

# A Healthy Heart Is a Fractal Heart

By Barry A. Cipra

*I have ideas and reasons,  
Know theories in all their parts,  
And never reach the heart.*  
—Fernando Pessoa

When you go to the doctor's office, one of the first things they do is jot down your blood pressure and pulse rate. According to Ary Goldberger of Harvard University, they might do well to include another number: your heartbeat's fractal dimension.

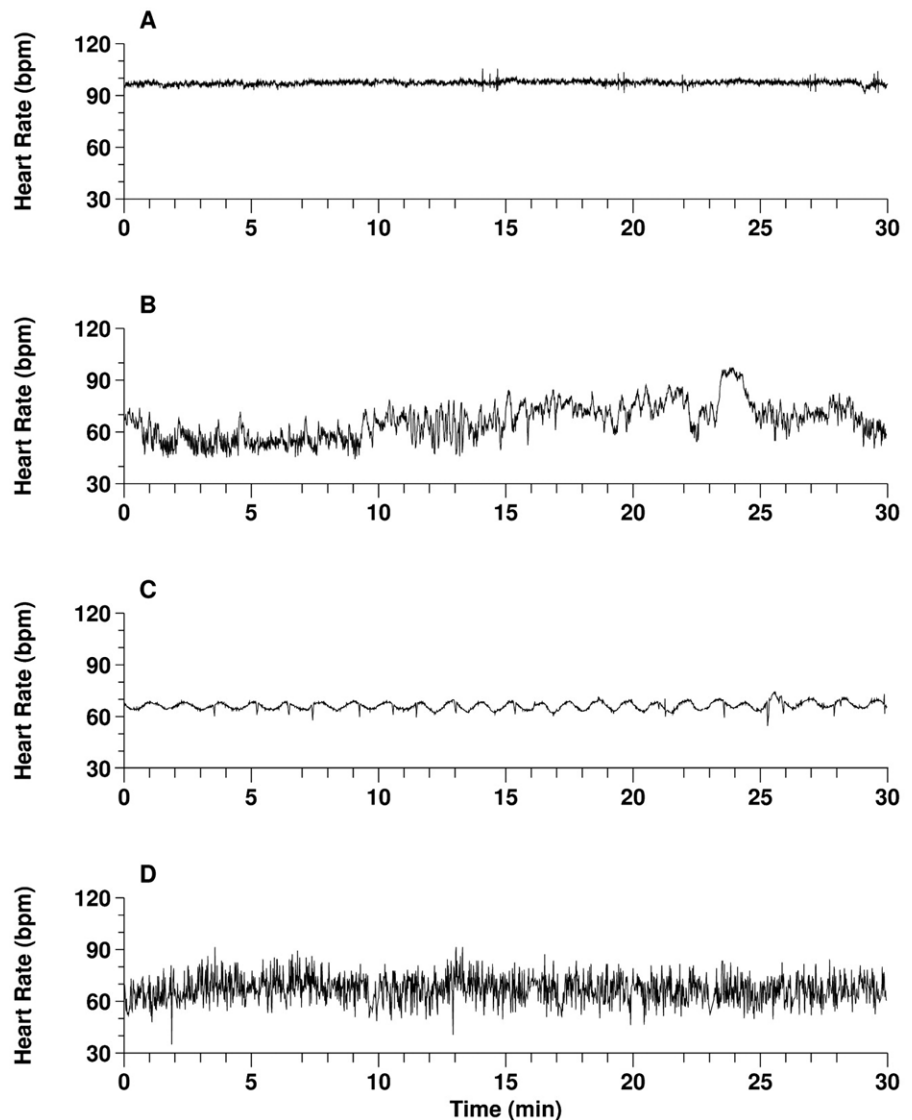
Goldberger spoke on the role of fractal dynamics in physiology at the SIAM 2003 Annual Meeting, held June 16–20 in Montreal. Careful analysis of heartbeat time-series could give cardiologists new diagnostic tools in the battle against heart disease. Similar analyses of brain waves and stride length in walking could give researchers new insights into such conditions as epilepsy and Parkinson's disease.

The heart is part of a large feedback system whose dynamics are nonlinear, nonstationary, and multiscale, Goldberger observes. As mathematicians well know, even simple nonlinear rules can lead to complex behavior—and the rules governing the heart are hardly simple. "It's an incredibly complicated system," Goldberger says. Consequently, the healthy heartbeat "is one of the most complex signals in nature."

All this runs counter to the view of the "regular sinus rhythm"—the comforting lub-dub we all associate with stress-free existence—as the gold standard of cardiology. To be sure, you don't want your heart beating erratically, as in D: That patient has a condition known as atrial fibrillation. But neither do you want a steady or sinusoidally varying pulse rate of the types shown in A and C; those are from patients with severe congestive heart failure. The healthy heart rate is the one shown in B.

Goldberger and colleagues, notably C.-K. Peng of Harvard, and Eugene Stanley and Plamen Ivanov of Boston University, have developed a number of methods for analyzing heartbeat and other physiologic data. One is a method they call "detrended fluctuation analysis" (DFA). The basic idea is to calculate the average amount of fluctuation over bins of different sizes—that is, the root mean square deviation between the signal and its trend in each bin—and then plot the result as a function of bin size. Remarkably, DFA for a healthy (young) heart forms an almost perfect line of slope 1—a hallmark of fractal behavior. (It's characteristic of what's called  $1/f$  noise and indicates the presence of long-range correlations in the signal. "White" and "brown" noise, by contrast, tend to line up with slopes of 0.5 and 1.5, respectively.)

If all hearts produced slope-1 plots, the finding would be intriguing but not clinically valuable. Goldberger's group has not found



**Time-Series Challenge:** Opening the 2003 SIAM Annual Meeting with an invited talk titled "Fractal Dynamics in Health and Their Breakdown with Disease and Aging," Ary Goldberger of Beth Israel Deaconess Medical Center and Harvard Medical School showed the audience these four heart rate recordings and invited them to choose the one they would most like to have. As hands went up for each possibility, Goldberger pointed out that only one was from a healthy patient; the other three came from "people at risk for something really bad." (When he presented the same challenge to medical people, he said, a cardiologist was among those who made the worst possible choice.) Which one would you hope to have?

Reprinted from "Fractal Dynamics in Physiology: Alterations with Disease and Aging," Ary L. Goldberger, Luis A.N. Amaral, Jeffrey M. Hausdorff, Plamen Ch. Ivanov, C.-K. Peng, and H. Eugene Stanley, Proceedings of the National Academy of Sciences, February 19, 2002, vol. 99, suppl. 1, 2466–2472. Copyright 2002, National Academy of Sciences, U.S.A.

that to be the case, however: Recordings from people with diseased hearts and from elderly people show marked departures from slope-1 straightness. This indicates a loss of complexity in the heartbeat as a result of illness or aging.

The difference between healthy and diseased heart signals is even more striking in a multifractal analysis. The signal from a beating heart shows signs of being a multifractal, which means that it is characterized by a range of exponents, of which the DFA slope is only the first. Indeed, a wavelet-based analysis of a healthy heart shows non-zero fractal dimension over a broad range of exponents, whereas the same analysis from a subject with congestive heart failure has a much more restricted range.

“You actually see very reproducible degradation of the fractal scaling pattern,” Goldberger says. “That also raises the possibility that there are diagnostic and prognostic uses—bedside applications—of some of these newer monitoring techniques.”

Peng, Goldberger, and Madalena Costa of the University of Lisbon have devised another technique, called multiscale entropy, which measures the complexity of physiologic signals like the heartbeat and demonstrates a consistent loss of information with aging and disease. Their paper on the technique appeared last year in *Physical Review Letters*.

For fractals and other complexity-related measures to reach the bedside will require close collaboration among researchers from different disciplines, Goldberger stresses. In particular, he says, “physiologists are not used to talking about fractals and nonlinear mechanisms and complex systems, although they deal with those every day.” The concept of homeostasis—the idea that organisms strive to maintain an ideal steady state—has been a staple of physiology for the last seventy years and still has strong appeal. The fractal patterns observed by Goldberger and colleagues indicate that organisms instead strive to maintain an adaptive variability, so that they don’t get locked into one mode of behavior.

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Progress in the field will also depend on researchers having ready access to data. “Data that are generated in an intensive care unit may be of huge interest to people who have been looking at complex systems in a very different guise,” Goldberger points out. Toward that end, his group has set up PhysioNet ([www.physionet.org](http://www.physionet.org)), with funding from the National Center for Research Resources of the National Institutes of Health. “It’s like a GenBank for physiology,” Goldberger says. “It allows people around the world to look at data sets that they otherwise wouldn’t have access to.”

PhysioNet includes an archive of physiologic data sets, such as the “Fantasia Database”: EKG and respiration records of 40 adults (20 young and 20 elderly) who spent two hours watching the classic Disney film. It also provides a toolkit of open-source software, plus a discussion site, tutorials, publications, and a set of challenges for all comers.

Goldberger is enthused by the possibilities. “Once there’s good data and a communications network, then anything and everything can happen,” he says. “The potential for discovery is enormous.”

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