



Heart Ecosystems: Interactions Between Cells, Molecules, and Microbes

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DESCRIPTION

The heart is far more than a mechanical pump it is a dynamic ecosystem where multiple cell types communicate through intricate molecular networks to maintain homeostasis. Cardiomyocytes, fibroblasts, endothelial cells, and immune cells form a tightly regulated community whose interactions determine both health and disease outcomes. Recent advances in single-cell transcriptomics, spatial omics, and high-resolution imaging have revealed that these cellular dialogues are far more complex than previously appreciated. For instance, fibroblasts not only provide structural support but also secrete signaling molecules that influence cardiomyocyte function and immune cell recruitment. Similarly, endothelial cells act as active gatekeepers, regulating vascular tone, nutrient delivery, and inflammatory responses. Disruptions in these interactions whether through stress, ischemia, or systemic inflammation can tip the ecosystem into maladaptive remodeling, fibrosis, or heart failure.

Cellular conversations: Decoding the heart's internal networks

At the molecular level, the heart's ecosystem relies on an intricate web of cytokines, chemokines, growth factors, and extracellular matrix components. Intercellular communication is mediated by both soluble molecules and extracellular vesicles, allowing the rapid propagation of stress signals and adaptive responses. Inflammatory mediators such as Interleukin-6 (IL-6) and Tumor Necrosis Factor-alpha (TNF- α) play dual roles, orchestrating repair in the acute phase but contributing to chronic dysfunction if uncontrolled. Equally important are the cardiac metabolic pathways and Reactive Oxygen Species (ROS), which act as molecular messengers but can become pathological when excessive. This delicate balance underscores the heart's identity as an ecosystem: Its health depends on the harmony and feedback among diverse cellular and molecular actors, rather than isolated components acting independently.

Microbial influences: The heart beyond the body

Emerging research has expanded the concept of the cardiac ecosystem beyond its resident cells and molecules to include microbial interactions. The gut-heart axis, for instance, has gained considerable attention, highlighting how microbial metabolites can influence cardiac structure and function. Short-chain fatty acids, Trimethylamine N-Oxide (TMAO), and other microbial byproducts modulate systemic inflammation, endothelial function, and even myocardial metabolism. Dysbiosis an imbalance in the gut microbial community has been associated with hypertension, atherosclerosis, and heart failure, suggesting that microbial inputs are integral to the heart's ecological network. Beyond the gut, recent studies have detected microbial genetic material signatures in cardiac tissue, raising intriguing possibilities that local microbiota may directly affect immune signaling and tissue remodeling within the heart.

Translating these insights into clinical practice presents both challenges and opportunities. Understanding the heart as an ecosystem requires integrated approaches that combine cellular biology, molecular profiling, and microbiome science. Multi-omics platforms, systems biology models, and computational simulations allow researchers to capture the dynamic interactions within this complex network. Therapeutically, interventions may evolve from targeting single molecules to modulating entire ecological pathways for example, by restoring microbial balance, fine-tuning immune signaling, or enhancing cardiomyocyte resilience. Early identification of ecosystem dysregulation could enable preventive strategies before overt disease manifests, aligning with the principles of precision medicine. Ultimately, viewing the heart as a multi-layered ecosystem composed of cells, molecules, and microbes redefines our understanding of cardiovascular health and opens new avenues for research, diagnostics, and therapeutic innovation.

In conclusion, the heart ecosystem paradigm emphasizes the interconnectedness of cellular, molecular, and microbial factors in shaping cardiac function. Recognizing these interactions is

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crucial for early disease detection, personalized interventions, and the development of novel therapies. As technology continues to illuminate the heart's intricate networks, the integration of cellular, molecular, and microbial data will likely

transform cardiovascular medicine, offering a holistic perspective on the heart that extends well beyond the traditional focus on anatomy and contractile performance.