Wavelet analysis of arterial pressure and blood velocity pulsations in the aorta of anesthetized dogs

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The arterial pressure and blood velocity pulsations were recorded from the aorta of anesthetized dogs by means of micro-tip pressure and velocity transducers. Wavelet transforms (WT) were obtained by converting the analog signals into digital samples at the rate of 42.7 per second, which were subsequently subjected to an algorithm of WT. An iterative rarefaction (2^0 to 2^{-4} resolutions) of the number of samples was followed by a substraction of the high frequency components (wavelet coefficients) from the corresponding resolutions.

Analyses of the arterial pulsations revealed that the second WT always yielded four types of systolic apexes, which were apparently devoid of physiological meaning, since they were inherent to the "triangulation phase" of the WT algorithm. In addition, the third WT occasionally revealed slow amplitude modulations, which could not be identified in the original recordings and whose significance deserves further investigation. This is also valid for the wavelet coefficients, whose biological meaning is still obscure.

In summary, the WT operates as a low pass filter, which brings to light the lower frequency components of arterial pulsations and which finally yields the mean values of both arterial pressure and blood velocities.

INTRODUCTION

The aim of this preliminary study was to assay a new mathematical tool, known as *wavelet transform (WT)* or as multiresolution analysis (Mallat, 1989; Meyer, 1992), to investigate arterial pressure and blood velocity pulsations in the aorta of anesthetized dogs. Customarily, rhythmic cardiovascular phenomena were subjected to Fourier analysis (FA), either by applying FA to a single pulsation, or else to numerous pulsations which evolved during a given period; in both instances, FA yields a "global" frequency spectrum (Attinger, 1964; Fung, 1984; McDonald, 1974). In contrast, the WT gives a "local" frequency analysis with different resolutions. The original pressure or velocity recordings are defined as resolution 2^0, and to obtain the next resolution (2^{-1}) the total number of samples (N) should be halved, *i.e.*, if N= 512 in the original record, N = 256 at resolution 2^{-1}. The high frequency components (wavelet coefficients) were eliminated from the original signal and, consequently, these coefficients should be considered as the complements of the 2^{-1} resolutions. The same operations (WT) can be repeated, until the mean arterial pressure or the mean blood velocity are obtained.

In sum, WT analyses allows the differentiation of four kinds of apical configurations. Slow amplitude modulations, not detected in the original recordings, may be obtained from the second and third WT. Furthermore, this procedure provides the mean values of arterial pressure fluctuations and blood velocity oscillations.

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METHODS

Experiments were conducted on adult mongrel dogs of either sex, weighing 10-25 kg. Sodium pentobarbital (30 mg/kg) was administered intravenously for anesthesia. The trachea of each animal was intubated to assure normal ventilation. The dogs rectal temperature was monitored by means of a thermistor thermometer (Cole-Palmer). A cannula was inserted into the thoracic aorta (via right femoral artery) to measure systemic arterial pressure by means of micro-tip catheter transducer (model SPG-350, Millar Instruments, USA), and a second cannula was introduced through the left femoral artery to measure blood velocity in the aorta by a micro-tip Doppler catheter (model DC-201, Millar Instruments, USA), which was connected to a single channel 20 MHz pulse Doppler velocimeter (model MDV-20); both transducer tips were located 5 cm apart. After catheterization, a bolus of sodium heparin (5000 IU) was administered i.v. An eight channel Gilson polygraph was used to record the electrocardiogram (lead II), the cardiotachogram (instantaneous heart rate). the aortic pressure, the blood velocity pulsations, and the pneumogram, which was obtained through rubber bellows fastened around the chest and connected to a Statham pressure transducer (P23BB).

Data processing. Analog signals of aortic pressure or blood velocity were alternatively sampled by means of an Opto 22 (LC4) single channel analog-digital converter. Each of these recordings comprised 512 numerical values, obtained within a 12 second period, *i.e.*, at a rate of 42.7 samples per second.

In this preliminary report we have used orthogonal wavelet analysis following Daubechies (1988), as well as the algorithm of Mallat (1989).

RESULTS

Wavelet transform of arterial pressure pulsations

Figure 1 shows the pneumogram, electrocardiogram, blood velocity, blood pressure and heart rate, recorded on a polygraph at

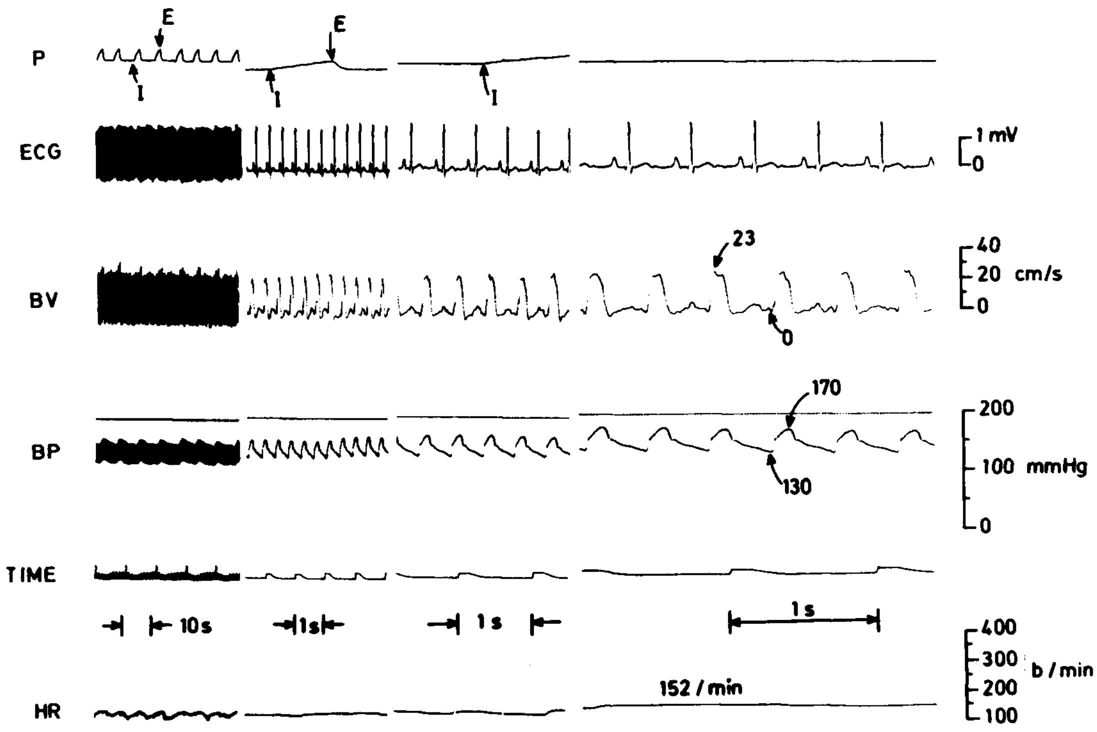

Fig. 1: Polygraph recordings from thoracic aorta of an anesthetized female dog of 16 kg body weight. From top to bottom: P, pneumogram (I, inspiration; E, expiration); ECG, electrocardiogram (second lead); BV, blood velocity; BP, blood pressure; time, seconds; HR, heart rate (beats per minute).

different paper speeds. It is noteworthy that pressure and velocity recordings showed no marked differences in subsequent cardiac cycles.

Figure 2 shows the original (2^0 resolution) arterial pressure pulsations and the corresponding WT after the analog-digital conversion. The left column illustrates the 2^{-1} to 2^{-3} resolutions. The corresponding wavelet coefficients (D^{-1}, D^{-2}, and D^{-3}) appear in the right column. These wavelet coefficients operate as high pass filters and correspond to the high frequency components of the respective resolutions. In 2A' are the wavelet coefficients of 2A and, similarly, in 2B' are the coefficients of 2B. Consequently, the 2^{-1} resolution is obtained after substracting 2A' from 2A. It is noteworthy that only minute differences in the apical pressure recordings may be observed in the original records, but they are clearly differentiated at the 2^{-2} resolution (Fig 2C), where four kinds of apexes can be distinguished: ascending (a), descending (d), plateau (p), and spike (s). The most frequent configuration is the spike type, whereas the rarest is the plateau type. Furthermore, the 2^{-3} resolution (Fig 2D) displays slow periodic cycles of amplitude modulations, which are closely correlated with the analogous wavelet coefficients (D^{-3}), as illustrated in Figure 2C. In Figure 2F, the

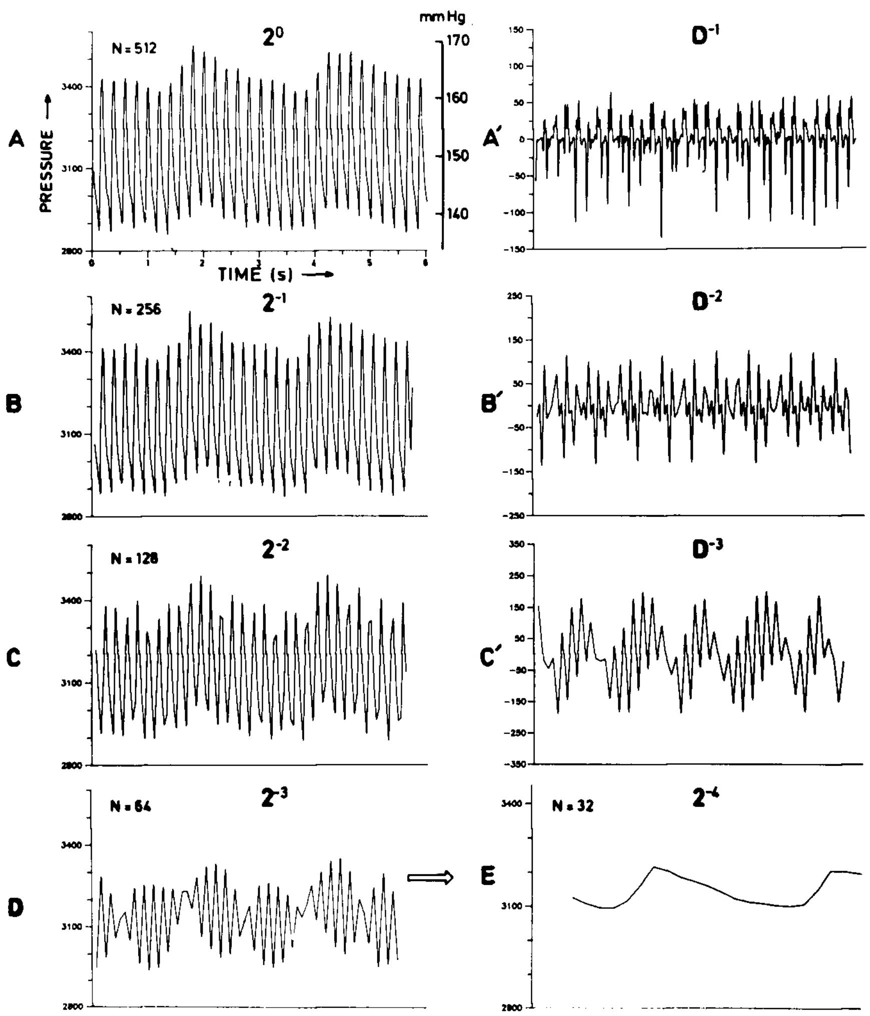

Fig. 2: Wavelet transforms (WT) of arterial pressure pulsations at different resolutions, according to Daubechies'orthogonal wavelet with two coefficients (left). Corresponding wavelet coefficients (D^{-n}) on right side column. For explanation, see text.

original pressure pulsations are absent, and only the mean arterial pressure is recorded, whereas the respiratory influence is still present in the form of two very slow waves.

Wavelet transform of blood flow velocity pulsations

Figure 3 shows the aortic blood velocity pulsations (2^0), the WT at different resolutions (2^{-1} to 2^{-3}) and the corresponding wavelet coefficients (D^{-1} to D^{-3}), in analogy to the outcome shown in the previous figure. It is interesting to note that the four types of apexes (Fig 3C), as well as the amplitude modulation (Fig 3D), are similar to those obtained from the WT analyses of the arterial pressure pulsations.

DISCUSSION

In essence, the WT algorithm consists of two processes: 1) the substraction of the highest frequency components from the previous record, starting with the 2^0 resolution; and 2) the progressive reduction (rarefaction) of the number (N) of samples to be considered, beginning with the 2^0 resolution, following with the 2^{-1} resolution, then to the 2^{-2} resolution and so forth. In the present study we started with N = 512.

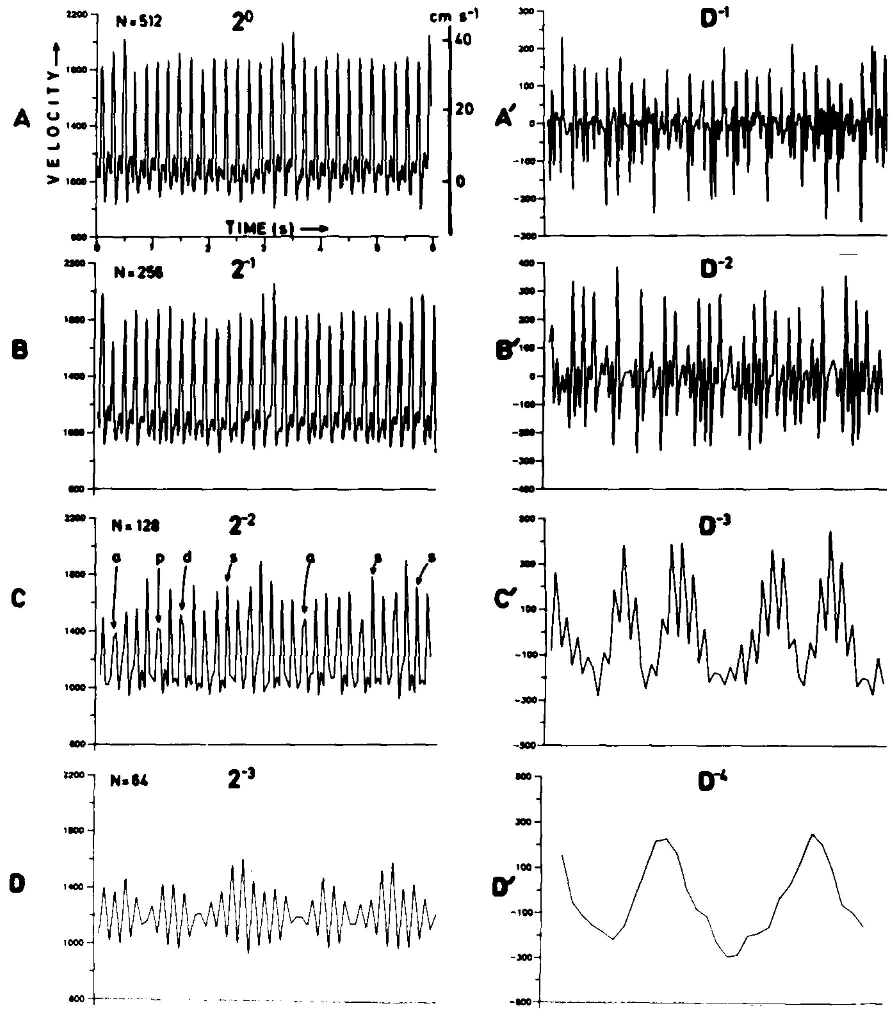

Fig. 3: Wavelet transforms (WT) of blood velocity pulsations in thoracic aorta. Ordinates: left, analog-digital transform; right, blood velocities in cm/s. Left column, WT from 2^0 to 2^{-3}; right column, corresponding wavelet coefficients (D^{-n}). For explanation, see text.

To illustrate the first steps, *i.e.*, the progressive substraction of the highest frequencies (D^{-n}), which is equivalent to the elimination of the tangents of the greatest steepness, a single arterial pressure recording is shown in Figure 4, together with the corresponding 13 tangents. In the present example, the 2^{-1} resolution corresponds to the elimination of the tangents with the greatest slopes, *i.e.*, tangents 1, 2 and 7. The next resolution (2^{-2}) would probably eliminate the following tangents (3 and 6). The tangents with slopes close to zero would finally remain.

With regard to the second WT process, *i.e.*, the progressive "rarefaction" of the number of samples (N), the sequence will be 512 at 2^0 resolution, 256 at 2^{-1}, 128 at 2^{-2} and 64 at 2^{-3} resolution. As illustrated in Figure 5, the step by step rarefaction of the number (N) of samples to be processed yields a geometric simplification of the original arterial pulse recordings. Figure 5A shows five very similar pressure pulsations– within two seconds. At resolution 2^{-1} (Fig 5B) these arterial pulsations were simplified to a sequence of five triangular configurations, a process which was accentuated at resolution 2^{-2}, where the four kinds of apexes clearly appeared (Fig 5C). Finally, at resolution 2^{-3} the triangular form was prevalent, with clear signals of amplitude modulation (Fig 5D). It is noteworthy that this amplitude modulation was completely absent in the original recording, as well as in the previous resolutions (2^{-1} and 2^{-2}). Therefore, it seems that amplitude modulations cannot be directly observed in straight physiological recordings of pressure pulsations (Koepchen, 1962). The duration of these amplitude modulations varies between 2 and 3 s, and can be due either to vagal reflexes with a time constant of the order of 1 s (Korner,

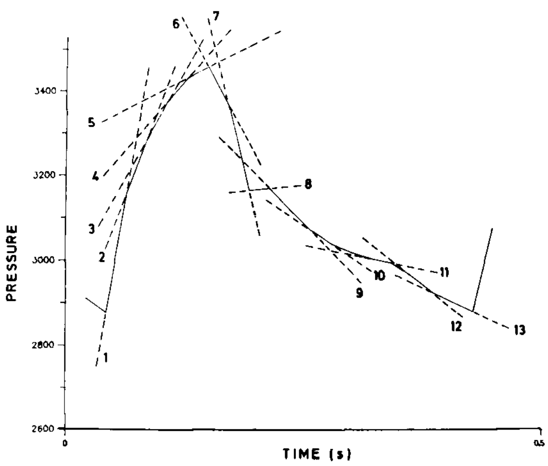

Fig. 4: One pressure pulsation with 13 tangents. Time scale, 0.1 s. For explanation, see text.

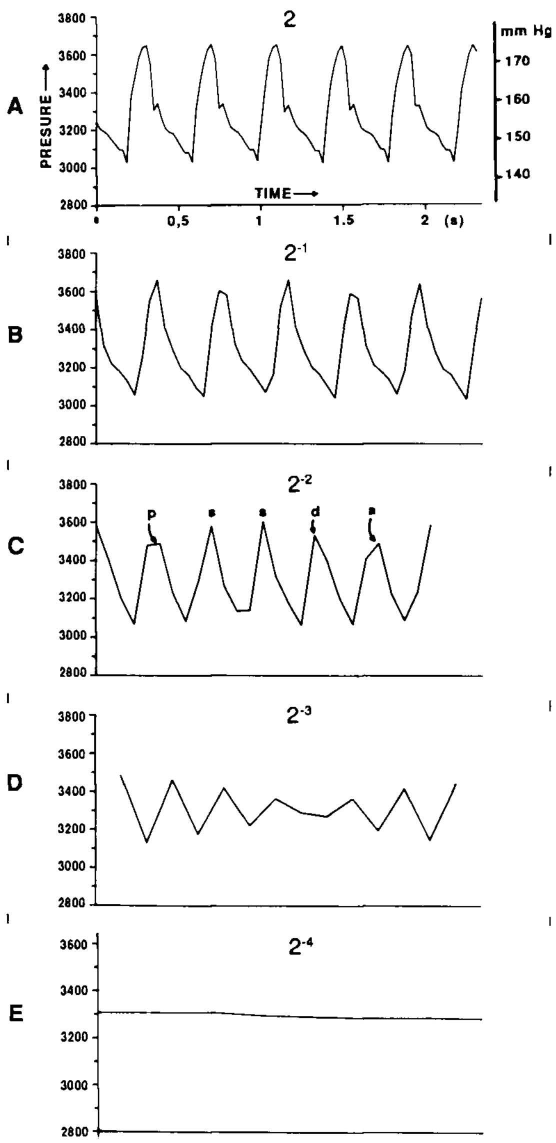

Fig. 5: Five pressure pulsations and corresponding WT from 2^0 to 2^{-4} resolutions, the latter being the mean arterial pressure.

1971), or to an interference phenomenon caused by wave reflections of the arterial pulse (O'Rourke, 1982; Li *et al.*, 1984).

The possible sources of error of the mathematical procedures could be eliminated by utilizing Daubechies wavelets with two, four, eight, and ten coefficients, as well as by applying the spline cubic wavelet. Different time delays at the beginning of WT analysis were also introduced with no significant changes with regard to the above mentioned control procedures. Consequently, we are confident that these sources of error can be reasonably excluded.

The four types of apexes mentioned above may depend on the features of the original arterial pressure and velocity pulsations or pertain exclusively to the intermediate triangulation phase of the WT algorithm. To check this point, we subjected both iterative step functions and rhythmic sinusoidal pulsations to WT analyses and in both instances a sequence of triangular figures, including four kinds of apexes, was obtained. Thus, we came to the conclusion that these different apexes are the result of the rarefaction and subsequent triangulation of the original recordings; both phenomena are inherent to the WT algorithm and, consequently, devoid of physiological meaning.

Otherwise, the slow amplitude modulations revealed by the 2^{-2} or 2^{-3} resolutions, are not associated with respiratory cycles, since they persist during the prolonged apneic periods following positive–pressure hyperventilation.

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