Spectral analysis of closing sounds produced by Ionescu-Shiley bioprosthetic aortic heart valves

Part 2 Computer simulation of aortic closing sounds and estimation of their truncation level and signal-to-noise ratio

G. Cloutier[1] M.-C. Grenier[1] R. Guardo[2] L.-G. Durand[1]

[1]Clinical Research Institute of Montreal, University of Montreal and Biomedical Engineering Institute, École Polytechnique, University of Montreal, Quebec, Canada; [2]Biomedical Engineering Institute, École Polytechnique, University of Montreal, Quebec, Canada.

Abstract—*The objective of the paper is to document the temporal characteristics of the aortic component (A_2) of the second heart sound (S_2). Two important features of A_2 have been estimated on a group of 15 patients: the truncation level and the signal-to-noise (S/N) ratio. A database of simulated aortic closing sounds has been developed to estimate the truncation level of A_2. This approach was used because the simulated signals are free from interference due to acoustic vibration of other cardiac structures. The S/N ratio of A_2 was estimated by computing the energy of the background noise in the diastolic phase of the phonocardiogram and by assuming that no cardiac events occur during this period. Results show that averaging of 20 closing sounds increases the S/N ratio of A_2 from 30 dB to 40 dB and that the mean truncation level of the A_2 components is 8 per cent. In addition, we show that simulations of A_2 can produce an acoustic transient signal with two distinct waves which were traditionally associated with the aortic and pulmonary components of S_2. This phenomenon should be kept in mind when studying the second heart sound.*

Keywords—*Ionescu-Shiley bioprosthetic heart valve, Phonocardiography, Second heart sound, Signal simulation, Signal-to-noise ratio, Truncation*

Med. & Biol. Eng. & Comput., 1987, **25**, 492–496

List of abbreviations

A_2	aortic component of the second heart sound
dB	decibel
ECG	electrocardiogram
FFT	fast Fourier transform
FM	frequency modulation
Hz	Hertz
MA_2	mean aortic closing sound
ms	millisecond
NRMSE	normalised root-mean-square error
PCG	phonocardiogram
P_2	pulmonary component of the second heart sound
QRS	electrocardiographic waveform corresponding to ventricular depolarisation
RMS	root-mean-square
SD	standard deviation
S/N	signal-to-noise
S_2	second heart sound

Correspondence should be addressed to Guy Cloutier, Clinical Research Institute of Montreal, 110 Pine Avenue West, Montreal, Quebec H2W 1R7, Canada

First received 31st October 1986 and in final form 13th April 1987

1 Introduction

IT IS WELL recognised that the second heart sound S_2 is composed of two major transient waves, A_2 and P_2, which are related to the closure of the aortic and pulmonary heart valves (TILKIAN and BOUDREAU-CONOVER, 1984). More precisely, SHAVER *et al.* (1985) have shown that the onset of both A_2 and P_2 is coincident with completion of closure of both valves. Normally, A_2 is composed of high-frequency components of duration less than 30 ms and has a higher amplitude than P_2, whatever the recording site used (LEATHAM, 1975). P_2 is normally characterised by lower frequency components than those of A_2 and has a duration of less than 30 ms.

The timing between A_2 and P_2 is determined by cardiac dynamics. Normally, P_2 occurs after A_2 because right ventricular ejection begins prior to left ventricular ejection, has a longer duration, and terminates after left ventricular ejection (TILKIAN and BOUDREAU-CONOVER, 1984; SHAVER *et al.*, 1985). Different factors influence the splitting of A_2 and P_2, among which the respiration of the patient is the most common. During expiration, A_2 and P_2 are normally separated by an interval of less than 30 ms. During inspiration, the splitting interval widens, primarily due to the delayed P_2 (TILKIAN and BOUDREAU-CONOVER, 1984; SHAVER *et al.*, 1985). This interval is also influenced by the age of the patient. For instance, HARRIS and SUTTON (1968) have often observed a single S_2 during both phases of respiration in normal subjects over 40. In addition, it has been shown by TILKIAN and BOUDREAU-CONOVER (1984) and SHAVER *et al.* (1985) that the pulmonary area is the best site to hear splitting of S_2. However, LEATHAM (1975) and TILKIAN and BOUDREAU-CONOVER (1984) have shown that A_2 is best recorded in the aortic area.

To study closing sounds of bioprosthetic valves implanted in the aortic position, only the A_2 component of S_2 is of interest. Because A_2 and P_2 are not temporally correlated during normal breathing and P_2 is generally smaller than A_2, coherent detection of A_2 and averaging over several cardiac cycles has been used to minimise contributions of P_2. Coherent detection and averaging should increase the signal-to-noise (S/N) ratio of the A_2 component. To verify this hypothesis, the S/N ratio of A_2 was estimated before and after the coherent detection of A_2 by computing the energy of the background noise in the diastolic phase of the PCG and by assuming that no cardiac event occurs during this period. In addition, a typical aortic closing sound was used in the coherent detection algorithm in order to select only A_2 components. However, coherent detection and averaging of the PCG cycles does not totally eliminate the pulmonary component. To achieve this goal, the residual transient portion of A_2 superimposed on P_2 was excluded from the subsequent analysis.

The information on A_2 that is lost during this process is difficult to evaluate from direct analysis of the PCG because of the superimposition on P_2. A simulation approach, based on the representation of the signal by a series of exponentially decaying sinusoids of variable amplitude, frequency, damping and phase, was used to bypass this difficulty. The truncation level of the valve closing sounds can be computed from the simulated signals because they are free from interference due to acoustic vibration of other cardiac structures. Results show the effectiveness of the coherent detection algorithm with an increase in the S/N ratio of A_2 of 10 dB. In addition, this process eliminates 8 per cent of the aortic closing sounds energy when excluding the residual A_2 superimposed on P_2.

2 Materials and methods

2.1 *Data acquisition*

A group of 15 patients, aged between 36 and 72 at the beginning of the analysis and having normally functioning Ionescu-Shiley bioprosthetic valves implanted in the aortic position, was selected for this study. The valve status of these subjects was assessed by clinical history and physical examination. The valves were considered as 'normal' when the subject had no symptom or auscultatory sign of valve degeneration or malfunction. For each patient, an electrocardiogram and a phonocardiogram were recorded with a multichannel FM recorder having a bandwidth of 0–2500 Hz. Three recordings were obtained from each patient within a period of three years. No patient had a valve implanted for more than five years. Table 1 shows the chronology of each recording.

Table 1 Chronology of the three recordings for the 15 patients of our study group. The values shown represent the number of months separating the implantation of the heart valve from each recording session

	Recording, months after implantation		
Patient	First	Second	Third
1	24	37	44
2	0	18	30
3	23	35	47
4	27	38	50
5	22	33	46
6	19	30	42
7	18	29	41
8	4	16	27
9	31	41	53
10	13	23	35
11	24	34	46
12	27	39	51
13	2	26	37
14	10	33	44
15	45	48	56

The PCG was recorded with a contact microphone placed in the aortic area of the patient, while the latter was in a supine position. This recording site is known to produce a maximum contribution of A_2 to the PCG. The microphone used (Hewlett Packard, 21050A) had a flat frequency response (± 3 dB) from 0·2 to 2000 Hz. Prior to recording, the PCG was preprocessed by a third-order high-pass filter (18 dB octave^{-1}) with a cutoff frequency of 100 Hz to emphasise the medium- and high-frequency components of the prosthetic closing sounds. At playback, the PCG was low-pass filtered (-48 dB octave^{-1}) at 900 Hz with an eight-order filter to prevent aliasing. The ECG and PCG were digitised with a 12-bit analogue-to-digital convertor at sampling rates of 250 and 2500 Hz, respectively. An example of a PCG recorded in the aortic site from a patient with a normal Ionescu-Shiley aortic heart valve is shown in Fig. 1.

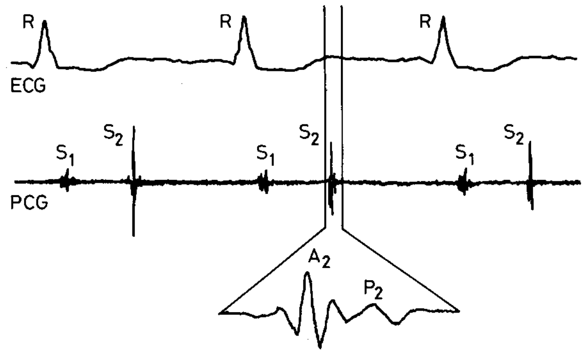


Fig. 1 *Example of the ECG and PCG recorded in a patient with an Ionescu-Shiley pericardial xenograft valve implanted in the aortic position. (Reproduced with permission from* DURAND *et al., 1986)*

During processing of the PCG signal, a QRS coherent detection algorithm was used to locate automatically the beginning of each cardiac cycle. From the first recording of each patient, a typical aortic closing sound occurring during maximal separation of A_2 from P_2 was selected as a reference closing sound. The interval between the QRS of the corresponding cardiac cycle and the beginning of the reference closing sound was then used as a coarse indicator of the next closing sounds. Final selection of the closing sounds was done interactively. Time alignment with the reference sound was performed by a correlation technique and 20 closing sounds, having a correlation level greater than 60 per cent with the reference sound, were chosen for further processing. An ensemble average of the 20 signals was finally computed to represent the 'mean' aortic closing sound (MA_2) for a particular patient and recording session.

When processing subsequent recordings of the same patient, the reference template obtained from the first session was used by the A_2 selection algorithm to maximise the probability of finding similar closing sounds. The reproducibility of the closing sounds from one session to the other was assessed independently for each patient by computing the correlation levels between the mean closing sounds obtained from the three sets of recordings. Data from 15 patients whose mean closing sounds showed a correlation level greater than 80 per cent for the three recording sessions were retained for further analysis.

2.2 *Simulation of the aortic valve sounds*

To estimate the truncation level of the bioprosthetic valve sounds, we first developed a database of simulated bioprosthetic valve closing sounds (CLOUTIER *et al.*, 1985*a*; CLOUTIER 1985*b*). Acoustic closing sounds produced by bioprosthetic heart valves are composed of transient signals of short duration and fast decaying amplitude, superimposed on a background of random noise. These signals may be conveniently synthesised by adding several exponentially decaying sinusoids of variable amplitude, frequency, damping and phase. More precisely, a mean aortic closing sound $s(n)$ was modelled by

$$\hat{s}(n) = \sum_{i=1}^{R} A(i)e^{-n/T(i)} \sin(n\omega(i) + \phi(i)) \qquad n \geq 0 \qquad (1)$$

where $\hat{s}(n)$ = simulated mean aortic sound
R = number of decaying sinusoids
$A(i)$ = amplitude of the ith sinusoid
$T(i)$ = decay time constant of the ith sinusoid, s
$\omega(i)$ = frequency of the ith sinusoid, rad s^{-1}
$\phi(i)$ = phase of the ith sinusoid, rad.

Fig. 2 shows an example of a synthesised aortic sound obtained by adding six decaying sinusoids of variable amplitude, frequency, damping and phase.

The simulated sounds were considered to be representative of the real aortic closing sounds only if the following criteria were met:

(*a*) the correlation level between MA_2 and the simulated sound was greater than 98 per cent
(*b*) the normalised root-mean-square error (NRMSE)*, found at the maximum of the correlation function, was less than 20 per cent
(*c*) the decaying envelope of the simulated sound was such that 95 per cent of the sound energy was contained in the first 30 ms segment
(*d*) 99 per cent of the energy was contained in the first 50 ms segment.

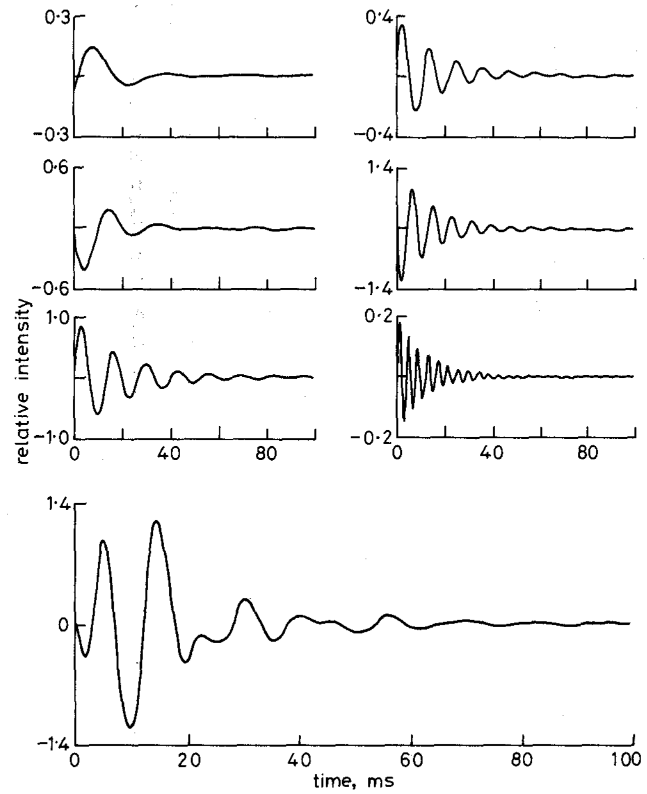


Fig. 2 *Example of a synthesised aortic sound obtained by adding six decaying sinusoids of variable amplitude, frequency, damping and phase*

The percentage of sound energy was obtained by dividing the sound energy in a given segment with the energy of the simulated sound over a duration of 120 ms. The last two criteria were used to ensure that the duration of the simulated sound was in accordance with the information published in the literature.

Valve closing sounds were simulated as follows. First, the FFT power spectrum of the valve mean closing sound to be simulated was computed. *A priori* knowledge of the duration of A_2 was used to choose the decay time constant of the simulated sound. From this spectrum, the relative amplitude and frequency location of the dominant peak were used as first estimates for the parameters of the first decaying sinusoid ($R = 1$). Phase values of 0 and π rad were used as initial estimates. Then, the FFT power spectrum of the simulated sound was evaluated after truncating the signal to the same duration as the valve sound and computing its RMS value. The simulated and valve mean closing sound spectra were normalised with respect to their RMS values, compared and the parameters readjusted to obtain a closer fit. Depending on the morphology of the valve mean closing sound being simulated, other decaying sinusoids were added. The three last steps of this interactive procedure, involving the parameter adjustment and the spectral comparison, were repeated until the simulated sound matched the valve sound within a level of precision determined by the four criteria described previously.

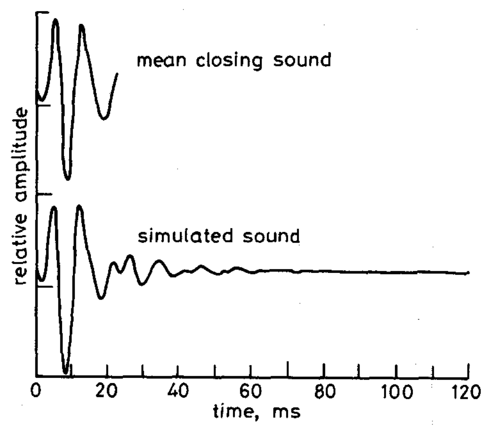


Fig. 3 *Comparison of a simulated sound with the corresponding mean aortic closing sounds. (Reproduced with permission from* CLOUTIER *et al., 1985a)*

2.3 *Estimation of the truncation level and signal-to-noise ratio*

The truncation level of the mean closing sounds has been computed from the simulated sounds. This procedure is justified by the fact that the decaying rate of the simulated sounds was chosen to match that of the real valve closing sounds. The following equation was thus used to estimate the truncation level of A_2:

$$\text{per cent of truncation} = 100 - ((E(A_2)/E(SA_2)) \times 100) \qquad (2)$$

* $NRMSE = \sum_{n=0}^{N-1} [(s(n) - \hat{s}(n))^2/s(n)^2]^{1/2}$

where $E(A_2)$ is the energy of the simulated sound corresponding to the aortic portion of the valve closing sound and $E(SA_2)$, the energy of the entire A_2 synthesised sound (see Fig. 3).

The signal-to-noise ratio of the aortic closing sounds was estimated by repeating the data acquisition with the same typical sounds. For this purpose, each session of the 15 patients was reanalysed and time alignment between the typical sound and 20 aortic closing sounds was used as a coherent time reference on the PCG cycles. From this reference, the sampled interval was increased to include the diastolic phase by extending it to 40 ms before and 200 ms after the onset of A_2. The 20 PCG segments and an ensemble average of these were then saved for further analysis. Fig. 4 shows an example of a PCG segment used to estimate the S/N ratio.

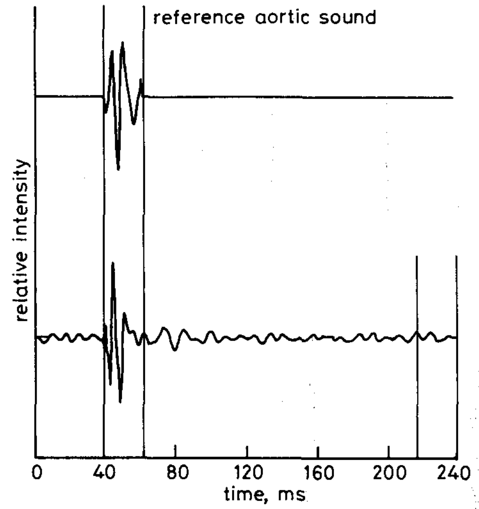


Fig. 4 *Example of a PCG segment used to estimate the S/N ratio of Ionescu-Shiley aortic valves*

Assuming that the background noise in the normal PCG is stationary and that no significant cardiac event (such as a diastolic murmur) occurs during diastole, the S/N ratio of the aortic valve sounds was estimated by

$$S/N = 10 \log ((E(A_2) - E(N))/E(N)) \tag{3}$$

where $E(A_2)$ is the energy of the aortic component of duration M, and $E(N)$ the energy of the background noise computed during the diastolic phase by using the last M samples of the PCG segments as shown in Fig. 4. Two measurements of the S/N ratio were then taken from each recording of every patient:

(*a*) the S/N ratio of the valve closing sounds as recorded on the chest of the patients

(*b*) the S/N ratio of the mean aortic closing sounds obtained by coherent detection.

The first measurement was computed by averaging the S/N ratios of the 20 PCG segments, and the second was computed from the mean coherent PCG segments.

3 Results

The mean aortic closing sounds obtained by coherent detection were characterised by a duration of 24 ± 9 ms (mean $\pm$ SD). The minimum and maximum durations of A_2 were 14 and 44 ms, respectively.

The interactive procedure for simulating the valve sounds was applied only to the first recording from each patient. A mean correlation level of $98{\cdot}8 \pm 0{\cdot}5$ per cent (range 97·9–99·5 per cent) and a mean NRMSE of 16 ± 3 per cent (range 10–20 per cent) were obtained by summing between 4 and 11 decaying sinusoids to simulate the real valve closing sounds. This high correlation level combined to the low NRMSE ensure that the morphology of the synthesised sounds reflects with good accuracy the characteristics of Ionescu-Shiley aortic valve closing sounds.

Two other criteria were used to validate the simulations: the percentage of energy of the synthesised sounds found in the first 30 and 50 ms segments. Mean values of 98 ± 1 per cent (range 95–100 per cent) and $99{\cdot}9 \pm 0{\cdot}1$ per cent (range 99·6–100 per cent) were obtained respectively. Because the entire S_2 has a duration between 40 and 60 ms and because the duration of A_2 is often less than 30 ms for normal subjects, these last two criteria ensured that the decaying rate of the simulated sound was similar to that of the real valve closing sound.

Truncation levels of the aortic valve sounds were thus estimated from the simulated sounds. The results show that the A_2 component of S_2 has a mean energy loss of 8 per cent (range 1–38 per cent). Most MA_2 signals do not seem to lose much energy by truncation. However, a few sounds were truncated severely in duration because of the presence of P_2. Indeed, a truncation level of 38 per cent was found for one patient.

Table 2 (a) Mean S/N ratio of A_2; (b) mean S/N ratio of MA_2; (c) increase in S/N ratio following averaging of A_2 taken from the first, second and third recordings of the 15 patients

Recording	1	2	3
(*a*)	32 ± 6 dB	30 ± 7 dB	30 ± 6 dB
(*b*)	43 ± 5 dB	38 ± 6 dB	39 ± 7 dB
(*c*)	11 ± 4 dB	9 ± 4 dB	9 ± 3 dB

From the three recordings of all patients, a mean S/N ratio of 30 ± 6 dB (range 15–43 dB) was found for A_2. Similar measurements were performed for MA_2 and an S/N ratio of 40 ± 6 dB (range 26–53 dB) was obtained. This last result proves the effectiveness of the coherent detection algorithm and averaging procedure used to compute MA_2. As shown in Table 2, the increase in S/N ratio due to coherent detection is relatively consistent from recording to recording.

4 Discussion and conclusion

A mean energy loss of 8 per cent and a mean S/N ratio of 40 dB characterise the MA_2 components obtained by coherent detection. Theoretically, the coherent detection algorithm used to compute MA_2 should increase the S/N ratio by 13 dB after averaging 20 aortic closing sounds. In the present study a mean increase of 10 dB was found. This suggests that, in some patients, coherent events of small amplitude may have been present during the diastolic phase.

The morphology of the simulated aortic closing sounds brings a new hypothesis in the discussion concerning the composition of normal S_2 recorded in the aortic area. As shown in Figs. 2 and 3, two distinct transient waves are often seen on the simulated sounds. Traditional analysis would associate these two waves with A_2 and P_2. However, it should be noted that the synthesised sounds are obtained by adding a series of decaying sinusoids associated only with A2. This dissociation of the simulated sound into two apparent transient waves is due to a beating phenomenon which results when more than two waves of unequal amplitude and frequency are combined. Thus, the summation of the decaying sinusoids creates a local null in the resulting signal which may appear like A_2 and P_2 waves.

From our analysis, the phase ($\phi(i)$) and the frequency

($\omega(i)$) parameters seem to be the most important factors determining the apparent dissociation of the simulated signal. In addition, we found that the phase affects the shape of the synthesised sounds tremendously. Transmission of valve sounds, from within the heart up to the surface of the thorax of the patient, is done through a dynamic system that modifies the phase and the amplitude of the original signal (DURAND *et al.*, 1985). Nonlinear properties and dynamic phenomena, such as respiration, may also affect the properties of the transfer function of the heart-thorax acoustic system and influence the apparent splitting of the S_2 wave.

Traditionally, the effect of respiration on the splitting interval was explained by changes in the dynamics of the right and left hearts. During inspiration, the increased splitting interval was associated with the delayed closure of the pulmonary heart valve (TILKIAN *et al.*, 1984; SHAVER *et al.*, 1985). The simulations reported in this paper demonstrate that a single valve closing sound can produce an acoustic signal with two distinct waves. This phenomenon should be kept in mind when studying S_2. Indeed, the beating phenomenon described here could also be used to explain some aspects of the splitting of S_2.

Acknowledgments—This research was supported by grants from the Canadian Heart Foundation, the Fonds pour la Formation des Chercheurs et Action Concertée and the Natural Sciences & Engineering Council of Canada.

References

CLOUTIER, G., DURAND, L.-G., GRENIER, M.-C., GUARDO, R. and BRAIS, M. (1985*a*) Computer simulations of acoustic closing sounds produced by bioprosthetic heart valves. Proc. IEEE Computers in Cardiology, Linköping, Sweden, 243–246.

CLOUTIER, G. (1985*b*) Evaluation de méthodes d'analyse spectrale pour l'étude de phénomènes transitoires: application aux sons produits par la fermeture des bioprothèses valvulaires cardiaques. Master's Thesis, École Polytechnique de Montréal.

DURAND, L.-G., GENEST, J. Jr. and GUARDO, R. (1985) Modeling of the transfer function of the heart-thorax acoustic system in dogs. *IEEE Trans.*, **BME-32,** 592–601.

DURAND, L.-G., DE GUISE, J., CLOUTIER, G., GUARDO, R. and BRAIS, M. (1986) Evaluation of FFT-based and modern parametric methods for the spectral analysis of bioprosthetic valve sounds. *Ibid.*, **BME-33,** 572–578.

HARRIS, A. and SUTTON, G. (1968) Second heart sound in normal subjects. *Br. Heart J.*, **30,** 739–742.

LEATHAM, A. (1975) *Auscultation of the heart and phonocardiography, 2nd edn.* Churchill Livingstone, New York.

SHAVER, J. A., SALERNI, R. and REDDY, P. S. (1985) Normal and abnormal heart sounds in cardiac diagnosis. Part 1: Systolic sounds. *Curr. Probl. Cardiol.*, **10,** 1–69.

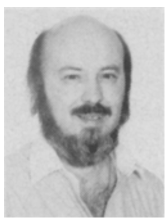
TILKIAN, A. G. and BOUDREAU-CONOVER, M. (1984) *Understanding heart sounds and murmurs with an introduction to lung sounds, 2nd edn.* W. B. Saunders.

Authors' biographies

Guy Cloutier was born in Trois-Rivières, Quebec, Canada, in 1961. He received the B.Eng. degree in Electrical Engineering from the Université du Québec à Trois-Rivières in 1984 and the M.Sc.A. degree in Biomedical Engineering from the École Polytechnique, University of Montreal in 1986. He is currently working towards a Ph.D. degree in Biomedical Engineering at the École Polytechnique and the Clinical Research Institute of Montreal. His principal interests are in digital signal processing and pattern recognition of biomedical signals.

Marie-Claude Grenier was born in Montréal, Quebec, Canada, in 1962. She received the B.Eng. degree in Electrical Engineering from the École Polytechnique, University of Montreal, in 1986 and is presently pursuing the M.Sc. degree in Biomedical Engineering at the École Polytechnique and Clinical Research Institute of Montreal. Her principal interests are image processing and digital signal processing of biomedical signals.

Robert Guardo was born in Siracusa, Italy, in 1946. He received the B.Sc. degree in Engineering Physics from the École Polytechnique, Montreal, Canada, in 1968 and the Ph.D. degree in Electrical Engineering from Imperial College, London, UK in 1972. From 1972 to 1973 he was a research associate at the Neurosurgery Clinic of the University of Düsseldorf, West Germany. He then joined the Biomedical Engineering Institute of the École Polytechnique, University of Montreal, where he is currently an associate professor. His major interests are cardiac electrophysiology and haemodynamics, digital signal processing and instrumentation design.



Louis-Gilles Durand was born in St-Jean de Matha, Quebec, Canada in 1949. He is Director of the Biomedical Engineering Laboratory at the Clinical Research Institute of Montreal, Research Assistant Professor in the Department of Medicine at the University of Montreal and Visiting Professor at the Institute of Biomedical Engineering of the École Polytechnique, Montreal, Canada. He has B.Sc., M.Sc. and Ph.D. degrees in Electrical Engineering from the École Polytechnique, University of Montreal. In 1975 he set up a biomedical engineering service at the Clinical Research Institute of Montreal. His major interests are digital signal processing of physiological signals, computer modelling of physiological systems and medical instrumentation.