Internet Digital Phonocardiography in Clinical Settings and in Population Screening

E. Kail[1], S. Khoór[2], B. Kail[1], K. Fügedi[2], F. Balázs[3]

[1]Artintell Ltd., Budapest, Hungary
[2]Szent István Hospital, Budapest, Hungary
[3]Budapest University of Technology and Economics, Dept. of Telecommunications

Abstract

A computerized phonocardiographic telemedicine system was developed with the visual interpretation module based on the Morlet wavelet scalograms. Four studies are shown how to use this method: the special diagnostic role of PCG in 287 subjects, the feature extraction capabilities of the Morlet scalogram in 594 patients, the comparison of PCG and echocardiography method in the cardiologic diagnosis of 773 subjects, and the role of PCG in population screening and monitoring in 427 patients. The presented system is the second part – the first was the ECG – of the ongoing development of a complex vital signs measuring wireless system.

1. Introduction

The computerized heart sound and murmur analysis helps the better visualization of phonocardiographic (PCG) recordings [1, 2, 3, 4]. The continuous wavelet analysis (CWT) is frequently used, and the Morlet wavelet seems to be a proper choice [5, 6, 7, 8, 9, 10].

An expert system for phono-mechanocardiographic data have been developed by our team 20 years ago. The results were implemented in the new internet based version, where the continuous Morlet wavelet analysis was used. Our aim is to develop a complex vital signs measuring on/off-line wireless system, based on our previously implemented ECG system, the HeartSpy [11], and this work on clinical phonocardiography.

2. Methods

Two decades ago the PCGs were recorded with our lab developed digitizing equipment with a sampling frequency of 4096 Hz, at 12-bit resolution [12]. The bandwidth is limited to 50 Hz to 2000 Hz using third and fourth order Chebyshev filters, respectively. A moving-average filter was also applied (Savitzky-Golay) to both signals to eliminate and smooth additive noise originated from the stethoscope. Later a commercial stethoscope was equipped with a microphone, the auscultation signals were processed by a DSP unit. Nowadays, the commercial mobile phone with our electric stethoscope is used; the data in '.wav' format are transferred to the internet database via conventional PC network or with a mobile modem by wireless connection. The central, internet part collects and stores the data. In the post-processing phase the time-frequency analysis of the signals was used with spectral and the wavelet methods. During the digital acoustic analysis the signal (duration is 10 seconds) was processed using the continuous Morlet wavelet method. The wavelet transformation (WT) of a signal is the decomposition of the signal over a set of functions obtained after dilatation and translation of an analyzing wavelet. The main advantage of the WT is that it has a varying window size, being broad at low frequencies and narrow at high frequencies, thus leading to an optimal time-frequency resolution in all frequency ranges. These windows are adopted to the transients of each scale, so the wavelets lack of the requirement of stationarity. Continuous wavelet transform (CWT) is defined by

$$\mathrm{CWT}(a,b) = \int_{-\infty}^{\infty} x(t)\Psi^*_{a,b}(t)\mathrm{d}t, \tag{1}$$

where $x(t)$ represents the analyzed signal, a and b represent the scaling factor (dilation/compression coefficient), and the time shifting coefficient, respectively, and the superscript $()^*$ asterisk denotes the complex conjugation. And

$$\Psi^*_{a,b}(t) = \left(\frac{1}{\sqrt{a}}\right)\Psi\left(\frac{t-b}{a}\right), \tag{2}$$

where $\Psi(t)$ represents the wavelet. The Morlet wavelet was used and it is defined as $\Psi(t) = e^z$, where

$$z = \left(\frac{-t^2}{2}\right) + (j2\pi f t)\,.$$

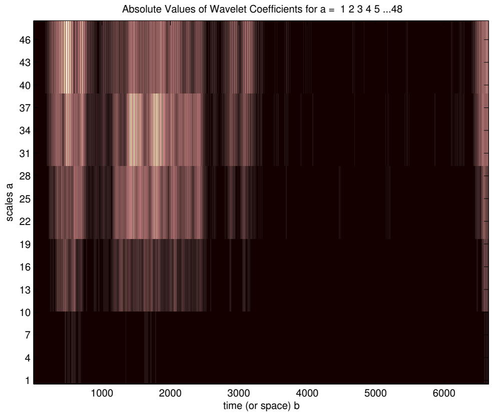

Figure 1. Morlet scalogram of a patient with aortic stenosis.

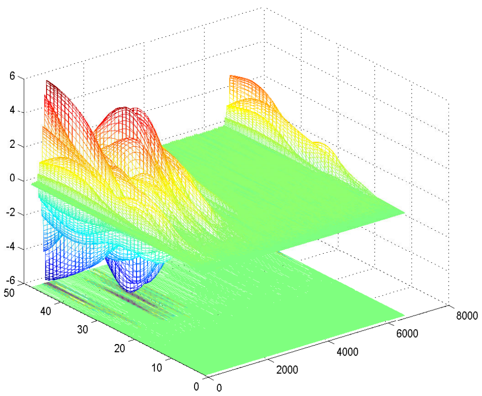

Figure 2. 3-D view of the Morlet scalogram of a patient with aortic stenosis.

The data were displayed by amplitude, frequency (wavelet energy), and time. Two independent cardiologists were interpreted the time-frequency "images". Figure 1-4. show an example of the Morlet scalogram.

In Study-1. the role of the cardiac auscultation in the telemedicine era was analyzed. The simplified version of our PCG expert system with the results is discussed later.

In Study-2. some important features of the heart sounds and murmurs were analyzed. The following phonocardiographic entities of the PCG database were used: loud first heart sound (ldS1, number of registrations: N=32), systolic murmur (SM; N=128), abnormal splitting of $S2$ (abspS2; N=27), opening snap (OS, N=55), $S3$ (n=48), $S4$ (N=66), diastolic murmurs (DM; N=92), carotid arterial murmur (CAM; N=146).

In Study-3. some diagnostic categories were compared to the data of standard echocardiographic examination. The disease categories were the follows: S4 with increased ventricular stiffness (Disease Group: DG-A; number of patients: N=122), $S4$ in Chronic Heart Failure (CHF) with low ($<$ 35%) ejection fraction - without primary valvular disease or high cardiac output (DG-B; N=98), valvular heart disease: Mitral Valve Prolapse (MVP) (DG-C; N=116), Mitral Stenosis (DG-D; N=28), Mitral Regurgitation (MR) (DG-E; N=47), pure Aortic Regurgitation (pAR) (DG-E; N=24), Aortic Stenosis (AS) (DG-F; N=118), combined Mitral Valve Disease (cMVD) (DG-G; N=56), combined Aortic Valve Disease (aAVD) (DG-H; N=87), significant Carotid Artery Stenosis (sCAS) (DG-I;N=77).

In Study-4. the registration of PCG and carotid murmurs were collected from a general population with higher cardiovascular risk (Group-A, N=284), from patients with cerebral lesion due to vascular events (Group-B, N=97), and from postinfarction patients after the hospital discharge (Group-C, N=46). The registrations were repeated every year for Group-A., and every two weeks for 6 months in Group-C.

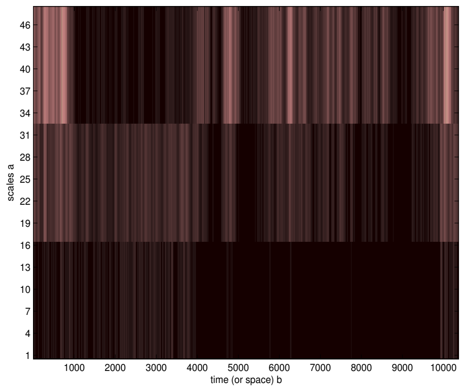

Figure 3. Morlet scalogram of a patient with combined mitral valvular disease

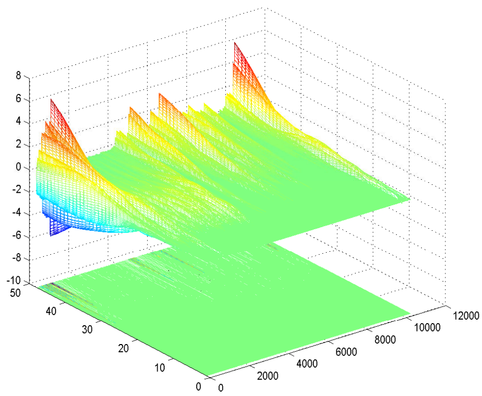

Figure 4. 3-D view of the Morlet scalogram of a patient with combined mitral valvular disease.

3. Results

In Study-1. the aim of our work was to implement the traditional PCG interpretations [13, 14] with the use of an expert system based on modern signal analysis techniques. Some examples are shown, where the echocardiography has lesser diagnostic value, than the phonocardiography. The number of patients represents our cases, where the PCG technique helps us in the diagnostic field during the last 15 years: ejection sound (click) may presents in bicuspid aortic valve disease, and may indicates the proper function of mechanical prosthetic valve (N=7); mid/late systolic click is most likely diagnostic of mitral/tricuspid valve prolapse (N=28); audible $S4$ reflects diastolic dysfunction (forceful left atrial contraction with reduced left ventricular compliance/increased stiffness) (N=66); $S3$, detected in older patients without primary valvular disease or high output syndrome, represents reduced systolic function (EF $< 30 - 50\%$) (N=118); $S3$ in pts with primary valvular disease (except mitral regurgitation) is a sign of systolic dysfunction and elevation of left ventricular filling pressure (N=66); pericardial ”knock”: a diastolic sound resembling the $S3$, but earlier means pericardial thickening or calcification (N=2).

In Study-2. the descriptive values of the wavelet scalograms were studied. Table 1. represents the results of the feature extraction and quality control of the PCGs with the Morlet wavelet analysis. In the case of the agreement of the two cardiologists, the Morlet scalogram was good for the special feature (sound, murmur) extraction, and has a good quality.

Table 1. Validitation of the Morlet scalograms of two cardiologist

	Total Nr.	2 of 2 %	1 of 2 %	Bad Quality (%)
ldS1	32	18 (56.3)	9 (28.1)	5 (15.6)
SM	128	119 (93.0)	6 (4.7)	3 (3.2)
abspS2	27	13 (48.1)	11 (40.7)	3 (11.1)
OS	55	36 (65.5)	14 (25.5)	5 (9.1)
S3	48	38 (79.2)	6 (12.5)	4 (8.3)
S4	66	57 (86.4)	4 (6.1)	5 (7.6)
DM	92	85 (92.4)	5 (5.4)	2 (2.2)
CAM	146	107 (73.3)	36 (24.7)	3 (2.1)

Abbreviations: ”2 of 2” = agreement of the two cardiologists, ”1 of 2” = disagreement of the two, other abbreviations see in the text.

In Study-3. the diagnostic strength of PCG was analyzed in various disease groups. Table 3. shows the specificity, sensitivity, positive and negative predictive values PCG diagnosis based on the Morlet scalograms compared to the standard echocardiographic examinations.

Abbreviations to Table 2 and Table 3: No. = number of patients, E+/- = positive/negative echocardiographic diagnosis, P+/- = positive/negative PCG diagnosis, Sens. = sensitivity, Sec. = specificity, PosPed = positive predictive value, NegPred = negative predictive value, others see in the text.

Table 2. Comparison of echocardiographic and PCG diagnosis in various heart disease. I.

	Nr.	E+P+	E+P-	E-P+	E-P-
S4&IVS	122	47	16	18	41
S4&CHF&EF↓	98	40	12	11	35
MVP	116	39	21	18	38
MS	28	13	3	1	11
MR	47	19	6	8	14
pAR	24	9	5	3	7
AS	118	49	6	12	51
cMVD	56	21	7	9	19
sAVD	87	30	17	8	32
sCAS	77	28	14	10	25

Table 3. Comparison of echocardiographic and PCG diagnosis in various heart disease. II.

	Sens	Spec	PosPred	NegPred
S4&IVS	0.75	0.69	0.72	0.72
S4&CHF&EF↓	0.77	0.76	0.78	0.74
MVP	0.65	0.68	0.68	0.64
MS	0.81	0.92	0.93	0.79
MR	0.76	0.64	0.70	0.70
pAR	0.64	0.70	0.75	0.58
AS	0.89	0.81	0.90	0.89
cMVD	0.67	0.71	0.70	0.73
sAVD	0.64	0.80	0.79	0.65
sCAS	0.67	0.71	0.74	0.64

In Study-4. the registrations of PCG and carotid murmurs were collected from a general population with higher cardiovascular risk (Group-A, N=284), from patients with cerebral lesion due to vascular events (Group-B, N=97), and from postinfarction patients after the hospital discharge (Group-C, N=46). In Group-A the initial PCG evaluation showed ejection carotid murmur in 67 asymptomatic patients (sensitivity, specificity, positive and negative predictive value were: 0.55, 05, 0.48, and 0.88, respectively. In Group-B these values were: 0.64, 0.75, 0.42, and 0.88 with a pathologic carotid murmur of 33. During the monitoring phase of the postinfarction patient (Group-C), mitral regurgitation was developed in 16 of 46 pts, the sensitivity, specificity, positive and negative predictive values were: 0.44, 0.73, 0.47, and 0.71, respectively.

4. Discussion and conclusions

The CWT – and the Morlet wavelet is the best of it – is the most suitable method in the analysis of the heart sounds and murmurs characterized by transients and fast changes. The PCG scalograms were used in our telemedicine system for medical consultations and the mobile equipment for population screening of cardiovascular diseases. Our computerized phonocardiographic telemedicine system was useful in the decision making process before and between the standard cardiologic, more sophisticated (echocardiography and others) diagnostic methods, especially in primary non-cardiologic patients. The presented system is the second part – the first was the ECG – of the ongoing development of a complex vital signs measuring, internet based wireless system.

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References

[1] Obaidat MS. Phonocardiogram signal analysis: techniques and performance comparison. J Med Eng Technol 1993;17:221-227.

[2] Durand LG, Pibarot P. Digital signal processing of the phonocardiogram: a review of the most recent advancements. Crit Rev Biomed Eng 1995;23:163-219.

[3] Telatar Z, Erugul O. Heart sounds modification for the diagnosis of cardiac disorders. Proc Int Conf on Signal Processing 2003;1:100-105.

[4] Malarvili MB, Kamarulafizam I, Hussain S, Helmi D. Heart sound segmentation algorithm based on instaneous energy of electrocardiogram. Computers in Cardiology 2003;30:327-330.

[5] Khadra L, El-Asir B, Mawagdeh S. The wavelet transform and its application to phonocardiogram signal analysis. Med Inform 1991;16(3):271-277.

[6] Bentley PM. Wavelet transform: An introduction. Electronics and Communications Engineering Journal 1994;32;175-186.

[7] Mgdob HM, Torry JN, Vincent R, Al-Naami B. Application of Morlet transform wavelet in the detection of paradoxical splitting of the second heart sound. Computers in Cardiology 2003;30:323-326.

[8] Torry JN. Heart sound analysis comparing wavelet and autoregressive techniques. Computers in Cardiology 2003;30:657-660.

[9] Addison PS. The illustrated wavelet transform handbook. Institute of Physics Publishing. 2002.

[10] Ergen B, Tatar Y. Optimal continuous wavelet analysis of phonocardiogram signals. Proc Int Conf on Signal Processing 2003;1:188-192.

[11] Khoór S, Nieberl J, Fügedi K, Kail E. Internet based, GPRS, long-term monitoring and non-linear heart-rate analysis for cardiovascular telemedicine management. Computers in Cardiology 2003;30:209-212.

[12] Khoór S, Kekes E., Fügedi K, et al Expert System on Microcomputer: a beside Analysis of Mechanocardiograms Acta Cardiol 1988;43(3):273-276.

[13] Tavel ME. Cardiac Auscultation. A glorious past - but does it have future? Circulation 1996;93:1250-1253.

[14] Dalla Volta S (ed). Cardiology. McGraw-Hill. 1999.

Address for correspondence:

Sándor Khoór, MD.Ph.D.

Szent István Hospital Nagyvárad tér 1., Budapest, Hungary H-1096

E-mail address: skhoor@bion.hu