Chaotic behavior of blood pressure and heart rate in the conscious dog

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Abstract-Initial studies in five conscious dogs with their baroreceptors either intact or surgically isolated, demonstrate that deterministic chaos is likely to exist in both heart interval and mean arterial blood pressure. The nature of this chaotic activity is not qualitatively different between the intact and open loop preparations.

To assess nonlinear dynamical behavior, we constructed phase space trajectories from the time series data. The fractal dimension of the reconstructed trajectories was measured using the Grassberger-Procaccia algorithm. In four out of five dogs the fractal dimension of the reconstructed trajectory did not clearly converge for embedding dimensions up to 5. In one dog the fractal dimension of the attractor converged to a value between 2 and 3 for both heart interval and blood pressure in open and closed loop cases. Further evidence for deterministic chaos was provided by the reliability of data forecasts based on the fractal attractor.

I. INTRODUCTION

Much of what is known about physiologic systems has been learned using linear system theory. However, this cannot explain the known non-linear behavior in arterial blood pressure and heart interval. Arterial blood pressure exhibits all the hallmarks of a deterministic chaotic system; it is repetitive but unpredictable, there is underlying order in the apparently random behavior, and there is sensitive dependence on initial conditions. Non-linear dynamical behavior (deterministic chaos) has been observed in heart interval [1], and other physiologic parameters including sympathetic nerve discharge, renal tubular pressure and flow. These studies indicate that the normal variability seen in these parameters is not random, but instead follows a pattern known as a strange attractor. If deterministic chaos is seen in these physiologic variables, then it is logical to test the hypothesis that arterial blood pressure also exhibits this behavior.

It is now well known that low dimensional nonlinear dynamical systems can generate random time series data. However random fluctuations in the time series data for an observable dynamical variable may also be due to other sources such as measurement errors, unpredictable environmental changes and coupling to large numbers of other dynamical variables.

The purpose of the work described here was to determine whether or not time series data from blood pressure and heart interval measurements could be described within the framework of low dimensional nonlinear dynamics. The analysis represents one of the first applications of chaos theory to arterial blood pressure and its control. In this initial study the incidence and nature of the chaotic activity is described qualitatively rather than quantitatively (e.g., using Lyapunov exponents).

II. METHODS

In five dogs the carotid sinus region was isolated using a preparation used extensively in Dr Brunner's laboratory [2]. Catheters were placed in both lingual arteries for the measurement and control of carotid sinus pressure (CSP). Hydraulic vascular occluder cuffs (In Vivo Metrics, Inc) were placed around the distal external carotid artery and the proximal common carotid artery. All other arteries in the region were ligated, and the preparation tested to ensure that no leaks were present in the blind sac preparation. The lingual arteries were connected via a feedback amplifier to a syringe pump mechanism. Autonomic tone was thus manipulated via modulation of the baroreflex response. Using this procedure, the baroreflex was investigated in an open loop situation by altering the CSP. From the physiological viewpoint this procedure is much more realistic than electrical nerve stimulation of either the stellate ganglion or vagus nerve, or by pharmacological interventions, as it involves direct manipulation of the baroreflex arc.

Arterial pressure, peak aortic flow, CSP and heart interval (RR) was measured for 20 minutes (approximately 2000 beats). Data was sampled at 250 Hz and stored in digitized form for later analysis. In random order we measured, a control record (baroreceptors closed loop), a record with CSP fixed low (75 mmHg), and a record with CSP set high (150 mmHg).

Both mean arterial blood pressure (MAP) and heart interval were analyzed in the five dogs. As a first step in the analysis we used the method of time delays [3] to construct phase space trajectories from the time series data. Reconstructions were carried out over a range of the two parameters; delay time and embedding dimension. The fractal dimension of the reconstructed trajectories was measured using the Grassberger-Procaccia algorithm [4]. In a deterministic chaotic system the fractal dimension of the reconstructed trajectory remains constant as a function of the embedding dimension after a threshold embedding dimension is exceeded. The minimum threshold embedding dimension is the nearest integer dimension above the dimension of the attractor. The search for the dimension of the attractor using this technique is limited by the number of data points in the data set. A data set with N points can at best reliably reconstruct an attractor with a fractal dimension of $2 \log(N)$ [5]. Our data sets were typically of order $N \approx 10^3$ and so we varied the embedding dimension between 1 and 5.

In the cases where the fractal dimension converged we used linear forecasting techniques [6,7] to predict the future path on
the fractal attractor. By comparing forecasts using the early part of
the data with actual data in later segments of the same record,
we were able to confirm the deterministic nature of the signal.

III. RESULTS and DISCUSSION

In four out of five dogs the fractal dimension of the attractor
did not clearly converge for embedding dimensions up to 5. As
we could not reliably extend our embedding dimension beyond
5 due to the limited sequence length [5], no further analysis was
performed on these dogs.

In the fifth dog the fractal dimension of the attractor con-
verged to a value between 2 and 3 for both heart interval and
blood pressure in both open and closed loop cases. The reason
for the difference in fractal dimension between this and the
other dogs is unknown: as there were no other apparent diff-
cences.

Figure 1 shows the heart interval phase-space trajectories for
a delay time of 1, an embedding dimension of 3 and a fixed
carotid sinus pressure of 75 mmHg. A very similar graph ex-
isted for MAP (not shown). The characteristic doughnut shape
is indicative of deterministic dynamics. Qualitatively there ap-
peared to be no difference in the fractal dimension or the
phase-space trajectories between high and low CSP and control.
In this animal, data forecasting using a delay time of
embedding dimension of 3, confirmed the existence of determi-
nistic chaos as shown in Figure 2. In heart interval (MAP
forecast is not shown but was similar in terms of forecasting
ability). Correlation coefficients confirmed the reliability of the
forecasts at differing forecasting times. Furthermore the corre-
lation coefficient decreased with forecasting time in agreement
with the description of the data as deterministic chaos rather
than uncorrelated noise [7].

There have been no other reports on the literature to date on
chaotic activity and the baroreflex with the exception of [8]
where the correlation dimension was found to be 3.05±0.23 in
an intact conscious dog and 1.74±0.20 in a denervated animal.
This first result agrees with data from the one dog in which
forecasting was performed.

REFERENCES

namics, sudden death, and clinical cardiology. In The
Head and Heart of Chaos: Non-linear dynamics in bi-
ological systems. Abstracts of an NIH Workshop: June
15-6.

nous vasopressin does not enhance carotid baroreflex
control in the conscious dog. Am. J. Physiol. 266:
R1510-R1516.

ence. In Dynamical Systems and Turbulence, (eds D.A.


as a way of distinguishing chaos from measurement error

(1995). Complexity and "chaos" in blood pressure after
baroreceptor denervation of conscious dogs. Am. J.
Physiol. 269: H1760-6.