

*Arthur S. Iberall Distinguished Lecture on Life and the Sciences of Complexity*  
December 3, 2004 ☿ University of Connecticut ☿ 4:00 p.m.  
Konover Auditorium, Thomas Dodd Research Center

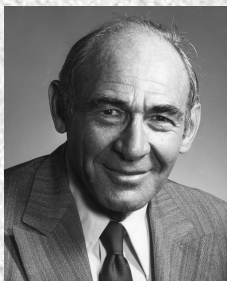
## **Fractal Lessons from the Heart: Scaling and Multicausality in Physiological Systems**

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### Abstract

Regional blood flows in the normally functioning heart range from 20% to 200% of the average flow, though the heart is a “monofunctional” organ excited everywhere with each beat. The flow distributions are spatial fractals, the variance being a power law function of the element size in which the observations are made. How can this heterogeneity be explained, and how does the heart work so well in spite of it? Are all organs like this? Why should it be this way? Explorations of these questions lead to studies of diverse aspects of the functions of multicellular organs. Bassingthwaite and Beard (1995) constructed a three-dimensional model of the coronary arterial network and found that the flow distribution is explicable in terms of network-scaled branching properties. This does not explain the heterogeneity or its stability over time. This raises the question “Did the vascular network grow in response to local metabolic demands?” In dogs and humans, positron emission tomography (PET) with a single breath of  $^{15}\text{O}$ -oxygen gas as input showed that regional oxygen consumption is proportional to regional flows and is also a spatial fractal. This characteristic, in the heart, is attributable, we think, to the local needs for oxygen and ATP for contraction in a complex geometric arrangement of muscle fibers.

But the lung, the kidney, and the liver are also fractal, so is there a more general basis? Vascular, sympathetic neural, and lymphatic systems are all fractal branching networks, whose branching rules are like those of trees, but differ from trees in that the volume served is a solid organ. Power law relationships fit these fractals, but don't explain them. For example, the heterogeneity of local ventilation-perfusion ratios in the lung is small even though blood flows are broadly heterogeneous: this matching is analogous to that in the heart, namely that the flow distribution matches the functional needs. Given this generality, one can speculate that each situation where matching occurs is a result of adaptation or modulation of the fractal process in response to local signals.



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James Bassingthwaite is Professor of Bioengineering and Radiology at the University of Washington. His current research is centered on the mechanisms of flow, transport, and metabolism of substrates and hormones in the heart and throughout the body. The work emphasizes the use of quantitative mathematical models for integrative systems analysis in physiology and in image analysis. He is the originator of the Human Physiome Project, a large-scale international program for developing databasing and biological systems modeling for understanding genomic and pharmaceutical effects on human physiology. He has been elected to the National Academy of Engineering.

