

## Fractal and Fractional Approaches to the Analysis of Heart Rate Variability

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### INTRODUCTION & AIM

Heart Rate Variability (HRV) is a key non-invasive marker of autonomic regulation. However, biological RR-interval signals are inherently nonlinear and non-stationary, characterized by long-range correlations and fractal properties that integer-order models fail to capture. Traditional linear methods cannot integrate the "memory" and multiscale dynamics of adaptive biological systems. In contrast, fractal geometry and fractional calculus provide the mathematical rigor needed to model structural roughness and non-local temporal dependencies, offering a superior representation of homeostatic control.

**Objective:** This work, structured as a systematic review, critically evaluates the capacity of fractal methodologies (e.g., Detrended Fluctuation Analysis) and non-integer order operators to model physiological complexity. The aim is to demonstrate the superiority of these approaches in quantifying cardiac adaptability and identifying early markers of cardiovascular degradation, offering a multiscale perspective inaccessible to conventional linear methods.

### METHOD

This work is conducted as a systematic review, utilizing a comparative approach to analyze non-integer order descriptors reported in specialized literature. The methodology focuses on the following core analytical frameworks:

- **Fractal Analysis:** Evaluating structural self-similarity and scaling properties through Detrended Fluctuation Analysis (DFA) to quantify the "roughness" and regularity of RR-interval time series.
- **Fractional-Order Modeling:** Investigating the integration of non-integer order operators ( $\gamma$ ) to represent the system's intrinsic memory and anomalous fluctuations in cardiac control.
- **Synthesis Criteria:** Evaluating identified methodologies based on their analytical performance, sensitivity in detecting cardiovascular pathologies, and the biological interpretability of the resulting parameters.

### RESULTS & DISCUSSION

Data synthesis demonstrates that nonlinear approaches provide diagnostic markers with significantly higher sensitivity compared to standard linear statistics (e.g., SDNN/RMSSD). The findings indicate that:

- **Complexity and Resilience:** A healthy cardiac rhythm is characterized by a scaling exponent of  $\alpha \approx 1.0$  ( $1/f$  noise). The transition toward pathology is marked by a loss of fractal complexity, where the signal tends toward either white noise ( $\alpha \rightarrow 0.5$ , indicating unpredictability) or Brownian motion ( $\alpha \rightarrow 1.5$ , indicating excessive regularity/monotony).
- **Memory and Non-locality:** Fractional calculus enables the modeling of the current state's dependence on the signal's temporal history. Non-integer order operators ( $\gamma$ ) accurately capture anomalous diffusion, providing a faithful description of neurovegetative feedback mechanisms that traditional integer-order models fail to represent.
- **Clinical Value:** These advanced methodologies facilitate the early identification of cardiac control mechanism degradation. By quantifying the "ruggedness" and memory effects of the RR-interval time series, they serve as robust predictive tools for cardiovascular risk assessment and physiological stress adaptation.

### CONCLUSION

Fractal and fractional models represent a necessary evolution in quantitative biology. By overcoming the limitations of linear modeling, they provide a robust foundation for personalized cardiovascular monitoring and precise assessment of biological resilience.

### REFERENCES

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