Fractal structures optimize entropy production in complex dissipative systems

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In the realm of complexity science that is being applied at the bedside of patients, multiorgan variability monitoring offers real potential to improve care for patients at risk for or with existing critical illness. The origin of the complex fractal temporal structures that characterize healthy biologic variability remains unknown. In this exploratory paper, drawing insight and understanding from the science of non-equilibrium thermodynamics, a hypothesis linking the Principle of Maximum Entropy Production to the spontaneous self-organization of fractal structures in both time and space is presented. As this paper is purely hypothetical, its refutation or validation, and importantly, the necessary conditions for this hypothesis require further study. Last, in light of this hypothesis, the potential clinical applications of multiorgan variability monitoring are alluded to.

1 Introduction

1.1 Complexity

Complex systems science has offered novel means of conceptualizing and evaluating patients with critical illness. Numerous clinician scientists are actively engaged in
bringing the science of complex systems to the bedside for the benefit of acutely ill patients. Nonetheless, concepts from complexity remain largely unknown. Without evidence of clinical benefit, complex systems science remains dwarfed by the cultures of basic science and evidence based medicine. Thus, demonstrable individual patient benefit is the overall aim of our research team and the center of our investigation of the clinical utility of complex systems science.

One of the applications of complex systems science to critical illness surrounds the study of time-series of vital signs (e.g. heart and respiratory rate). Research over the past three decades has pioneered novel techniques of measuring patterns of variation over intervals-in-time. These techniques are rooted in non-linear dynamics, mathematical physics, information theory and more. Innumerable clinical studies have documented reduced overall variability, reduced irregularity, and breakdown in fractal scale-invariant temporal structures in association with illness and aging. Not only is variability reduced in illness, the degree to which it is reduced correlates with illness severity. As variability represents comprehensive data integration over time, we hypothesize it reflects a measure of the integrity of the whole system, and change in variability reflects change in its emergent properties.

1.2 Variability

Given that complexity science and clinical experience inform us of the irreducible uncertainty (i.e. infinite knowledge of the present can not predict the future) and irreducible complexity (i.e. infinite knowledge of the parts of a complex system do not characterize its emergent properties) inherent to complex systems, then monitoring a system’s emergent properties continuously over time offers a complementary alternative to probabilistic predictions. Rooted in these ideas, our laboratory develops and clinically evaluates clinical decision support software that performs multiorgan variability monitoring to track the emergent properties of a complex system. Our clinical research hypotheses state that tracking multiorgan variability over time will enable earlier detection of critical illness, better prognostication of its severity, and potentially lead to novel variability-guided therapy to improve outcomes. We develop and clinically evaluate software to perform Continuous Individualized Multiorgan Variability Analysis (CIMVA™) to facilitate the translation of waveform data (e.g. electrocardiogram, end-tidal capnography) into variability monitoring. CIMVA includes detection of beats and breaths, noise and artifact removal, comprehensive standardized variability analysis, and display of individualized change in variability over time.

1.3 Fractal Variability

Investigators are also seeking to understand the origin of physiologic patterns of variability, and the pathophysiologic causes of altered variability. Research has focused on the role of an activated autonomic nervous system, diminished coupling between organ systems, and reduced inherent “complexity” of the organism as explanations for loss of variability in illness. However, the explanation of the origin
for fractal variability, namely time-series that demonstrate similar patterns of fluctuations over a broad range of time-scales, remains wanting and unexplored. The specific research objective of this abstract is to introduce a novel hypothesis for the spontaneous appearance of fractal variability inherent to complex dissipative systems.

Fractal structures are self-similar objects, whereupon magnification reveals additional layers of detail that defy characterization using integer-dimension Euclidean geometry. They are ubiquitous, spontaneously self-organizing in both time and space. The tracheobronchial tree and heart rate variability represent examples of physiologic spatial and temporal fractal structures. Tree growth, lightning, coastlines and river deltas are evidence for the spontaneously emergence of fractal order and beauty of our world, which notably exist for variable timespans. Life, a network of fractal structures, provides the quintessential example for the spontaneous creation of order through embryogenesis. Given this inherent creation of order is seemingly in violation of the Second Law of Thermodynamics, one of the fundamental laws of physics, it is necessary to briefly consult with the science of thermodynamics.

2 Non-Equilibrium Thermodynamics

2.1 Entropy

The Second Law of Thermodynamics states that entropy always increases, that there is always a loss of quality of energy, and that order spontaneously tends to disorder, and that energy gradients spontaneously disperse. Entropy is produced when there is dispersal of energy gradients, and the Second Law simply observes that this spontaneously occurs. Returning to how nature creates order, Schrödinger thus observed in 1944 that in order for complex living systems to create order or stable energy gradients (i.e. produce negative entropy), they must be dissipative, and release greater entropy to the environment, than the negative entropy created internally. Thus, living complex systems are necessarily dissipative, as they must participate in degrading energy gradients to a greater extent that the local energy gradients created.

2.1 Maximum Entropy Production

Building upon this realization, thermodynamics has furthered its science greatly over the last century, particularly in the domain of non-equilibrium thermodynamics. Scientists within the sciences of planetary and atmospheric scientists, mathematical physicists and more have pioneered the Principle of Maximum Entropy Production (MEP). This Principle is labelled as a principle, not a law, as the conditions by which the principle hold true are not understood or well defined. Critics are concerned that the lack of defined necessary conditions make falsifiability challenging if not impossible. Nonetheless, increasing empiric evidence supports the hypothesis, recently reviewed by Alex Kleidon, Ralph Lorenz and colleagues.

What the MEP Principle states is that not only will entropy be increased, but also it will do so in the maximal, most efficient way possible. An example popularized by
Frank Lambert highlights how heat will not only spontaneously escape from a heated cabin to a cold outdoor environment, but MEP states that heat will seek the optimal route to do so, for example preferentially going out a window if opened. Water will flow down a hill and take the path that provides the least resistance for the dissolution of the gravitational energy gradient represented by that slope. Not only does nature abhor an energy gradient, it seeks to optimally eliminate the gradient.

This forcing of the system to maximal entropy production, that is the spontaneous optimization of the dissipation of high quality energy to lower quality energy, appears to be central to the origin of life itself. Peter Macklem highlighted the analogy between life and a funnel in a bathtub; spontaneously forming, an ordered structure defying the laws of gravity, the funnel is highly dynamic (almost certainly a fractal structure in time and space) yet remain remarkably stable, as long as there was a gradient of bathwater to empty. Akin to a Bénard cell, an ordered structure may spontaneously form is if it is more efficient at dissipating an energy gradient. Broadening this observation, life and complex systems spontaneously get formed because they are consummate dissipative systems.

In summary, in their vigorous attempts to produce entropy and channel energy gradients, an ordered complex dissipative structure may spontaneously form, such as a tornado or whirlpool in a bath, and continue to live as long as there are energy gradients to dissipate. Humans are remarkably stable, robust, healthy creatures, live for decades, yet die in minutes in the absence of the ability to burn oxygen to carbon dioxide. Robust yet fragile, creation of fractal order (negative entropy) is made possible because the fractal ordered structure functions to produce a greater level of entropy to the environment.

3 The Hypothesis

After this foray into the science of non-equilibrium thermodynamics, we return to fractal structures in time and space to our specific objective, namely to introduce the hypothesis. The above arguments logically lead to a hypothesis linking the MEP Principle with fractal structure; namely that fractal structures are spontaneously created because they enable the optimal dissipation of energy gradients. This hypothesis may be stated in physiologically and clinically relevant terms: a fractal tracheobronchial tree driven by a fractal respiratory rate time series, connected to a fractal pulmonary vasculature driven by a separate heart rate fractal time series, is spontaneously created during embryogenesis because it offers the optimal geometry in time and space to enable dissipation of the energy gradients, principally the exchange oxygen and carbon dioxide and the production of heat. In a shorter version, the hypothesis simply state that fractals spontaneously form to optimize entropy production in complex dissipative systems.

Circumstantial evidence to support this hypothesis includes the ubiquitous association between energy gradient dissipation and fractal structures that appear in nature,
including both spatial (e.g. river deltas, lightning, coastline, mountain ranges) and temporal (e.g. avalanche, earthquake and solar flare dynamics). In addition, the drive towards increased entropy production has been observed by Eric J Chaisson, who has quantified the rising 'energy rate density' (or throughput of energy per unit time and mass) over the history of the universe as well as the history of life and human civilization. Last, animal and human studies led by W. Allan C. Mutch demonstrate that biologically variable life support improves delivery of oxygen to tissues when compared to monotonic life support. Nonetheless, the hypothesis that fractal structures spontaneously form because they optimize entropy production and energy dissipation requires further investigation, in particular, identifying the conditions necessary to enable this emergence of order.

The necessary conditions for this hypothesis may well invoke the definition of what is a complex dissipative system. In other words, fractal structures may form spontaneously only in the presence of a complex dissipative system, which requires complexity, large numbers of inter-connected elements, stochasticity, and much more. The study of planets, weather, turbulence, whirlpools, tornadoes and physiologic fractals merits transdisciplinary investigation to uncover commonly expressed necessary conditions. While unifying theory awaits, I am sure that much has already been uncovered by numerous scientists in these fields.

4 Clinical Application

Returning to the goal for individualized clinical benefit, the focus of our investigation. As discussed, there is extensive and growing evidence demonstrating the association between health and the presence of both a high degree of variability as well as the presence of fractal patterns of variation. Seeking a physiologic understanding, Peter Macklem, I and others have hypothesized that overall degree of variability is reduced related to degree of stress and loss of physiologic reserve (i.e. reduced adaptability), and given the hypothesis presented, the fractal variability properties may be related to the quality of the system to produce entropy. While this requires a better physiologic understanding, it is clearly related to the efficiency of oxygen consumption, and production of carbon dioxide along with heat. Thus, our research group is pursuing the capacity to utilize monitoring of multiorgan variability to track illness severity (generally associated with an impairment in entropy production), its trajectory, measure physiologic reserve and possibly guide therapy.

In summary, life, the quintessential complex dissipative system, may have developed as it is enables the dissipation of energy gradients, the production of entropy, and the conversion of high quality energy to waste. In so doing, there occurs the spontaneous creation of fractal patterns in time and space precisely because they are optimally dissipative. Finally, seeking to improve individual patient care, monitoring multiorgan variability as a real-time measure of stress, physiologic reserve and entropy production may provide clinicians with a novel means of diagnosing, prognosticating and treating illness.
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Disclosure
Andrew J.E. Seely is founder and Chief Science Officer for Therapeutic Monitoring Systems Inc, created to commercialize patented Continuous Individualized Multiorgan Variability Analysis (CIMVA™) technology, with the objective of delivering variability-directed clinical decision support to improve quality and efficiency of care.

Bibliography