversian canal that interconnects with a network of microchannels called canaliculi. The Haversian canals and canaliculi are axially and transversely oriented within cortical bone, respectively (Figure 8.1.a). Neighboring Haversian canals and the bone surface are connected via transverse Volkmann canals. Despite these multiaxially oriented vascular features, bone possesses exceptional fracture toughness. Fractographic studies find that cracks preferentially initiate and propagate within the lamellar osteons, thereby avoiding fracture of the Haversian canals [2–4]. This exceptional fracture behavior is attributed to bone's gradient mechanical properties near the Haversian canals. Analysis of the mechanical stiffness shows that the stiffness increases in the vicinity of the Haversian canal relative to the far-field value, then decreases by an order of magnitude directly at the inner canal surface [5]. Figure 8.1.b schematically plots the gradient stiffness profile in the vicinity of within human structural biocomposites and is representative of cortical bone. The effect of this gradient structuring is to substantially reduce stresses at the interior channel surface in order to prevent local fracture initiation, while shielding the canal from cracks propagating external to the channel [6].

Dentin is a calcified biocomposite covered within teeth. The vascularized structure is significantly less complex than in cortical bone. Dentinal tubules are channels that traverse the dentin layer to connect the interior pulp layer to the outer enamel layer. The tubule sizes and areal densities vary depending on the tooth location. In general, the tubules vary from 0.8 to 2.5 μm in diameter and comprise 2.5% to 22.5% of the cross-sectional area at the dentin-enamel junction and the pulp regions, respectively [7]. The vicinity of dentinal tubules also possess gradient mechanical properties. The Young's modulus rises from the far-field average of 21 GPa to 29 GPa within 1 μm of the tubule, then drops to 25 GPa within 0.1 μm of the tubule inner surface [8]; hence, dentinal tubules exhibit a gradient stiffness also represented by Figure 8.1.b. Fracture toughness is 60% higher for cracks propagating parallel to the dentinal tubule axis due to crack plane bridging by collagen fibrils [9].

Wood is a plant-based microvascular fiber-reinforced biocomposite. Plant-based

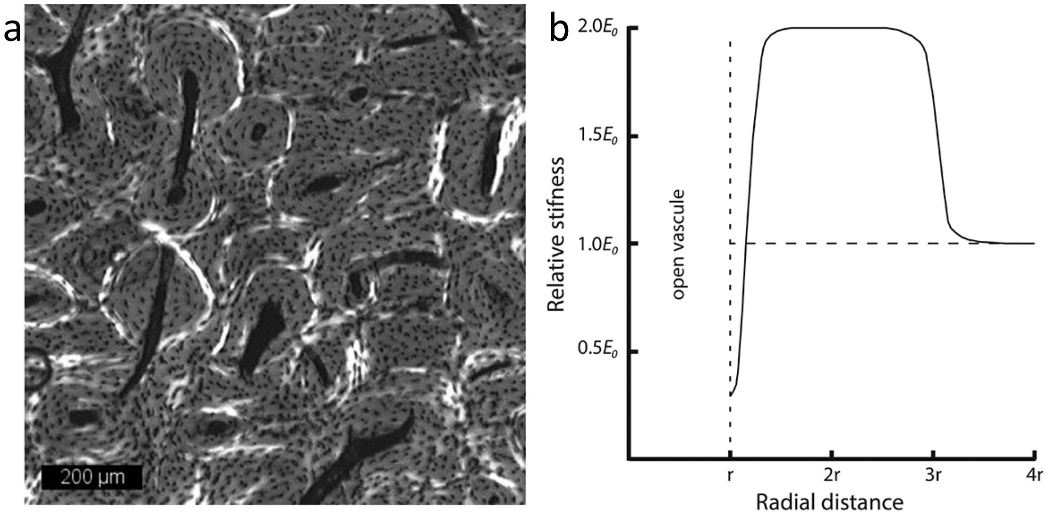

Figure 8.1: Microstructure of structural biocomposites. (a) Micrograph of cortical bone, with Haversian canals (out-of-plane, dark circular features) interconnected by Volkmann canals (in-plane, dark channel features), reproduced from [5], copyright (2003), with permission from Elsevier. (b) Schematic plot of the stiffness normalized by the far-field elastic modulus E_0 as a function of radial distance normalized by the vascular feature radius r.

vascular networks are distinct from animal vasculature in that plants typically possess segregated networks that lack interconnectivity. Whereas animals' hierarchical vasculature have a parent channel that furcates into child channels, the branching of the dendritic canopy network in some plants is achieved by physical change in the growth direction of adjacent channels and involves no furcation [10]. This morphologically distinct design prevents catastrophic failure of the vascular system in the event of a breach of a segment of the overall network [11]. The mechanical function of wood and the hydraulic conductance of its vascular network are conflicting demands which are balanced within the tree structure, leading to fewer and narrower conduits in the distal branches and a hydraulically less efficient structure [12,13].

8.3 Engineering design of microvascular transport

An overview of the design constraints and objectives that determine the multifunctional design trade-offs for microvascular systems is presented in this section. Physical constraints, such as fluid transport and structural degradation by embedded channels, impact the engineering design of the vascular network geometry and pumping redundancy. Analytical and computational optimization techniques are discussed in the context of microvascular designs.