CHAOS IN THE CARDIOVASCULAR SYSTEM:
Analysis of Heart Rate Variability
as a Diagnostic Tool

Richard T. Mihran
UNIVERSITY OF COLORADO

Dept. of Electrical and Computer Engineering
BOULDER, CO
HEART DISEASE

- Greatest killer of people in the western world
- Underlying pathology is slow-forming, often without symptoms for decades
- The so-called "heart attack" can kill in minutes, or go unnoticed
- Sudden Cardiac Death (SCD) kills over 500,000 Americans each year

WHAT IS A "HEART ATTACK"?

- Acute manifestation of underlying occlusive vessel disease, may take several forms

1. Acute formation of a blood clot in an occluded section of coronary artery: MYOCARDIAL INFARCT
   - Can kill if massive, but usually results in local damage

2. Disruption of normal control of electrical signals in the heart tissue (arrhythmia)
   - Fatal form is VENTRICULAR FIBRILLATION
   - Incoherent, unsynchronized contraction of myocardium
   - Loss of consciousness in 5 sec, death in 4-6 minutes
THE CHALLENGE:

- SCD generally occurs in a percentage of people who have had previous myocardial infarction

- How can people at risk of SCD be identified?

  Traditional tests are invasive, often inconclusive

- Analysis of Heart Rate Variability (HRV) may provide the solution

HEART RATE VARIABILITY

- Typically represent heart rate as mean rate over one minute (e.g. 72 bpm)

- Instantaneous heart rate (IHR) can be defined with each new beat, as

  \[
  1/(t_n - t_{n-1})
  \]

  where \( t_n - t_{n-1} \) is the time between beats

- Each heart beat defines a "point event" in a series process
MEASUREMENT OF THE IHR

- Easily extracted from the Electrocardigram (ECG or EKG)

- Spread of electrical excitation assoc. with contraction starts at SA node and can be measured on surface of body as potentials

\[ IHR = \frac{1}{t_n - t_{n-1}} \]
IS A STABLE HEART A HEALTHY HEART? NO!

- Healthy people exhibit complex variability in beat-beat intervals

- Variability is intrinsic, occurs even at rest

VARIABILITY OF THE "UNHEALTHY" HEART

- Variability is typically much lower, and/or exhibits strong periodicity:
HRV as a function of time: Normal
HRV as a function of time: ABNORMAL
PREDICTIVE POWER OF HRV FOR SUDDEN CARDIAC DEATH (Preliminary)

![Graph showing survival analysis with time after MI (years)]

### Table III. Ranked Univariate Relation of Holter Variables with Survival

<table>
<thead>
<tr>
<th>Variable</th>
<th>n</th>
<th>Proportional Hazards ($\chi^2$)</th>
<th>Relative Risk†</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heart rate variability</td>
<td>125</td>
<td>29.08</td>
<td>3.4</td>
</tr>
<tr>
<td>&lt;50 ms</td>
<td>158</td>
<td>34.26</td>
<td>2.6</td>
</tr>
<tr>
<td>VPC frequency ≥10/hr</td>
<td>225</td>
<td>29.84</td>
<td>2.3</td>
</tr>
<tr>
<td>Repetitive VPC</td>
<td>91</td>
<td>26.14</td>
<td>2.7</td>
</tr>
<tr>
<td>VPC runs</td>
<td>191</td>
<td>25.55</td>
<td>2.5</td>
</tr>
<tr>
<td>Pair VPC</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Average RR interval</td>
<td>211</td>
<td>8.84</td>
<td>2.0</td>
</tr>
<tr>
<td>&lt;750 ms</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
THE HEALTHY HEARTBEAT MAY BE A "TEMPORAL FRACTAL"

Fractals: Defined generally by property of self-similarity
- repeats similar structure over range of scales
- can be geometric, temporal, or statistical
- certain aspects of the heart anatomy also claimed to be fractal

Arbitrary Spatial Fractal

IS CARDIOVASCULAR CONTROL "CHAOTIC"?

Characteristics of chaotic systems:

- System behavior is "deterministic", i.e. not stochastic or statistically driven
- Mechanisms underlying behavior are very sensitive to initial conditions
- Resulting behavior is complex, with underlying patterns
- Behavior is bounded, characterized by "strange attractor"
CHAOS?

- The unhealthy condition is clearly not chaotic
- Examine healthy variability using phase space or return maps

- These will plot IHR at time $n$ vs IHR at some previous time, e.g. at $n-1$

<table>
<thead>
<tr>
<th>Random:</th>
<th>no pattern</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stable:</td>
<td>will be a point (point attractor)</td>
</tr>
<tr>
<td>Periodic:</td>
<td>trajectory will appear elliptical or circular</td>
</tr>
<tr>
<td>Chaotic:</td>
<td>trajectory will appear complex but patterned, as well as bounded (strange attractor)</td>
</tr>
</tbody>
</table>
S. Heart rate time series from a healthy subject has complex variability. Two-dimensional phase space plot reveals a complex trajectory suggestive of a so-called strange attractor. Delay map plots heart rate in beats per minute (bpm) at a given time against the heart rate after a fixed delay (in this case, 4 seconds), and then tracks the evolution of this heart rate vector after an arbitrary time (also 4 seconds in this case). Data in this example and Fig. 6 were filtered with singular value decomposition.
6. Normal sinus rhythm in healthy subjects (left) shows complex variability with a broad spectrum and a phase space plot consistent with a strange (chaotic) attractor. Patients with heart disease may show altered dynamics, sometimes with oscillatory sinus rhythms heart rate dynamics (middle) or an overall loss of sinus variability (right). With the oscillatory pattern, the spectrum shows a sharp peak, and the phase space plot shows a more periodic attractor, with trajectories rotating about a central hub. With the flat pattern, the spectrum shows an overall loss of power, and the phase space plot is more reminiscent of a fixed-point attractor. (Adapted from [8].)
WHAT IS THE PHYSIOLOGICAL ORIGIN OF VARIABILITY?

- Heart has intrinsic pacemaker (SA node) which sets the bias heart rate (approx 65-75 bpm)

- Two major neural pathways from brain can speed up (sympathetic) or slow down (vagal, or parasympathetic) this basic rate

**SYMPATHETIC:** Raises blood pressure, speeds the heart rate, incr. stroke volume, incr. respiration rate etc.

**VAGAL:** Lowers blood pressure, dilates blood vessels, slows heart rate, slows respiration etc.

Normal control is a competition between these antagonistic feedback mechanisms.
SUMMARY

Chronic loss of HRV has been associated with:
- chronic heart disease
- higher risk of SCD
- fetal distress syndrome
- transplanted hearts

Normal HRV is associated with:
- broad 1/f-like spectrum, with up to three superimposed peaks:
  i. 0.25-0.35 Hz. Due to respiration
  ii. 0.1 Hz. Oscillation due to slight underdamping in the baroreceptor control system
  iii. very low oscillations of unknown origin

- Complex, if not "strange", attractors