Early detection of arrhythmia using chaos theory

Mohammad Mostafa Asheghan[1], Farhad R. Nezami[1]

[1]Division of Thoracic and Cardiac Surgery, Brigham and Women's Hospital, 75 Francis St, Boston, MA 02115

BRIGHAM HEALTH
BRIGHAM AND WOMEN'S HOSPITAL

HARVARD MEDICAL SCHOOL

BACKGROUND & AIMS

- Heart arrhythmia is a malfunction in the electrical impulses that coordinate heartbeats resulting in irregular, too fast or too slow heartbeats.
- We mathematically show that the behavior of an arrhythmic cardiac signal is governed by chaos dynamics.
- All known properties of chaotic systems to this signal can be applied. In particular, we focus on bifurcation that is the transient behavior when an ordinary system starts getting chaotic.
- We posit that while the ordinary heart is a neat periodic system opposing a chaotic arrhythmia, the detection of bifurcation in an apparently healthy heartbeat signal could predict arrythmia at early stages.

METHODS

Chaos is a special behavior appearing in some nonlinear dynamic systems, including biological organisms. The states of a chaotic system have a random-like behavior, yet the system is not stochastic.

Chaotic systems are extremely sensitive to the value of the initial conditions rendering them practically impossible to predict. This property is universally known as the butterfly effect in the literature (Figure1).

FIGURE 1. "Flying a butterfly in Brazil can make a storm in China". Butterfly effect is a property of chaotic systems that refers to their extreme sensitivity to the system parameters and history. (Photo adopted from happinesstobetour.com)

Butterfly effect makes the chaotic systems unpredictable. To see this in practice, a simulation on a chaotic recursive equation called logistic map is performed. This map is defined by

$$x[n+1] = \gamma x[n](1 - x[n]), \qquad x[0] = x_0 .$$

Figure 2 shows how the time series diverge after only twenty iterations when the initial values are infinitesimally altered. Due to this property, one cannot expect mimical trajectories in two identical chaotic systems with the same initial values [1].

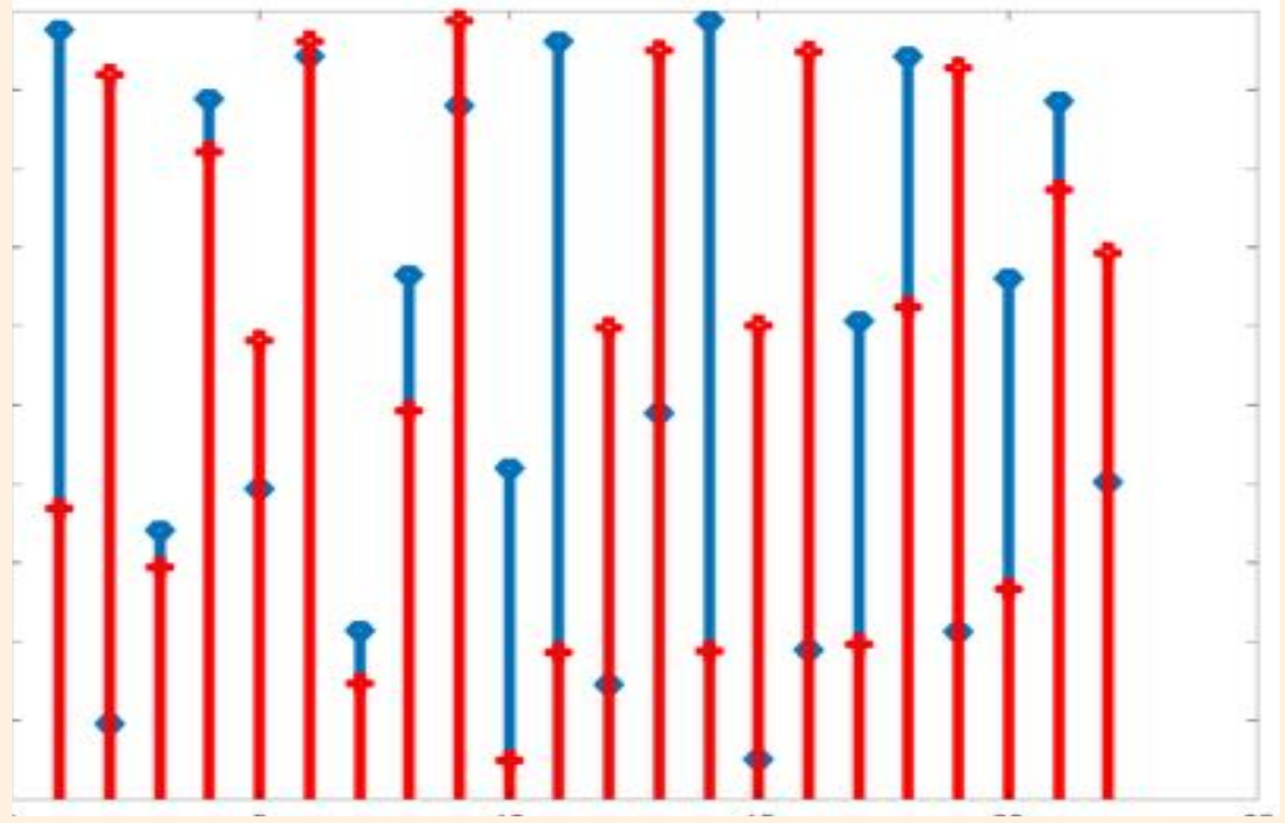

FIGURE 2. Divergence in logistic map with two different initial values. Blue: $x_0 = 0.5$. Red: $x_0 = 0.5001$.

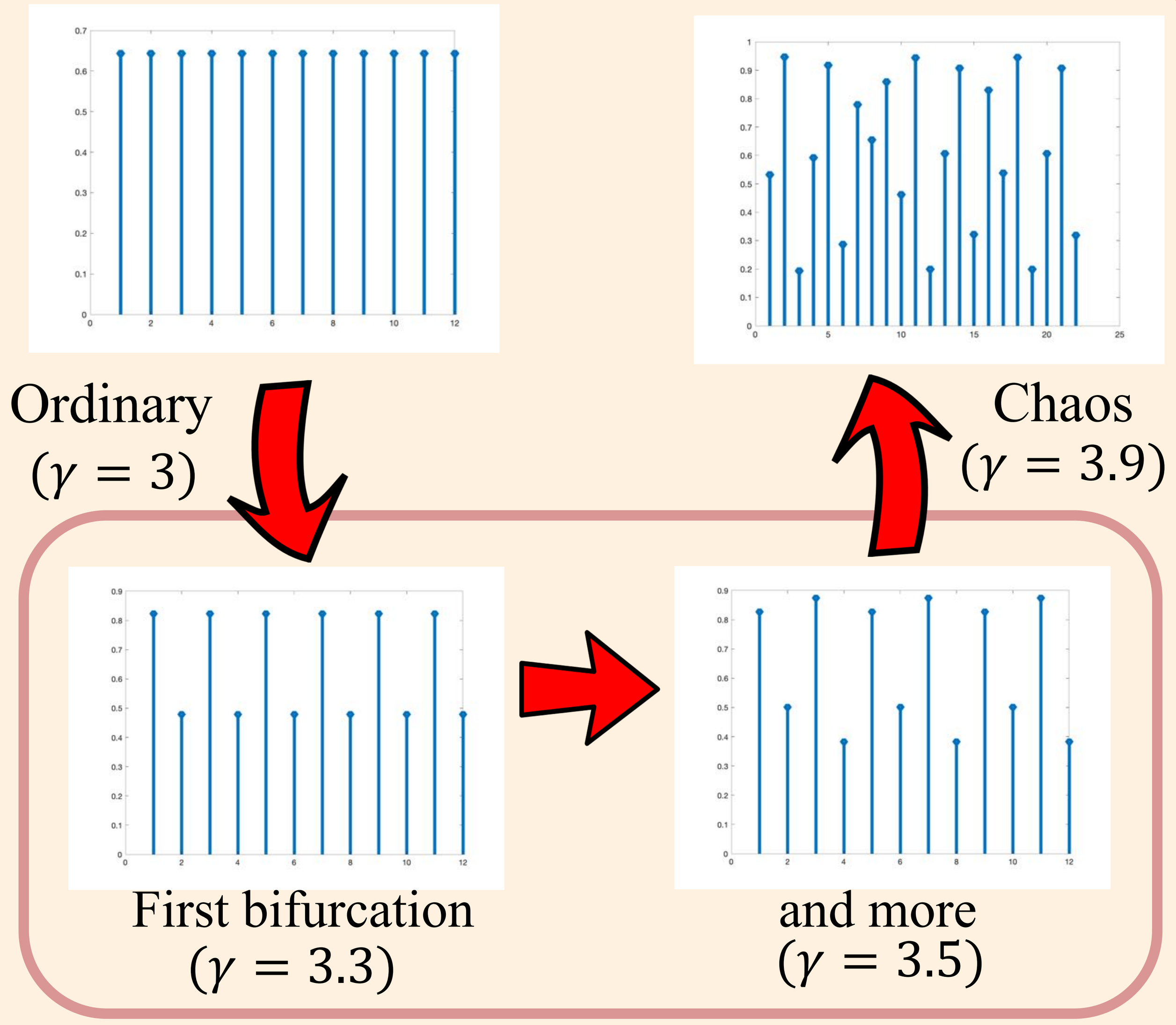

FIGURE 3. Ordinary to Chaos evolution in Logistic map by tuning the γ parameter.

Bifurcation literally means division into two parts. In chaos theory, bifurcation is a doubling in equilibrium points of a system. Since the bifurcation is the bridge between ordinary and chaos, it can be considered as a trigger sign for chaotic behavior of the system. In a consistent system, certain evolutions in the parameters can convert it to a periodic signal with two, and then more peak values, and eventually to chaos. The path from ordinary to chaos is bifurcation. Thus, bifurcation can be the alerting sign to expect chaotic behavior from the system in future. For instance, a simulation on logistic map has been run to show that how growing the parameter gamma in logistic map from 3 to 3.9 triggers a journey from ordinary to bifurcation, more bifurcations, and eventually chaos (Figure 3).

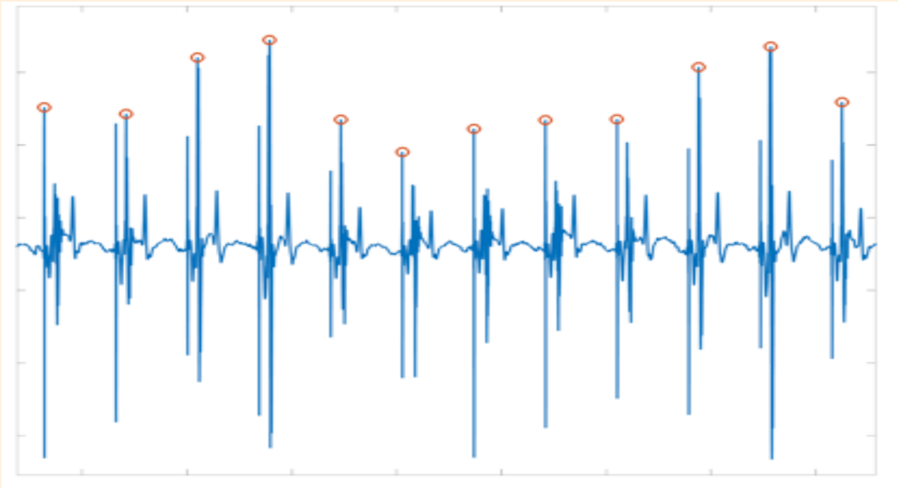

FIGURE 4. Peak values are detected automatically and leveraged to construct a new signal to explore chaos dynamic existence.

RESULTS

Peak values of the cardiac signal are automatically extracted from the raw data using an in-house code (Figure 4). While stochasticity is unavoidable in biological systems [2], the key-point is how to process data to avoid misleading results for chaos onset. Herein, the chaos detection test introduced in [3] was fed by the peak-chained data and surprisingly, chaotic dynamics was detected. In synergy with the fact that normal heart behaves periodically, we then posit that the existence of bifurcation in apparently healthy hearts will act as an early detector of arrhythmia. As an ongoing progress of this work, this algorithm is being applied to several clinical measurements. Chaos detection reveals further results, including that non-predictability of arrhythmic signal is guaranteed.

REFERENCES

[1] Asheghan, M. and Míguez, J., 2013. Chaos: An Interdisc. J of Nonlinear Science, 23(2), p.023108.
[2] Asheghan, M, et al, 2020. IFAC-PapersOnLine, 53(2), pp.16457-16461.
[3] BenSaïda, A., 2015. SoftwareX, 3, pp.1-5.

contact: masheghan@bwh.Harvard.edu