Physiological measurement

Cardiac Doppler blood-flow signal analysis

Part 1 Evaluation of the normality and stationarity of the temporal signal

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Abstract—*The normality (Gaussian property) and stationarity of the cardiac Doppler blood-flow signal were evaluated on short-time segments distributed over the cardiac cycle. The basic approaches used to perform statistical tests on the nonstationary and quasiperiodic cardiac Doppler signal are presented. The results obtained from the data of ten patients having a normal aortic valve and ten patients having a stenotic valve indicate that a complex Gaussian random process is an acceptable approximation for the clinical cardiac Doppler signal. For segments of 10 ms or less, 82 per cent of them were accepted to be stationary with a significance level of 0·05, whereas for durations greater than 40 ms, the percentage of stationary segments was less than 75 per cent. It was concluded that the 10 ms window generally used in practice is a good choice for Doppler spectrogram estimation, but a shorter time interval would be preferable.*

Keywords—*Aortic valve, Doppler ultrasound, Normality test, Signal processing, Stationarity test*

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1 Introduction

DOPPLER ULTRASOUND has been extensively used in noninvasive assessment of cardiovascular pathologies. Owing to the dynamics of the cardiac system, Doppler blood-flow signals are inherently nonstationary. Their time/frequency properties are usually characterised by computing the Doppler spectrograms on a cardiac-beat basis. By compromising between frequency resolution of the spectrogram and the blood ejection risetime, a 10 ms window is often used in practice (CANNON *et al.*, 1982; VAITKUS *et al.*, 1988; KALUZYNSKI, 1989) to isolate a segment of signal on which a power spectrum is computed by using a fast Fourier transform (FFT) or parametric modelling. The signal is assumed to be stationary over the 10 ms window, as it is argued that the statistics of the Doppler signal may not vary significantly during a time interval shorter than the time required for significant changes in the cardiac haemodynamics. However, the reliability and accuracy of the Doppler spectrograms may be influenced by the power density estimation methods and the underlying statistical properties of the signal analysed. To improve the technique for quantitative and sensitive assessment of cardiovascular disease, it is then important to have a better understanding of the statistical properties of the Doppler blood-flow signal over short time intervals.

According to the central limit theorem, the Doppler blood flow signal which results from red blood cell scatters tends toward a Gaussian random process (ANGELSEN, 1980). This was verified experimentally in part by MO and COBBOLD (1986) who applied the chi-square (χ^2) test on the peak-systolic signal segments taken from the internal carotid artery of a normal subject. The first objective of the present study is thus to investigate whether the Doppler signal could be assumed Gaussian not only at peak systole, but also over any short intervals selected throughout the entire cardiac cycle.

One limitation of the spectrographic technique for representing the time/frequency distribution of signals is based on the assumption that the signal is stationary during short time intervals. However, no study has been performed to assess the validity of the stationarity assumption of Doppler signals. This may be due to the fact that conventional statistical tests for stationarity, such as the run test and the reverse arrangement test, usually require a sample record long enough to permit nonstationary trends to be differentiated from the random fluctuations of the time history records (BENDAT and PIERSOL, 1986). The second objective of the present work is to investigate the stationarity of the Doppler signal over short time intervals.

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2 Materials and methods

2.1 *Patient population and data acquisition*

Cardiac Doppler signals of 20 patients referred to the Hotel-Dieu de Montreal Hospital for a cardiac catheterisation examination were included in the present study. Ten patients (Group 1) had a normal aortic valve (neither aortic pressure gradient nor regurgitation) and possible coronary artery disease. Another ten patients (Group 2) had aortic valve stenosis with a mean transvalvular pressure gradient of 78·2 ± 20 mm Hg, and concomitant aortic valve regurgitation.

A duplex ultrasound scanner system (Advanced Technological Laboratory, Ultramark 8), using a pulse-wave (PW) probe operating at 3 MHz, was used to record the Doppler signals at the midpoint of the left ventricular outflow tract, approximately 1 cm below the aortic valve. The apical echocardiographic view was used to obtain these signals. For each recording, the wall filter (high-pass) was set at 200 or 400 Hz to reduce the high-amplitude low-frequency signals that could be present because of heart wall and valve vibrations. During the investigation, the in-phase quadrature Doppler signals and the electrocardiogram (ECG) were recorded on magnetic tapes for a period of approximately 30 s. Both Doppler signals were recorded in direct mode, whereas the ECG was recorded in frequency modulation mode. At a speed of 7·5 in s^{-1}, the frequency response of the Doppler channels was uniform (−3 dB) between 50 and 20 000 Hz.

During tape playback, the ECG and PW-Doppler signals were digitised for about 20 s with 12-bit resolution, at sampling rates of 0·2 and 20 kHz, respectively. Prior to digitisation, the Doppler signals were low-pass filtered at 9 kHz with two eighth-order filters (−48 dB octave^{-1}). A QRS detection algorithm based on a correlation technique was used to locate the QRS wave of each cardiac cycle. The mean R-R interval of each patient was then computed and only the cardiac cycles having a duration within ±10 per cent of the mean R-R interval were kept for further analyses.

In the present study, only the in-phase component of the Doppler signal was studied, because the statistical properties of the quadrature component are similar to those of the in-phase component. For instance, the output of the Doppler quadrature demodulator (Atkinson and Woodcock, 1982) is given by:

$$D(t) = (B_f \cos(\omega_f t + \phi_f) + B_r \cos(\omega_r t - \phi_r))/2 \quad (1)$$

$$Q(t) = (B_f \cos(\omega_f t + \phi_f - \pi/2) + B_r \cos(\omega_r t - \phi_r + \pi/2))/2 \quad (2)$$

where $D(t)$ and $Q(t)$ are the in-phase and quadrature components of the Doppler signal, B_f is the forward blood-flow signal, and B_r is the inverse blood-flow signal. From these equations, it is clear that a constant phase shift of $\pi/2$ does not modify the statistical distribution of the signal.

2.2 *Normality test*

The normality of the Doppler signal was tested in stationary intervals. The most obvious way to test for normality of stationary random data is to compare their amplitude histogram with the theoretical Gaussian distribution by using the chi-square goodness-of-fit test. To be more specific, let the random data be grouped into K intervals according to their amplitude and assume f_i and F_i to be the observed and expected frequencies in the ith class interval, respectively; the goodness-of-fit is quantified by

$$X^2 = \sum_{i=1}^{K} \frac{(f_i - F_i)^2}{F_i} \quad (3)$$

The hypothesis of normality of the data is accepted at a certain significance level if $X^2 \leqslant \chi^2$, the theoretical chi-square value. The degree of freedom for X^2 is $K - 3$.

The data used to carry out the chi-square test must be stationary, independent and long enough. As the stationarity of the Doppler signal was another item to be investigated, we started with the generally assumed stationary interval of 10 ms. To ensure sample independence of the signal in this short time interval, the sampling frequency should be as low as possible but kept above the Nyquist rate to prevent frequency aliasing. Thus, the data available for the chi-square test is very limited for those segments having low frequency distribution because they must be sampled at a low frequency to ensure sample independence. To overcome this problem, many corresponding segments in different cardiac cycles were used for each patient to form segment ensembles on which the chi-square test was performed. The proposed method was based on the following two assumptions:

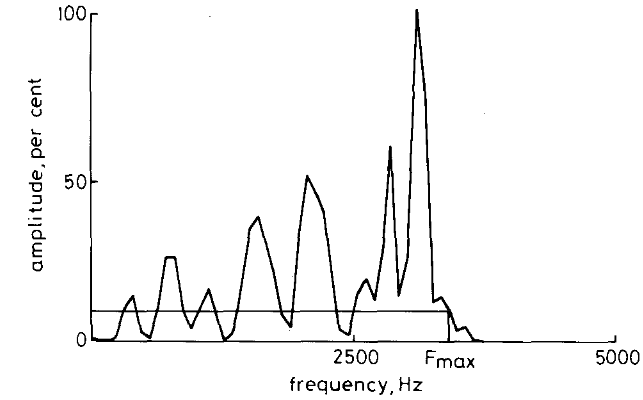

Fig. 1 *Example of maximum frequency estimate (F_{max}), found at 10 per cent of the maximum amplitude of Doppler spectrum*

(*a*) The Doppler signal can be considered to be essentially stationary in a 10 ms interval.
(*b*) The beat-to-beat statistical variation of the signal is negligible in patients with regular heart rate. This implies that the statistics of the cardiac Doppler signal are invariant under a time shift of one cardiac period.

In the present study, amplitude histograms were computed for ten different time locations equally distributed within the R-R interval. The procedure used to evaluate the normality of cardiac Doppler signals is as follows:

(i) The power spectrum of a 10 ms signal segment at one location from the first cardiac cycle was computed, and the maximum frequency (F_{max}) was determined at 10 per cent of the maximum amplitude, as shown in Fig. 1. The samples of the segment were then decimated to make the effective sampling frequency above but close to twice F_{max}.
(ii) The run test (Bendat and Piersol, 1986) was carried out to evaluate the sample independence of the decimated segment at the significance level of 0·05.
(iii) If sample independence was accepted, the decimation was then applied to the corresponding signal segments of ten consecutive cardiac cycles synchronised with the QRS wave of the ECG. All samples in these ten decimated segments were concatenated to form a time series $y(n)$. The chi-square test was then carried out on

$y(n)$ at the significance level of 0·05. The test was not carried out on the segments rejected by the sample independence test.

(iv) This procedure was repeated for all ten locations of the same patient and for the two groups of patients.

2.3 *Stationarity test*

In the previous section, the signal in 10 ms intervals was assumed to be stationary for the normality test. However, the length of the time interval in which the signal can be considered as stationary in fact depends on the location of the interval in the cardiac cycle. The longer stationary intervals correspond to slower time variations of blood flow (e.g. diastole) and vice versa. One requirement of a stationary process is that its probability density function (PDF) does not change with time. The time invariance of PDF can be used as a criterion in practice to test the stationarity of Doppler signals. As shown in the results (Section 3), the Gaussian distribution can be assumed for Doppler signals; the stationary interval of Doppler signals can thus be defined as the interval over which the mean and variance are time invariant. A reasonable and simple method for determining the stationary interval of the cardiac Doppler signals is to divide the interval into two consecutive sections, and then compare the sample means and sample variances of both sections. If these values in both sections are found statistically equal, the signal in the entire interval can be considered as stationary.

For a stationary Gaussian sample function, with mean μ, variance σ^2 and length N, the distribution of the sample mean is also Gaussian, with mean μ and variance σ^2/N. Assuming the statistical properties of the Doppler signal are invariant under a time shift of one cardiac period, the sample means can be obtained from a series of signal segments of different cardiac cycles synchronised with the ECG. In the present work, the segments were taken from 16 consecutive cardiac cycles for each patient. Each segment of N samples was then subdivided into two equal subsegments, and their means were computed by using

$$X_{1,j} = \frac{2}{N} \sum_{i=1}^{N/2} x_{1i,j} \qquad (4)$$

$$X_{2,j} = \frac{2}{N} \sum_{i=N/2+1}^{N} x_{2i,j} \qquad (5)$$

where $1 \leqslant j \leqslant 16$ is the index of the cardiac cycles, and $x_{1i,j}$ and $x_{2i,j}$ are the first and second subsegments in the jth cardiac cycle. The 16 signal segments were used to form two time series $Y_1 = X_{1,1}, X_{1,2}, \ldots, X_{1,16}$ and $Y_2 = X_{2,1}, X_{2,2}, \ldots, X_{2,16}$. As $x_{1i,j}$ and $x_{2i,j}$ were samples of two Gaussian distributions $N(\mu_1, \sigma_1)$ and $N(\mu_2, \sigma_2)$, the two time series Y_1 and Y_2 were samples of $N(\mu_1, \sigma_1/\sqrt{N/2})$ and $N(\mu_2, \sigma_2/\sqrt{N/2})$, respectively. If Y_1 and Y_2 have the same probability density function, this indicates that $\mu_1 = \mu_2$ and $\sigma_1 = \sigma_2$, owing to the equality of the two subsegments' length. Thus, $x_{1i,j}$ and $x_{2i,j}$ have same probability density function, too. The t-test and F-test (BENDAT and PIERSOL, 1986) were applied to these two time series Y_1 and Y_2 to test the equality of the means and variances at the significance of 0·05. As 16 cardiac cycles were used in the generation of the Y_1 and Y_2, the degrees of freedom were 30 for the t-test and (15, 15) for the F-test, and were independent of the segment duration.

To complete the analysis, the test was repeated for all nonoverlapping consecutive segments contained within the cardiac cycle. Different segment durations, varying from 2 to 45 ms, were tested.

3 Results

3.1 *Normality of cardiac Doppler signal*

Table 1 shows the results of the normality test for the 10 ms segments. Sample independence required for the test was evaluated, and the results are also shown in the table. It should be noted that, prior to decimation, no segment was accepted as sample independent, and the chi-square test could not be carried out directly. From Table 1, it can be seen that, after decimation, the degree of sample independence of the signal segments from two groups of patients were 89 per cent and 85 per cent at the significance level of 0·05. Among these segments, there were 68 (76 per cent) in Group 1 and 63 (74 per cent) in Group 2 accepted as Gaussian segments.

Table 2 shows how the occurrence of Gaussian segments varies with the location in the entire cardiac cycle. The occurrence of Gaussian segments is relatively uniform for patients with a normal valve. In patients with a stenotic valve, the occurrence of Gaussian segments during diastole (the last five values) is lower (52 per cent) than that of the first half (72 per cent).

Fig. 2*a* shows an example of the amplitude histogram of a segment ensemble taken from peak-systole fitted to a Gaussian distribution, and Fig. 2*b* gives an example of the data taken from diastole.

3.2 *Stationarity of cardiac Doppler signal*

Fig. 3 shows the results of the stationarity test. Each curve represents the average of the data of ten patients. A

Table 1 Results of sample independence and normality tests for 10 ms segments. For each patient, sample independence is expressed by the ratio of the number of segments accepted as sample independent over the ten segments equally distributed over the cardiac cycle. The results of normality are expressed as the number of segments accepted as Gaussian over the number of sample-independent segments. The last row shows the cumulative ratios for the 100 segments evaluated (ten patients)

Patient group 1			Patient group 2		
Patient number	Sample independence	Normality test	Patient number	Sample independence	Normality test
1	10/10	9/10	1	8/10	8/8
2	10/10	8/10	2	8/10	6/8
3	9/10	7/9	3	10/10	9/10
4	8/10	5/8	4	9/10	5/9
5	9/10	8/9	5	9/10	7/9
6	10/10	8/10	6	9/10	4/9
7	7/10	6/7	7	8/10	8/8
8	9/10	7/9	8	9/10	5/9
9	9/10	5/9	9	7/10	6/7
10	8/10	5/8	10	8/10	5/8
Total	89/100 (89 per cent)	68/89 (76 per cent)	Total	85/100 (85 per cent)	63/85 (74 per cent)

Table 2 *Results of sample independence and normality tests at ten equally distributed time locations in the cardiac cycle. The data are presented in the same way as in Table 1*

Patient group 1			Patient group 2		
Location	Sample independence	Normality test	Location	Sample independence	Normality test
1	8/10	6/8	1	9/10	7/9
2	8/10	7/8	2	8/10	8/8
3	10/10	6/10	3	7/10	6/7
4	9/10	7/9	4	7/10	7/7
5	8/10	7/8	5	9/10	8/9
6	9/10	7/9	6	9/10	4/9
7	9/10	9/9	7	8/10	6/8
8	10/10	8/10	8	9/10	4/9
9	9/10	5/9	9	9/10	5/9
10	9/10	6/9	10	10/10	7/10

signal segment is considered as stationary if the mean and variance of the first half of the segment equal those of the second half at a significance level of 0·05. As shown in Fig. 3, the occurrence of stationary segments decreases linearly with the increase in segment duration. Among the segments tested, above 82 per cent were found to be stationary for segment durations of 10 ms or less, whereas, for durations above 40 ms, the percentage of stationary segments was less than 75 per cent. This may explain the fact that the 10 ms window gives acceptable results for estimating the time/frequency representation of cardiac Doppler signals.

4 Discussion and conclusion

As shown in Table 1, the performance of the method used to ensure sample independence of the Doppler signal segments was 89 per cent for normal valves and 85 per cent for stenotic valves. The 100 per cent performance was not achieved probably because only about 85 per cent of the 10 ms segments used in the study were acceptable as stationary. As a result, the decimation factor computed may be good for one part of the segment but not for another part owing to some residual nonstationarity of the signal. A complementary study using 5 and 20 ms segments was then performed to evaluate the effect of segment duration on the sample independence and the normality test. The results of this complementary study, shown in Table 3, demonstrate that the sample independence of signal segments decreased with the increase of segment duration, and the number of segments that could be accepted as stationary Gaussian also decreased with the increase of segment duration. As stationarity is assumed in the test methods, these results further demonstrated the nonstationarity nature of the data. Consequently, shorter segments of the Doppler signal would behave more like segments from a stationary Gaussian process.

In the present study, we believe that ten locations equally distributed throughout the entire cardiac cycle may provide a good representation of the statistics of

Table 3 *Effects of segment duration on sample independence and normality tests. The data are presented in the same way as in Table 1*

	Patient group 1		Patient group 2	
Segment duration, ms	Sample independence	Normality test	Sample independence	Normality test
5	91/100	74/91	93/100	68/93
10	89/100	68/91	85/100	62/85
20	75/100	43/75	73/100	46/73

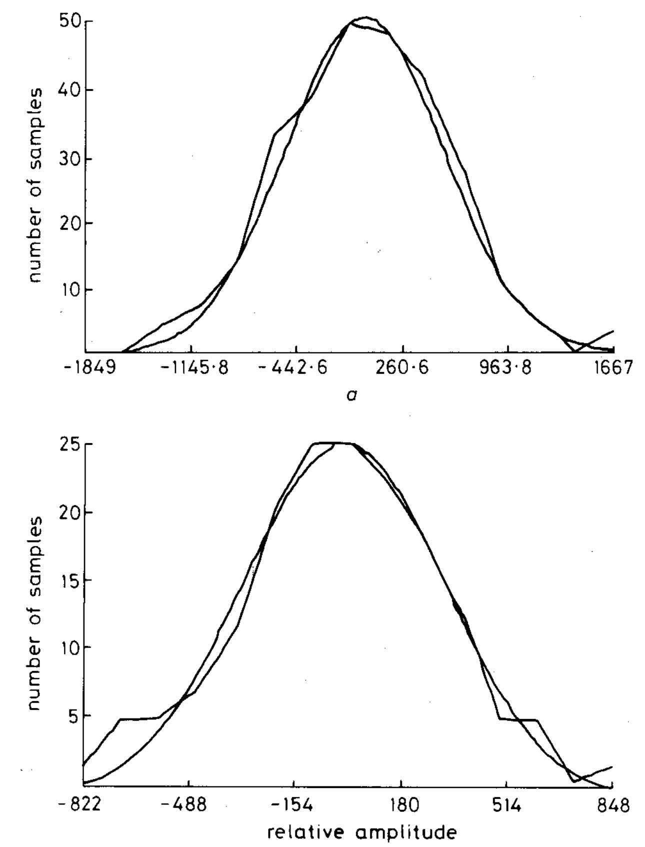

Fig. 2 *Amplitude histogram of a segment ensemble fitted to the theoretical Gaussian probability density (smooth curve): (a) data from systole and (b) from diastole*

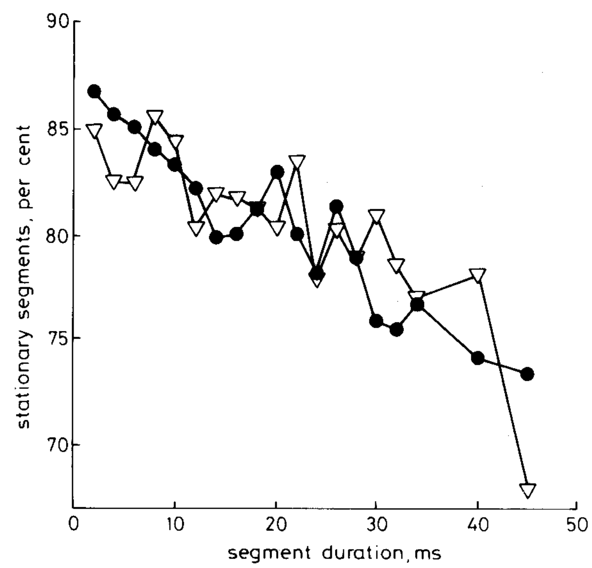

Fig. 3 *Percentage of stationary segments as a function of segment duration. Results are presented for normal valves (circles) and stenotic aortic valves (triangles)*

Doppler signals during the heartbeat period. The results of Table 1 show that most 10 ms segments of the Doppler signal can be considered as Gaussian signals with a significance level of 0·05. Even if the results obtained did not always guarantee Gaussian distribution at 0·05 significance level, the use of the stationary Gaussian assumption in cardiac Doppler blood-flow signal processing will most likely represent the true situation for segments less than 10 ms. Thus, we can assume that the Doppler signal in a long time interval, say one cardiac cycle, is a Gaussian process with time-varying mean and variance. In practice, the recorded Doppler signals contain artefactual components and background noise (both physiological and instrumental). The presence of such components and the non-negligible beat-to-beat variation in the physical signal may worsen the test results of stationarity and normality, as observed in the present study. Our results also suggest that the Gaussian hypothesis of cardiac Doppler signals can be accepted in both groups of patients.

In conclusion, the study shows that 10 ms short segments of the cardiac Doppler signal are an approximately stationary Gaussian process. The shorter the segment, the better the approximation. Because the quadrature component has the same statistical characteristics as the inphase component, short segments of cardiac Doppler signal can be considered as stationary sample functions from a complex Gaussian process.

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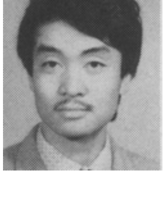
Authors' biographies



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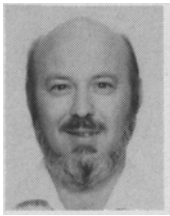

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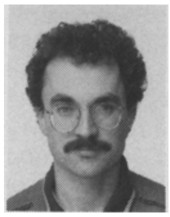

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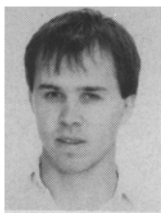

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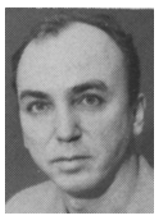

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