Lumped-parameter modeling of the cardiovascular system

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San Giovanni Battista Hospital
18 February 2015, Torino
Understand and quantify, through a stochastic modeling approach, the **impact of paroxysmal AF on the cardiovascular system** of a healthy young adult (structural remodeling effects neglected);
Motivation and Goal

- Understand and quantify, through a stochastic modeling approach, the impact of paroxysmal AF on the cardiovascular system of a healthy young adult (structural remodeling effects neglected);
- AF can be analyzed without other pathologies ⇒ highlight single cause-effect relations, trying to address the cardiovascular feedbacks which are currently poorly understood;
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- The main cardiac parameters can all be obtained at the same time (clinical studies usually focus only on a few of them at a time) ⇒ **overall good agreement with the current clinical measures**;

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Lumped-parameter modeling of atrial fibrillation
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- Accurate **statistical analysis** of the cardiovascular dynamics, which is not easily accomplished by in vivo measurements.
Cardiovascular scheme

P: pressure
V: volume
Q: flow rate
C: compliance
E: elastance
L: inductance
R: resistance
Reconstructed physiologic and fibrillated beating

- **Normal Sinus Rhythm (NSR)**
  - RR extracted from a correlated pink Gaussian distribution;
  - Time varying (right and left) atrial elastance;

- **Atrial Fibrillation (AF)**
  - RR extracted from an exponentially modified Gaussian distribution;
  - Constant (right and left) atrial elastance ⇒ No atrial kick;
Real RR series (MIT Database)

(a) Density plot of RR series

(b) Time decay of RR series

NSR 16773
NSR 18177
AF 71
AF 202

Sex
Age
NSR 16773
M 26
NSR 18177
F 26
AF 71/
AF 202/

Lumped-parameter modeling of atrial fibrillation
Real RR series (MIT Database)

(a) Distribution of RR intervals for different series:

- NSR 16773
- NSR 18177
- AF 71
- AF 202

(b) Cumulative distribution function of RR intervals for different series:

<table>
<thead>
<tr>
<th></th>
<th>$\mu$ [s]</th>
<th>$\sigma$ [s]</th>
<th>$c_v$</th>
<th>Sex</th>
<th>Age</th>
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</thead>
<tbody>
<tr>
<td>NSR 16773</td>
<td>1.03</td>
<td>0.13</td>
<td>0.12</td>
<td>M</td>
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<td>NSR 18177</td>
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<td>F</td>
<td>26</td>
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<td>AF 71</td>
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<td>0.19</td>
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<tr>
<td>AF 202</td>
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<td>0.17</td>
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Hemodynamic parameters

Systemic arterial pressure

Left heart

Real series analysis

Left ventricle

\[ P_{lv} \text{ [mmHg]} \]

\[ V_{lv} \text{ [ml]} \]

<table>
<thead>
<tr>
<th>CO [l/min]</th>
<th>NSR</th>
<th>AF</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.80</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4.38</td>
<td></td>
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<table>
<thead>
<tr>
<th>SV [ml]</th>
<th>NSR</th>
<th>AF</th>
</tr>
</thead>
<tbody>
<tr>
<td>63.84</td>
<td></td>
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<tr>
<td>47.21</td>
<td></td>
<td></td>
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<table>
<thead>
<tr>
<th>EF [%]</th>
<th>NSR</th>
<th>AF</th>
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<tbody>
<tr>
<td>53.27</td>
<td></td>
<td></td>
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<tr>
<td>37.12</td>
<td></td>
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</table>

<table>
<thead>
<tr>
<th>SW [J]</th>
<th>NSR</th>
<th>AF</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.87</td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.57</td>
<td></td>
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</tr>
</tbody>
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**Left ventricle**

Hemodynamic parameters
- Systemic arterial pressure
- Left heart
- Real series analysis

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Lumped-parameter modeling of atrial fibrillation
Arterial pressure: time series and statistics

<table>
<thead>
<tr>
<th>$P_{sas}$ [mmHg]</th>
<th>Mean</th>
<th>Systolic</th>
<th>Diastolic</th>
<th>Pulsatile</th>
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<tbody>
<tr>
<td>NSR</td>
<td>99.52</td>
<td>116.22</td>
<td>83.24</td>
<td>32.99</td>
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<tr>
<td>AF</td>
<td>89.12</td>
<td>103.66</td>
<td>77.24</td>
<td>26.42</td>
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</table>

Atrial pressure and volume

Hemodynamic parameters
- Systemic arterial pressure
- Left heart
- Real series analysis

**Introduction**

**Lumped-parameter modeling**

**Results**

**Conclusions**

**Hemodynamic parameters**

- **Systemic arterial pressure**
- **Left heart**
- **Real series analysis**

**Atrial pressure and volume**

**Figure (a)**
- **Atrial kick**
- **Rapid grow**
- **Plateau**

**Figure (b)**
- **Atrial kick**
- **Rapid grow**
- **Plateau**

<table>
<thead>
<tr>
<th>$V_{la}$ [ml]</th>
<th>Mean</th>
<th>End-Systolic</th>
<th>End-Diastolic</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>NSR</strong></td>
<td>56.53</td>
<td>64.41</td>
<td>55.37</td>
</tr>
<tr>
<td><strong>AF</strong></td>
<td>65.95</td>
<td>71.41</td>
<td>68.84</td>
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</tbody>
</table>

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Lumped-parameter modeling of atrial fibrillation
Mitral and aortic flow rates

<table>
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<tr>
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<th>NSR</th>
<th>AF</th>
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</thead>
<tbody>
<tr>
<td>Mitral RF [%]</td>
<td>13.59</td>
<td>9.94</td>
</tr>
<tr>
<td>Aortic RF [%]</td>
<td>7.62</td>
<td>10.91</td>
</tr>
</tbody>
</table>

- Different backflow valve openings during AF: Mi ↓, Ao ↑;
- Peak E wave velocity does not correlate with RF.

Bigger expense for the oxygen consumption (RPP, TTI/min, PVA/min) and decreased left ventricular efficiency (LVE) during AF;

The major effects of AF are due to HR acceleration, being rhythm changes less impacting.

**Scarsoglio, Med. Eng. & Phys., under review 2015.**
Analysis of the role of acute AF on the whole cardiovascular system through a stochastic modeling:

- Anatomical remodeling due to long-term effects and short-term regulation effects of the baroreceptor mechanism are absent;
Discussion and Conclusive Remarks

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- Present results should be interpreted as **pure consequences of AF alone** and not induced by other pathologies;

- Accurate **statistical description** of the cardiovascular dynamics, a task which is rarely accomplished by in vivo measurements;

- **New information** on hemodynamic parameters (e.g., flow rates, right ventricle dynamics), difficult to measure and almost never treated in literature.
Future work can be addressed to study:

- Response to AF together with *altered physical conditions* (e.g., during exertion, left atrial appendage clamping, etc);
Perspectives and future work

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- Combined presence of other cardiovascular pathologies (e.g., mitral insufficiency, hypertension, etc);
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- Response to AF together with altered physical conditions (e.g., during exertion, left atrial appendage clamping, etc);
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- Inclusion of the baroregulation mechanisms.