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Pressure oscillations in anesthetized dogs and its conversion into quasi-periodic orbits

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ABSTRACT

Using a basic representation of dynamic systems, arterial blood pressure pulsation is converted into quasi-periodic orbits with the purpose of transforming a periodic phenomena into a cyclical one by plotting the pressure p(t) versus its first derivative dp/dt. This elementary mathematical procedure made it possible to evaluate the variability of the systemic arterial pressure pulsations, both systolic and diastolic, as well as the slope variability of the anachrotic and catachrotic phases. Two periods, which can be used to estimate different sources of variability, can be distinguished in the catachrotic phase. One corresponds to the open aortic valves, and the other is associated with the closed valves. Furthermore, through the first derivative of pressure oscillations we were able to identify small changes in arterial pressure, which appeared when the sampling rate was at least 150 samples per second. Since the time variable was converted into a parameter, the result was a synoptic or holistic approach, which is a considerable improvement for the visual analysis of cardiovascular phenomena.
This simplified mathematical procedure can be easily implemented on a personal computer in real time and applied to all rhythmic phenomena in Physiology and Pathology.

Key words: Fast orbital transform, cardiovascular variability, sampling rate, first derivative of pressure oscillations.

INTRODUCTION

Arterial pressure pulsations can be recorded without inertia and in the absence of noise using different electronic devices (catheter tip manometers), which are able to display signals e.g., on the screen of personal computer (PC). This advanced methodology not only allowed us to precisely measure the evolution of the corresponding variable, but also to submit these values to different mathematical analyses (Hirsch & Smale, 1997). Examples include Fourier transform (FT), wavelet transform (WT) (Günther *et al.*, 1993; Günther *et al.*, 1996, and Jiménez *et al.*, 1997), or any other method based on statistical procedures. In addition to the spectral (FT) or the time-frequency analysis (WT), in the present study we attempted to obtain additional information using the graphic representation of the physiological function, in this case, the systemic arterial pressure pulsation p(t) versus the first derivative dp/dt (phase plane plot). Through this procedure we were able to convert a periodic phenomenon into a cyclical phenomenon, which will be designated Fast Orbital Transform (FOT).

This elementary methodology enabled us to quantitatively evaluate the variability of the systolic and diastolic arterial pressures, as well as the variability of the anachrotic and catachrotic slopes associated with the pressure pulsation. Furthermore, we can identify two periods during the catachrotic phase: the first is associated with open aortic valves, and the second with closed aortic valves.

Most standard procedures for measuring blood pressure consider a maximum sampling rate of 50 samples per second. This rate does not allow the visualization of significant information related to higher

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frequency phenomena associated with the process being studied. To obtain such information we intend to determine the optimal sampling rate.

MATERIALS AND METHODS

Experiments were carried out on fifteen adult mongrel dogs of either sex, weighing 10-14 kg. each. Sodium pentobarbital (30 mg/kg) was administered for anesthesia. The tracheae of all animals were intubated to ensure adequate alveolar ventilation during spontaneous breathing. A catheter equipped with a micro-tip pressure transducer (model SPG-350, Millar Instruments, USA), was introduced into the left femoral artery until the micro-tip reached the thoracic aorta at the heart level (the distance between femoral ligature and the desired heart level was previously determined outside the thorax).

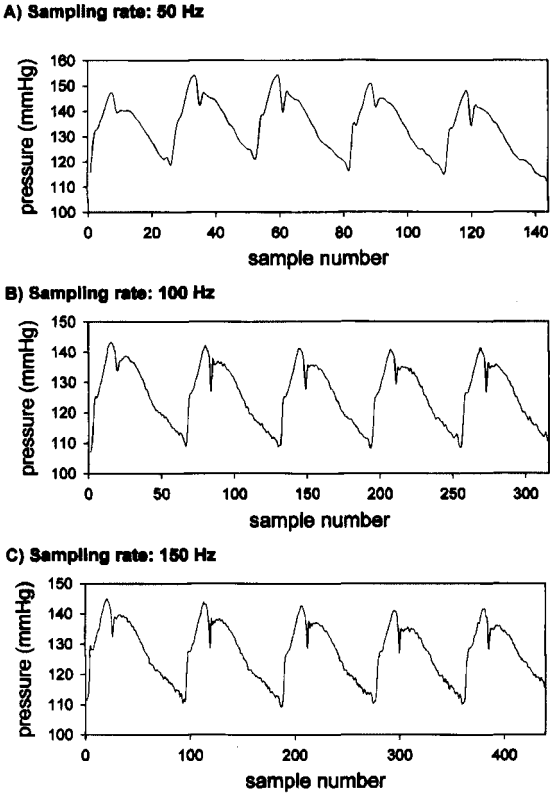

Figure 1. Systemic arterial pressure oscillations and effect of the sampling rate.
Shapes of five pressure pulsations at different sampling rates: 50, 100, and 150 samples per second.

The arterial pressure micro-tip transducers were calibrated to 5 V per mmHg; the response was almost linear, free of external noise, and had only 5% hysteresis. Since the sampling rate was of paramount importance in the present study, as shown in Figure 1, we compared the details obtained from different sampling rates of a sequence of pressure oscillations, with 30, 50, 100, 150, 200 and 250 samples per second. Samples obtained at rates higher than 150 samples per second did not provide relevant information. In accordance with this result, the rest of the study considered a rate of 150 samples per second.

To obtain the graphic representation of the physiological function of the systemic arterial pressure pulsation p(t) versus the first derivative dp/dt, it is necessary to calculate its discrete derivative

$$p'(t_i) = p(t_i+1) - p(t_i),$$

with t_i representing the corresponding sampling points.

RESULTS

The comparison of five pressure pulsations shows different results, depending on the sampling rates (Fig 1). At higher sampling rates, *i.e.*, 150 Hz (Fig 1C), there is significantly more information on high frequency components, adding variability to the signal, which needs to be studied further. In fact, when the sample rate is at least 100 samples per second, we found that the systolic peak was dual or diphasic, in correspondence with the rapid and reduced ejection periods (Figs 3A and 4A). It is also evident that the secondary waves are significantly more complex than those seen when sampling at rates under 50 Hz.

Figure 2 shows the analysis of one pressure pulse. Figure 2A shows one pressure pulse, and Figure 2B shows its transformation into a quasi-periodic orbit (clockwise) obtained by plotting p(t) versus dp/dt. The positive values of this orbital (A-D), *i.e.*, when dp/dt >0, correspond to the rapid and reduced systolic ejection period. Point A (where dp/dt = 0) corresponds to point A of

Figure 2A, where we have a local minimum (end diastolic point), and the arc AB is equivalent to the rapid ejection period; point B represents a local maximum of arterial pressure, *i.e.*, dp/dt= 0. Arc BCD corresponds to the reduced ejection period. The incisura (DEF) is very pronounced due to rapid pressure changes during this short period. The diastolic period is represented by several primarily negative oscillations (FGHIJKL). LM represents the beginning of the subsequent orbit.

When analyzing five pressure oscillations (Figure 3A), it is possible to obtain a pre-

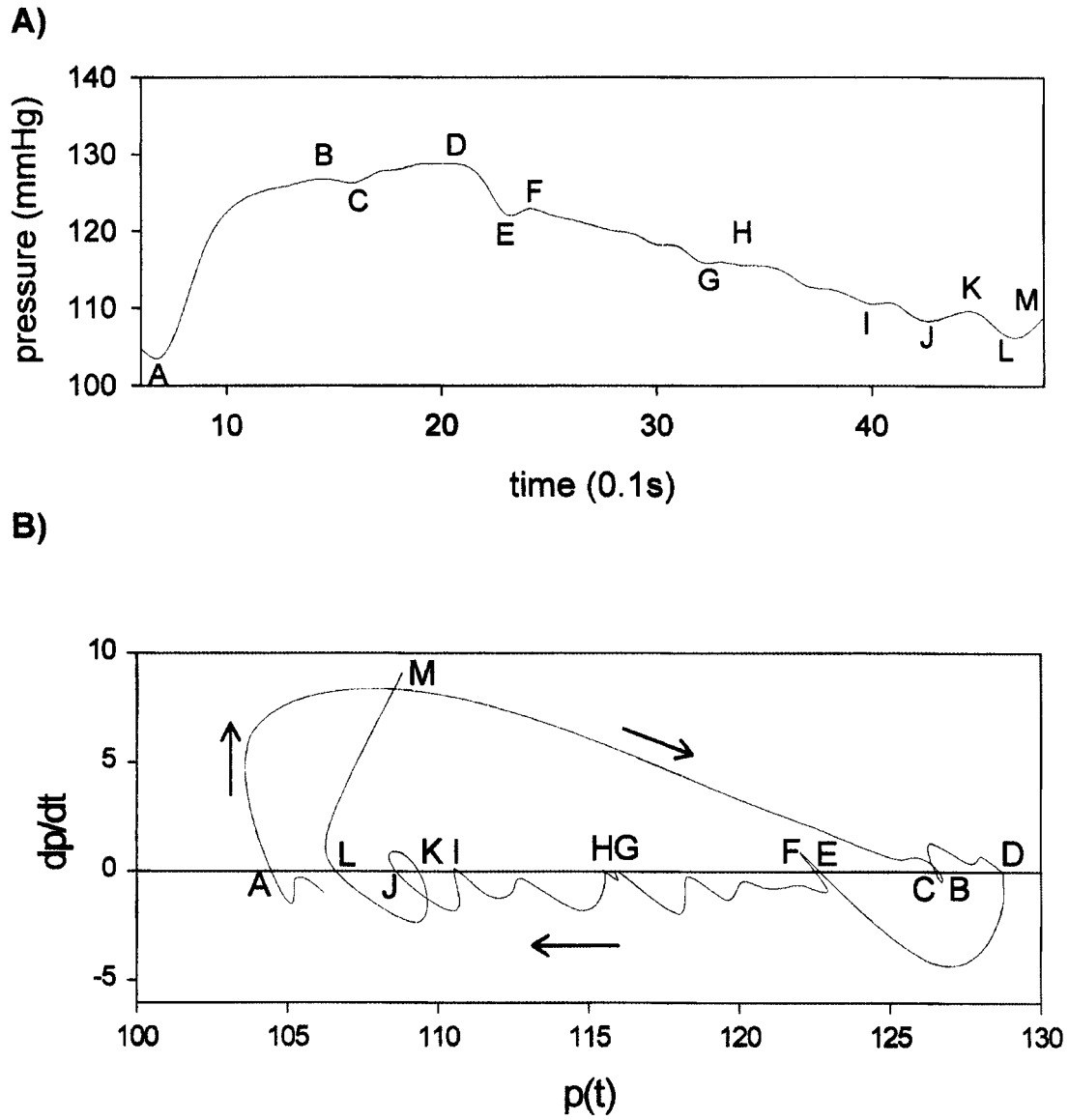

Figure 2. FOT analysis of one pressure pulsation.

A) One arterial pulsation with an interval of 10 milliseconds between points. Two systolic peaks can be observed (B and D), where A-B corresponds to the rapid systolic ejection, and C-D corresponds to the reduced systolic ejection. The incisura is represented by the negative deflection (D-E-F), while the secondary waves appear repeatedly during the diastolic period (G-H-I-J-K-L).

B) Quasi-periodic orbit obtained after applying the FOT to the arterial pulsation shown in A). Each periodic arterial pulsation is only quasi-periodic (A L) because the beginning of each cycle is not exactly the same as the end of the previous cycle (see points A and L of Fig 2A). Each orbit corresponds to one cardiac cycle, and the time sequence follows a clockwise direction.

liminary estimation of the variability of the systolic pressure (VSP) and the diastolic pressure (VDP). After the corresponding transformation of the orbits (Fig 3B), it is additionally possible to estimate the variability of the anachrotic (VAS) and catachrotic slopes (VCS). The VCS can also be decomposed into its corresponding open and closed valves phases, VCS ov and VCS cv respectively. The five positive arcs shown in Figure 3B, each with a different shape, provide the basis for estimating the VAS variability. The larger five negative arcs (dp/dt < 0) correspond to the incisurae, and the smaller ones represent the secondary waves.

In order to visualize the variability of the aortic pressure waves, both the diastolic

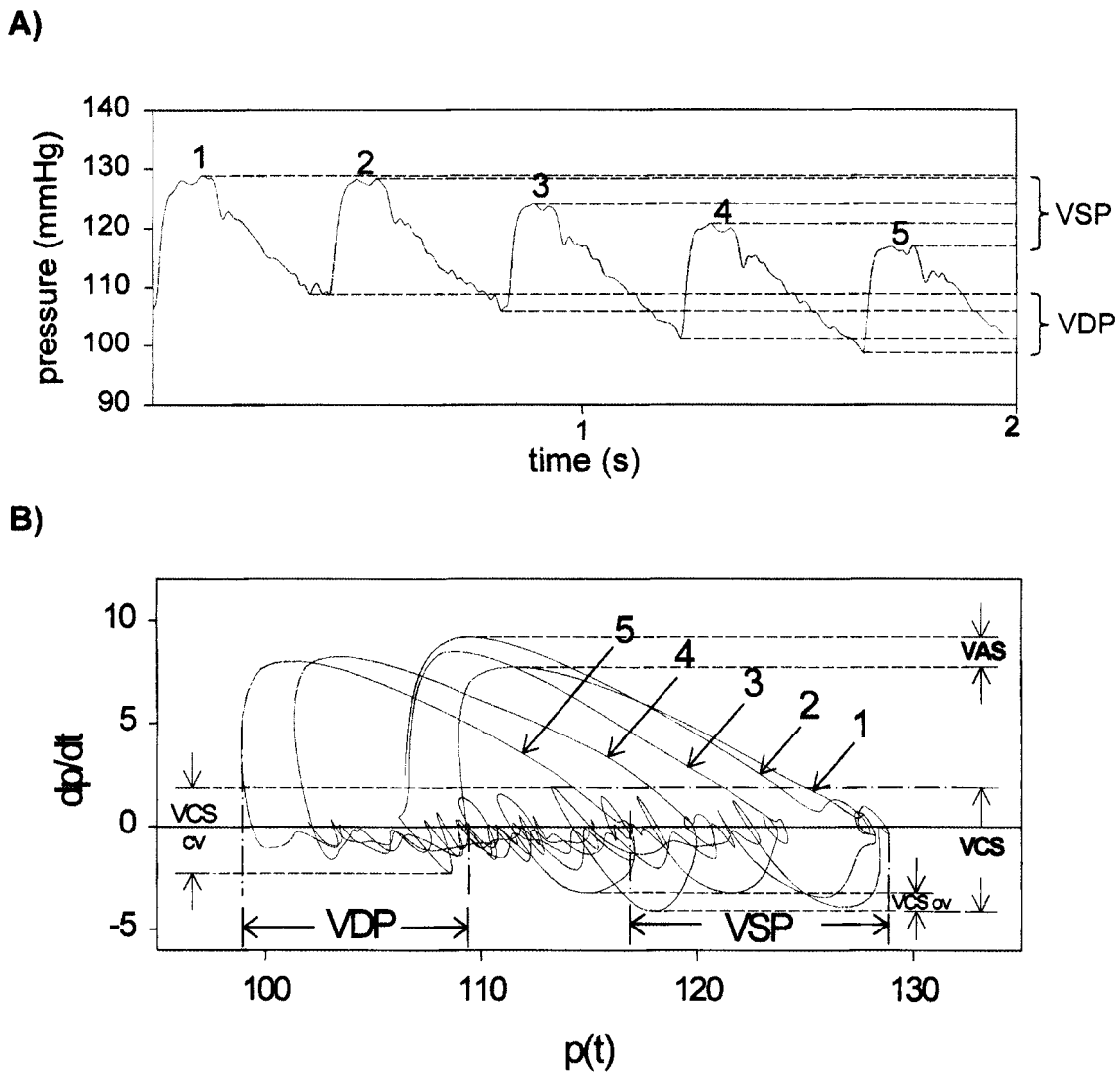

Figure 3. Analysis of five arterial pressure oscillations.

A) Five arterial pressure pulsations, showing the variability of the systolic and diastolic pressure, VSP and VDP respectively.

B) The five orbits correspond to the five pressure pulsations of Figure 2A. The variability of the systolic (VSP) and the diastolic pressures (VDP) can be observed on the corresponding horizontal lines. The slope variability of anachrotic phase corresponding to the maximum variability of the positive arch of the orbits can be visualized on VAS interval. The slope variability of catachrotic phase on the VCS interval at right is separated into two intervals: with aortic valve closed on interval VCS cv, left, and with aortic valve open on interval VCS ov, bottom right.

and systolic pressures and the corresponding increasing (anachrotic) and decreasing (catachrotic) slopes of the pressure pulsations, numerous orbits (Fig 4B) obtained from the original pressure oscillations of Figure 4A were plotted. Since the scales for measuring these variables are different, mmHg for pressure and dp/dt for slope, comparisons should only be made using the same scale, *i.e.*, systolic versus diastolic, and anachrotic versus catachrotic.

The four kinds of variability are shown in Figure 5, where VSP = variability of systolic pressures, VDP = variability of diastolic pressures, VAS = variability of anachrotic slope, and VCS = variability of catachrotic slope. The greatest variability corresponds to the systolic pressure and

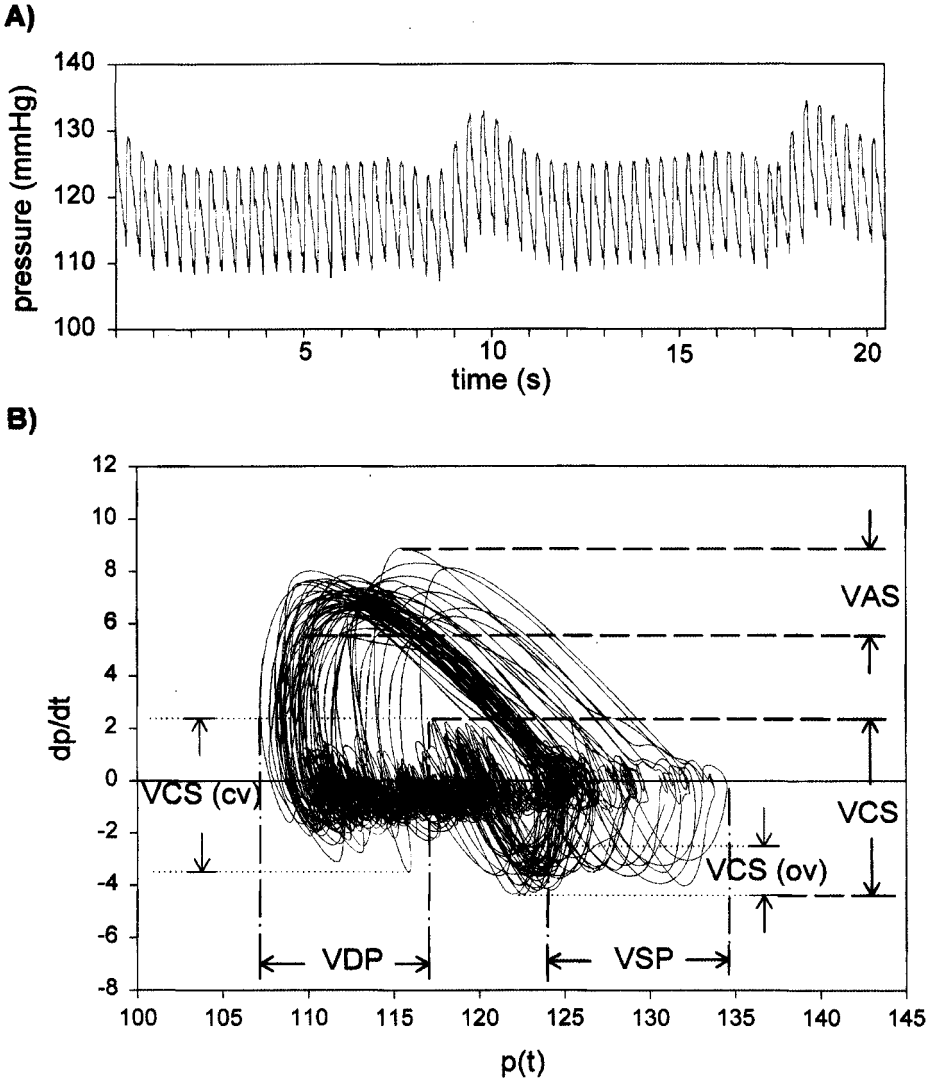

Figure 4. Analysis of 56 arterial pressure oscillations p(t).

A) The distribution of 56 arterial pressure oscillations against time. The observed vertical fluctuations correspond to respiratory cycles.

B) The corresponding 56 orbits. The variability of arterial pressure pulsations (abscissa) are represented by the intervals on the horizontal line of the variability of the diastolic pressure [VDP] and the variability of the systolic pressure [VSP]. The variability of the pressure slopes (dp/dt) during the systolic and diastolic periods, *i.e.*, the anachrotic [VAS] and catachrotic slopes [VCS], are represented by the intervals between the two vertical lines, at right. Moreover, we can visualize the variabilities during closed and open aortic valve ejection (VCS cv, VCS ov).

the anachrotic slopes; the least corresponds to the catachrotic slopes.

DISCUSSION

1. Importance of the sampling rate

In physiologics, the apex of the systolic pressure is commonly represented as a smooth curve. However, when the sample rate was at least 100 samples per second, we regularly found that the systolic peak was dual or diphasic, in correspondence with the rapid and reduced ejection periods (Figs 2A, 3A and 4A). This type of information could be of use in studying the ventricular function.

The complexity of the secondary waves, as visualized through the higher frequency sampling rates, provides information that could be useful in future studies of the types of hypertension.

2. Fast Orbital Transform (FOT)

The cardiovascular system is a biological structure with repetitive inputs and outputs, which in the present study was centered on the pulsating blood flow in the aorta of anesthetized dogs. The spontaneous rhythmic oscillations of the systemic arterial pressure was recorded as a function of time and subsequently analyzed by plotting the arterial pressure oscillations p(t) (abscissa) as functions of its first derivative dp/dt, which yielded a quasi-orbital and holistic transformation of each cardiac cycle.

We suggest that this elementary mathematical procedure may be designated as Fast Orbital Transform (FOT), which can also be obtained directly in real time, and its applicability includes all physiological rhythms.

Among the tools of nonlinear dynamics used to study chaos theory, Denton *et al.*, 1990, described the **phase plane plot,** which is the plane where FOT can be visualized.

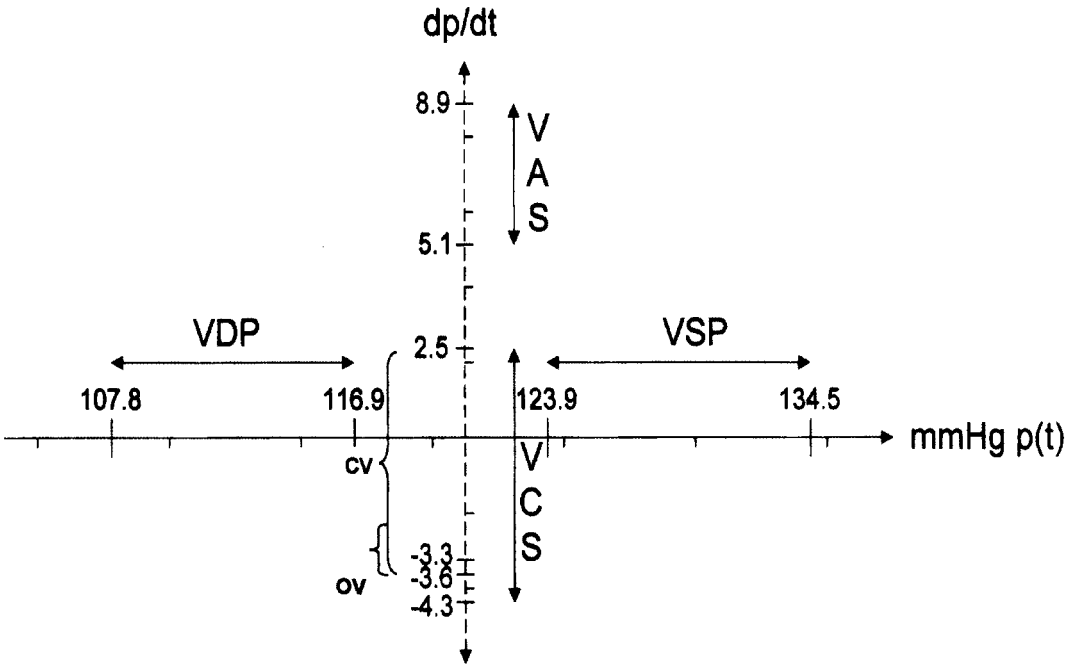

Figure 5. Using orthogonal axes, the variability of [VSP], [VDP], [VAS] and [VCS] can be assessed. [VSP] ranges between 123.9 and 134.5 mmHg, *i.e.*, 8.35% with respect to the mean systolic pressure 126.88 mmHg. [VDP] ranges between 107.8 and 116.9 mmHg, *i.e.*, 8.25% with respect to the mean diastolic pressure, 110.26 mmHg. The variability of the anachrotic (VAS) and catachrotic slopes (VCS), range between 5.1 and 8.9; and -4.3 and 2.5, respectively. The variability of VCS with closed valve ranges between -3.6 and 2.5, and the variability of VCS with open valve between -4.3 and -3.3.

According to Denton *et al.*, 1990, 1% noise can severely disrupt the structure of a plot, and therefore the data must be as noise-free as possible. In our recording methodology (catheter-tip manometer), noise-free conditions allowed us to obtain reliable information from the cardiovascular system.

3. Quantitative evaluation of biological variability

The quantitative evaluation of biological variability is of great importance in clinical medicine as fractal processes generate irregular fluctuations on different time scales, such that the temporal variability is statistically self-similar (Denton *et al.*, 1990). Healthy physiological organisms can be defined by their complexity and their spontaneous variability (Pool, 1989), whereas all pathological phenomena are characterized by monotonous, highly predictable, and therefore poor quality information, which is defined by Goldberger (1997) as stereotypy, meaning to repeat without variation. In summary, chaos provides the body with the flexibility to respond to various stimuli, so that healthy systems do not want homeostasis, they want chaos (Pool, 1989).

The great variability of all cardiovascular functions is a logical consequence of multivariable systems, since the final product (the systolic ejection into the aortic elastic reservoir or Windkessel) depends upon the autogenous intrinsic rhythmicity, the chronological sequence of myocardial activation, the preload of venous return, and the afterload of capacitative, inductive and resistive impedances of the aortic compartment. Furthermore, nervous and hormonal modulation of the effectors, the multiple reflex responses of the whole system, and the respiratory amplitude modulation, and many other factors should also be taken into account (Koepchen, 1962).

In addition to the two-dimensional approach discussed here, (a function of time p(t) versus its derivative dp/dt), the intrinsic variabilities of other phenomena (physics, chemistry, biology) have been extensively studied using deterministic nonlinear differential equations with a finite number of degrees of freedom, whose solutions can be identified with trajectories in a phase space as limited cycles (Bassingthwaighte *et al.*, 1994; Crutchfield *et al.*, 1986; McCarley *et al.*, 1986; Seifritz, 1987; West, 1980).

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