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Comment on "Proposed Test for Detection of Nonlinear Responses in Biological Preparations Exposed to RF Energy"

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Balzano [2002] proposed a test to measure "... the nonlinear response of biological cells..." to 0.9 GHz electromagnetic fields. In our view, the proposal obfuscates the meaning of nonlinearity (N) and dulls appreciation of its true significance regarding the biological effects of electromagnetic fields (EMFs).

Beginning in the 1950s, experimental evidence and theoretical considerations were advanced indicating that biological transduction of weak EMFs was more or less precluded, based on considerations of kT [Schwan, 1957; Schwan and Sher, 1969; Schwan, 1973; Schwan, 1982]. The argument has remained substantially unaltered despite the rising tide of the empirical evidence.

At least two general approaches evolved in opposition to the antitransductionist viewpoint. In one approach, N was invoked, ultimately leading to the concepts of "windows" and "resonance" as devices to explain how weak EMFs could produce biological effects. The basic idea was that the biological response exhibited a power law or periodic dependence on the applied field (Fig. 1). A key point is that although such functions are *algebraically* nonlinear, they are *dynamically* linear because they are solutions to *linear* differential equations. Solutions to linear differential equations follow the law of superposition, and from this property springs the traditional Holy Grail of the experimentalist—reproducibility of data.

The second approach was of an entirely different character because it did not address the kT argument, but rather the implicit claim of authority on which it was based. Those open to the possibility of transduction simply ignored the kT argument because, we think, at one level or another, it struck them as absurd that physics could explain biology, considering the conceptual simplicity of the former and the structural and functional complexity of the latter. The focus, in this approach, was on collecting empirical data.

Although the dispute has remained unresolved, what may be a solution has appeared [Lorenz, 1963; Abarbanel, 1994, 1996]—the nature of which is illustrated in Figure 2. Assume that a biological response is measured continuously in three different animals and that, upon presentation of an EMF, two of the animals react in opposite directions and the third does not react. Such behavior is not possible in systems governed by linear differential equations, but it is theoretically possible if the system is governed by nonlinear differential equations (Fig. 3). Experimental evidence suggesting that such behavior ("dynamic nonlinearity") can explain EMF induced bioeffects is described elsewhere [Marino, 1995; Marino et al., 2000; Marino et al., 2001a; Marino et al., 2001b; Marino et al., 2002].

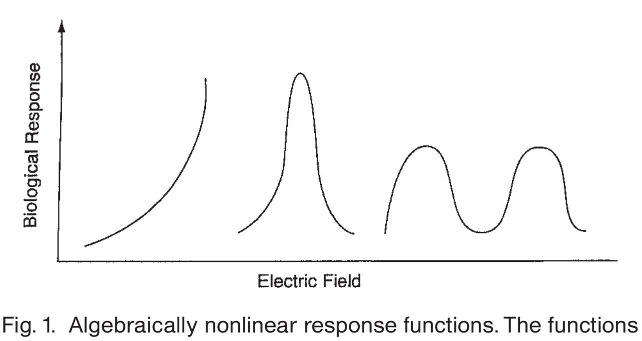

Fig. 1. Algebraically nonlinear response functions. The functions are solutions to linear differential equations.

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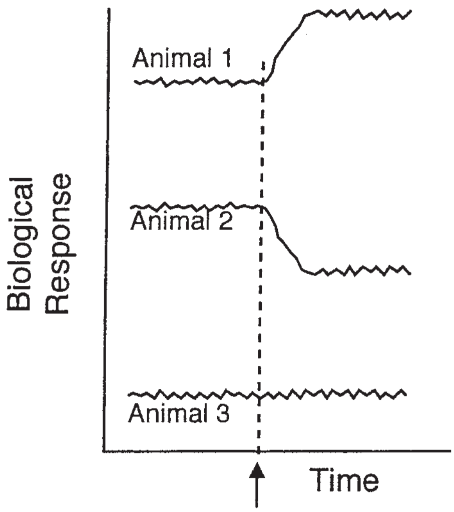

Fig. 2. Types of responses possible in systems governed by nonlinear differential equations. Arrow indicates time of application of an EMF.

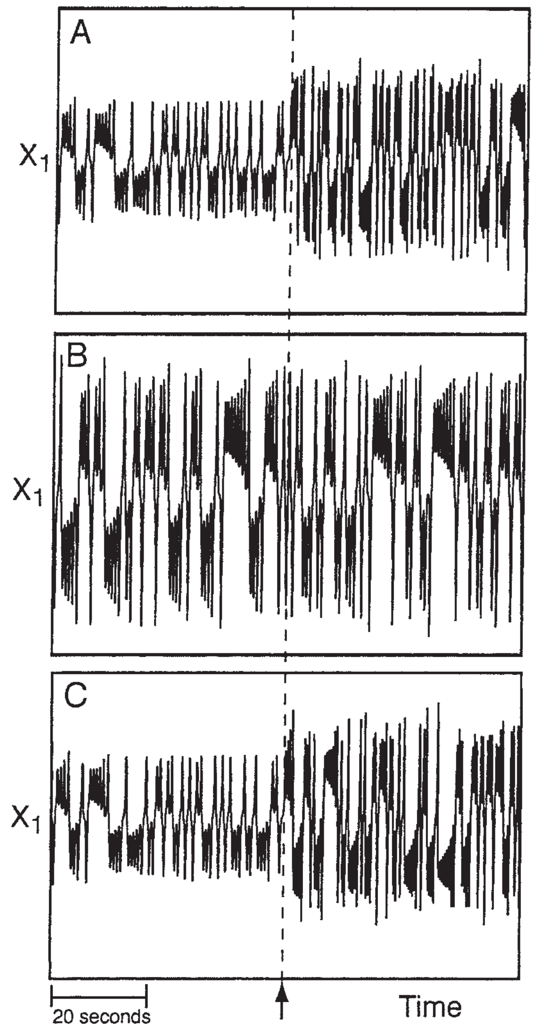

Fig. 3. Effects of EMFs on the time series of a generalized biological parameter (X_1), modeled using the Lorenz equations [Abarbanel, 1996]. Arrow indicates time of application of an EMF. Different kinds of reversible deterministic responses are possible during exposure to an EMF as a result of a change in the parameters (σ, r, b respectively, below) and the instantaneous state of the system. **A**: Change in variance and mean (*F* and *t* tests). **B**: Change in mean only (*t* test). **C**: Change in variance only (*F* test). Pre-exposure parameters: 10 (except 10.14 in B), 28, 2.67, x = (10, 1, 1). Exposure parameters: A, 16, 45.92, 4, x = (−10.14, 1, 1); B, 10, 28, 2.67, x = (12.246, 1, 1); C, 16, 45.92, 4, x = (10.14, 1, 1). $P < 0.05$ in all tests.

The interaction required to produce a response in a system governed by nonlinear differential equations can, in principle, be arbitrarily small, say $kT/10^6$. Consequently, dynamic nonlinearity can overcome both objections—kT and reproducibility of data; only the phenomenon of a field induced change need be reproducible, not the precise magnitude and sign.

Balzano never defined N. At one point he called a pendulum a "nonlinear system." Some pendulums are nonlinear systems because the differential equations that govern the motion of pendulums are nonlinear. Used in this sense, N refers to the nonlinear nature of the differential equations that govern the system. In three dimensions such systems can exhibit the phenomenon of nonperiodic evolution (chaos) [Abarbanel, 1994] (Fig. 3). At another point, however, Balzano referred to the "nonlinear response of living tissue" while discussing a Taylor series expansion of a hypothetical biological response to an applied electric field. In this instance, N referred to the algebraic relationship between a quadratic or higher order power of the electric field and the contribution it makes to a hypothetical response (Fig. 1). In most of the other 70 times he used N, it was not clear what sense he meant to convey.

Why does confounding the two senses of N dull appreciation of its significance? Rightly or wrongly, the concept of algebraic nonlinearity as rebuttal to the antitransductionist argument is moribund, having failed to win over "establishment" thinkers such as the American Physical Society [American Physical Society, 1995]; Nobel Prize winners [Adair et al., 1996]; or the National Academy of Sciences [Stevens et al., 1997]. The danger is that dynamic nonlinearity may not get a fair hearing by investigators if the modern sense of N is commingled with its older sense.

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