New perspectives for cardiology from chaos theory

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Abstract

Converging from a number of disciplines, non-linear systems theory and, in particular, chaos theory, offers new descriptive and prescriptive insights into physiological systems that may more accurately reflect underlying mechanisms. This paper describes the implications of these new perspectives and briefly outlines how they might be applied to the study of cardiology.

Key words: cardiology, non-linear, chaos.

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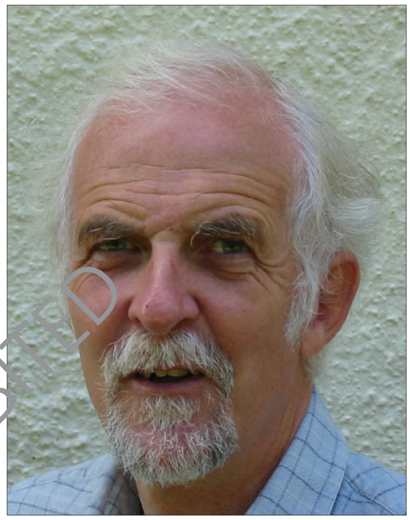

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Introduction

The predominant scientific paradigm views natural systems operating at a state of equilibrium, with feedback eliminating environmental challenge. System variables change in a smoothly continuous fashion and unexplained variation is viewed as random behaviour that can be described by statistical methods. A system can be understood by breaking it down into its component parts and, conversely, individual knowledge of all the parts of a system lead to an understanding of the whole.

Over the last 20 years this model has been challenged with insights from the study of non-linear dynamics and the associated behaviour known as chaos. It appears that other mechanisms may play an important role in the functioning of living systems.[1]

This paper has two aims. First, to describe the features of this new approach based on non-linear behaviour. Second, to illuminate its potential to the study of physiological systems in health and disease and, in particular, the area of cardiology.

Non-linearity and chaos

A wide range of physical and biological systems demonstrate properties that emerge from a network of elements that interact predominantly at a local level and which cannot always be explained using traditional scientific approaches. For example, the brain is a network of inter-connecting neurones that are excitatory or inhibitory. How each element responds to the information it is presented with is determined by a local activation rule that weighs and sums the inputs to determine whether there is an output. Activation rules are directed by discontinuous data and recursive feedback (i.e. the output of one interaction is fed back as the input of the next). Similar local recursive mechanisms are operating in all organ systems that give rise to unique features that are termed non-linear.

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The mathematical definition of non-linearity is beyond the scope of this text but, in qualitative terms, a number of important features can be recognised. For example, systems cannot be understood by a reduction into their component parts and rarely is there a simple relationship between cause and effect – small inputs can lead to large system changes, large inputs may have little impact.

From a global perspective, detailed system behaviour in non-linear systems can evolve from the interaction of elements at a local level without external direction or the presence of internal control. This property is known as emergence and gives systems the flexibility to adapt and self-organise in response to external challenge. Emergence is a pattern of system behaviour that could not have been predicted by an analysis of the component parts of that system.

Chaotic behaviour is an important feature of non-linear systems. Chaotic behaviour was suspected over 100 years ago but it has only been the availability of computational power that has enabled scientists to probe the complex interior of non-linear systems from a mathematical perspective. The publication of James Gleick's *Chaos: making a new science*[2] alerted a wider audience to the importance of an area that has now found applications as widespread as the study of weather, organisations, biological systems and the behaviour of stock markets.

Chaotic systems have a number of important features:

- Predictability or determinism. Chaos can be understood by comparing it with two other types of behaviour – randomness and periodicity. Chaos has characteristics of both behaviours. Although it looks random, it is predictable.
- There is extreme sensitivity of behaviour to initial conditions. Small changes in a variable in the system at one point will make a very large difference in the behaviour of a system at some future point. This has been termed the 'Butterfly Effect'. For example, the weather is a chaotic system and a butterfly flapping its wings in New York can be responsible for a hurricane in Tokyo. The Lyapunov exponent is a measure of the divergence of points that are initially very close and can be used to quantify chaotic systems. In practice, it is this extreme sensitivity to initial conditions that makes chaotic systems so unpredictable as it is impossible to quantify the state of real systems with exactitude.
- Fractal scaling. Chaotic systems demonstrate similar characteristics at different levels of scale or magnification. The fractal dimension is another approach to describing chaotic systems.
- The presence of a chaotic attractor. Although chaotic behaviour appears random, when studied in a particular way, patterned features are discernible. One way of describing a dynamic system is geometrically, plotting its trajectory with time. If a system is described using *n* variables and each variable is allocated one dimension, the trajectory of each system element can be plotted with time in an *n* dimensional graph or phase space. In a chaotic system, the trajectory will never repeat itself but forms a unique pattern as it is attracted to a particular area of phase space – a chaotic attractor. The dimension of this attractor gives an indication of the complexity of the system.

In summary, chaotic behaviour is a feature of non-linear systems that gives rise to a number of important characteristics that can be identified and quantified using mathematical techniques.

Applying non-linear insights to cardiology

Over the last decade, what was originally thought to be random variation in physiological systems has been shown to be low-dimensional chaos that may play an important functional role in terms of efficiency and adaptability.[3-5] Chaotic characteristics have been identified in a wide number of variables such as blood glucose,[6] heart rhythm[7] and brain electrical activity.[8]

Chaos could be described as the 'Mother of Physiology'. It appears to be the healthy signature of physiology whereas disease and ageing are associated with a generalised loss of complexity and consequent loss of adaptability in the dynamics of organ system function. These insights lead to a radically different model to those based on homeostasis and hierarchical control which may offer new descriptive and proscriptive possibilities.

For example, stochastic analyses such as standard deviation and power spectrum approaches have a reduced predictive sensitivity and specificity compared to attractor dimensional measures. A reduced standard deviation of heart beat intervals can predict increased mortality in a group of cardiac subjects but it cannot specify which individual will succumb. This is in contrast to the attractor dimension of the data which can indicate which patients will develop more serious pathology.[9]

In cardiology, however, it is the framework of fractals that finds the greatest application – a recognition that chaotic systems demonstrate self-similar patterns at different levels of scale or magnification. Statistically self-similar fractal patterns in both space and time are ubiquitous in biological systems and are a feature of a wide range of physiological systems, yielding important insights into normal physiology and pathophysiology.[10] Fractal patterns can also be produced with simple mathematical expressions or algorithms, allowing complex biological structures to be coded by relatively few genes.

For example, the heart has a large number of branching structures that include the coronary vasculature, electrical conduction fibres and supportive connective tissue structural elements, all of which demonstrate fractal scaling.[11] Fractal circulatory structures allow for rapid and efficient transport, providing more surface area than any other spatial organisation. The fractal cardiac conduction system ensures the efficient transport of electrical signals and the fractal organisation of connective tissue in the aortic valve leaflets leads to the efficient distribution of mechanical forces.[12] In diseased states, lower fractal dimensions are found in all these areas.

Fractal scaling can also be demonstrated in variables that change with time. Under pathological conditions, fractal scaling is lost. Heart rate variability is fractal in nature and is prognostic in disease areas such as myocardial infarction and heart failure in individual patients.[13] In extreme cases, fractal scaling is lost completely, transforming into a periodic output such as ventricular fibrillation dominated by a single scale or to uncorrected randomness such as atrial fibrillation.[3]

In addition to descriptive and predictive advantages, there are early indications that non-linear insights can be exploited to control the dynamics of chaotic systems. These techniques have found an early application in cardiology in the control of arrhythmias although the applicability of these techniques remain largely experimental.[14]

Conclusion

According to classical concepts of physiological control, healthy systems are regulated within a hierarchical control framework to reduce variability and maintain physiological constancy. However, contrary to the predictions of homeostasis, the output of a wide range of systems fluctuates in a complex manner that is underpinned by non-linear mechanisms and the low-dimensional dynamics of chaos that arises from recursive interaction at a local level. It is suggested that these complex non-linear dynamics represent interacting regulatory processes operating over multiple

Key messages

- Non-linear systems theory offers an alternative approach to understanding physiological systems that may more accurately reflect underlying mechanisms
- Chaotic behaviour is a feature of non-linear systems that can offer important descriptive and proscriptive possibilities
- Approaches to understanding and intervening in the cardiovascular system are being developed using these new models and are likely to become increasingly important over the next decade

time scales that prime the organism for adaptive response and physiological stress. Variability is a feature of health and a reduction or breakdown of non-linear dynamics is a marker of disease.

Chaos provides new concepts and methods of analysis that help to understand the dynamics of cardiology in both health and disease that complement existing approaches and may lead to new investigative opportunities. It is a model that seems more likely to reflect the underlying physiological processes. Although the analysis of non-linear systems is in its early stages, the practical applications of this approach for both prediction and intervention are likely to become increasingly important over the next decade.

Conflict of interest

None declared.

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