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Study of the impact of clicks and murmurs on cardiac sounds S1 and S2 through bispectral analysis

Yettou Nour El Houda BAAKEK^a, Imane DEBBAL^a, Hidayat BOUDIS^a, Sidi Mohammed El Amine DEBBAL^{a,*}

^a*Genie Biomedical Laboratory (GBM), Faculty of Technology, University A.B.Belkaid-Tlemcen BP 119, Tlemcen; Algeria BP 119*

^{*}*E-mail address: adebbal@yahoo.fr*

Abstract

This paper presents a study of the impact of clicks, and murmurs on cardiac sound S1, and S2, and the measure of severity degree through synchronization degree between frequencies, using bispectral analysis. The algorithm is applied on three groups of Phonocardiogram (PCG) signal: group A represents PCG signals having a morphology similar to that of the normal PCG signal without click or murmur, group B represents PCG signals with a click (reduced murmur), and group C represent PCG signals with murmurs.

The proposed algorithm permits us to evaluate and quantify the relationship between the two sounds S1 and S2 on one hand and between the two sounds, click and murmur on the other hand. The obtained results show that the clicks and murmurs can affect both the heart sounds, and vice versa. This study shows that the heart works in perfect harmony and that the frequencies of sounds S1, S2, clicks, and murmurs are not accidentally generated; but they are generated by the same generator system. It might also suggest that one of the obtained frequencies causes the others.

The proposed algorithm permits us also to determine the synchronization degree. It shows high values in group C; indicating high severity degrees, low values for group B, and zero in group A.

The algorithm is compared to Short-Time Fourier Transform (STFT) and continuous wavelet transform (CWT) analysis. Although the STFT can provide correctly the time, it can't distinguish between the internal components of sounds S1 and S2, which are successfully determined by CWT, which, in turn, cannot find the relationship between them.

The algorithm was also evaluated and compared to the energetic ratio. the obtained results show very satisfactory results and very good discrimination between the three groups.

We can conclude that the three algorithms (STFT, CWT, and bispectral analysis) are complementary to facilitate a good approach and to better understand the cardiac sounds

Key words: sound S1; sound S2; click, murmur; impact; bispectral; analysis, pathology; severity.

Introduction

The phonocardiogram (PCG) (**Figure 1**) is one of the most tools used for analyzing the mechanical activities of the heart, and for the diagnosis of abnormal heartbeat sounds such as murmur. PCG signal can describe with great precision its different components such as heart sounds: S1, S2, clicks, and murmurs.

When a healthy heartbeat, it makes a “lub-dub” sound. The first heart sound ‘lub’, also known as S1 is caused by the closing of atrioventricular (AV) valves after the atria have pumped blood onto the ventricles (**Figure 2**).

The second heart sound “dub”, or S2 originates from the closing of the aortic and pulmonary valves, right after the ventricles have ejected the blood. The time interval between S1 and S2 is when the ventricles contract, called Systole. The interval between S2 and next S1 is when the ventricles relax

and are filled with blood, called diastole. Diastole is longer than systole.

S1 is caused by the closure of mitral and tricuspid valves at the start of systole. The second heart sound S2, is caused by the closure of the aortic and pulmonic valves, marking the end of systole.^{1,2}

According to the literature, there are two major components of each sound.^{2,3} The components for the sound S1 are M1 and T1, one due to closure of the Mitral valve and the other due of the closure of the Tricuspid valve. Inspiration delays the closure of the tricuspid valve in a normal person, due to increased venous return, thereby enhancing the splitting of the S1 sound. This delays the closure of the tricuspid valve, resulting in a split S1 sound, and M1 and T1 are separated by a relatively short interval, however a split S1 can also be heard in the setting of a right bundle branch block (RBBB).

For the second sound S2, one sound is due to the closure of the aortic valve (A2) and the other sound is due to the closure of the pulmonary valve (P2).^{2,4,5} Specifically, during expiration, A2 and P2 are separated by a relatively short interval typically less than 30 ms.⁶ It is heard when aortic and pulmonic valves close at slightly different times.

However, there are two other kinds of heart sound which are: ejection clicks, and murmurs. Ejection clicks are high-pitched sounds that occur at the moment of maximal opening of the aortic or pulmonary valves. They are heard just after the first heart sound.

Heart murmurs are whooshing sounds produced by the turbulent flow of blood. Murmurs are diagnosed based on the time they occur in the cardiac cycle, their changes in intensity, over time, and the auscultation site where they are best heard.

PCG signal compared to other investigative techniques provides information in real-time with high resolution. In addition, from PCG signal some important parameters can be extracted such as: amplitude, frequency, number of components of the signal in each cycle, the intensity, the duration, the location, and the different shapes of each sound which are considered as indicators of diseases under study.

On the other hand, this kind of signal shows significant random and nonlinear properties, especially in the murmur sounds. Many studies have been carried out, on the behavior of this kind of signal. Some of these studies are discussed below.

Yaseen et al⁷ used Artificial Neural Networks (ANN) to detect and classify heart diseases. They extracted time domain and frequency domain features such as energy, mean, variance and Mel Frequency Cepstral Coefficients (MFCC). Various heart sound samples are classified using Support Vector Machine (SVM), K Nearest Neighbour (KNN), Bayesian and Gaussian Mixture Model (GMM) Classifiers.

Mohamed Boussaa et al⁸ describe in detail a medical assistance system that can detect and distinguish between normal and abnormal heart signals. Their system combines firstly between the MFCC as a descriptor of the cardiac signal and the artificial neural network-type MLP as a classifier and secondly between the discrete wavelet descriptor, statistical operations as reducing the characteristic vector of the dimensions extracted and the same type of classifier.

Maciej Rosół et al⁹ present a low-cost system of location and classification of heart sounds in S1 and S2 based on a single-chip microcontroller and MEMS microphone. They also used the temporal, frequency analysis, autocorrelation function, and time-frequency to analyze diastole and systole heart cycles.

However, all these methods can't give us a relationship between the different frequencies; on the contrary, the bispectral analysis can provide this relationship, and can distinguish between them.

This study is a complementary study to that which was made by Debbal et al². They found that the continuous wavelet transform is the most successful technique for the analysis of the internal components of these sounds. The continuous

wavelet transform allows the best representation of the internal components (M1, T1, A2 and P2) and the measure of the time delay between these components. However, the STFT can provide correctly the time but the components M1 and T1 of the sound S1 and the components A2 and P2 of the second sound are not obviously detected and not accurately represented. For more details see reference 2.

In this work, our contribution is to find the relationship between the different PCG sounds (S1, S2, Click, and murmurs) on one hand and between the internal components of each sound on the other hand. In addition, the proposed algorithm permits us to determine a new parameter that corresponds to the synchronization degree between the frequencies using bispectral analysis. This parameter can give us information about the severity degree of the pathology. Finally, the work is evaluated and finished by a comparison between bispectral analysis, CWT and energetic ratio.

Figure 1. PCG signals used

Figure 2. Human heart valves

Materials and Methods

Database

This database consists of 11 different cases of PCG signals (**Table 1**), taken from three different databases,¹⁰⁻¹² with different degrees of heart pathological severity. Each database has its own sampling frequency (see **Table 1**).

Heart sounds are auscultated at four different sites on the chest wall which corresponding to the location of blood flow as it passes through the aortic, pulmonic, tricuspid, and mitral valves, respectively. The diagnosis of the presence or absence of clicks and murmurs was taken from the source database. The severity of clicks and murmurs depends on the location of auscultation, the quality or the intensity, and their timing. We have grouped and classified the signals into three groups according to their pathological severity based on the segmentation of sounds and heart murmurs (**Figure 2**).¹³⁻¹⁶ Group A corresponding to PCG signals having a morphology similar to that of the normal PCG signal without click or murmur: “n” normal heartbeat cardiac sound, “coa” coarctation of the aorta, and “IM” Innocent murmur.

Group B corresponding to PCG signals with a click (reduced murmur), it contains five PCG signals: “EC” Ejection click, “AG” Aortic Gallop, “EC1” Ejection click, “MP” systolic Mitral Prolapse, and “LS” Late systolic.

Group C corresponding to PCG signals with murmurs it contains three PCG signals: “Mr” Mitral regurgitation, “ar” aortic regurgitation, and “tr” Tricuspid regurgitation.

Table 1. Description of the used database.

Group	Record	Sampling Frequency (Hz)	Signal length	Cycles number	Description of the pathology
A	n	11025	49400	6	Normal case
	coa	8012	11962	2	Coarctation of the aorta is a birth defect in a part of the aorta, the tube that carries oxygen-rich blood to the body, is narrower than usual. It forces the heart to pump harder to get blood through the aorta and on to the rest of the body.
	IM	8012	32465	5	An Innocent heart Murmur does not cause heart problems. It is often related to a temporary condition, causing high blood flow through the heart's valves.
B	EC, EC1	11025	54672	6, 7	Ejection Clicks are high-pitched sounds which are heard just after the first heart sound. They occur in the presence of a dilated aorta or pulmonary artery or in the presence of a bicuspid or flexible stenotic aortic or pulmonary valve.
	AG	11025	52878	6	Aortic Gallop is an abnormal rhythm of the heart on auscultation. It contains another sound, called S3 or S4, dependent upon where in the cycle this added sound comes.
	MP	11025	54381	6	Mitral Prolapse is a disorder, usually benign, of the functioning of the mitral valve and may be responsible for more or less severe mitral insufficiency. It is characterized by the displacement of an abnormally thickened mitral valve leaflet into the left atrium during systole. It is the primary form of myxomatous degeneration of the valve.
	LS	11025	57024	6	Late Systolic is a sharp, clicking sound heard during cardiac late systole. It signifies mitral insufficiency, may also be due to pleuropericardial adhesions or other extracardiac mechanisms
	Mr	44100	329728	9	Mitral Regurgitation It is one of the most common diseases among heart valve pathologies. In this case, the heart's mitral valve doesn't close tightly, causing a backflow of blood from the left ventricle into the left atrium during the phase of expulsion of the blood (systole), instead of going into the aorta.
C	ar	44100	586530	14	Aortic Regurgitation, is a heart valve disease corresponding to a failure to check the aortic valves of the heart which causes retrograde blood flow during diastole, from the aorta to the left ventricle
	tr	44100	200112	8	TRicuspid insufficiency is an impairment of the tricuspid valve allowing blood to flow back from the right ventricle to the right atrium.

Preprocessing

Usually, PCG signals after acquisition are disturbed by various noises. One of the first operations is therefore to apply a filter that eliminates these disturbances. It is therefore preferable to filter this signal as a first step and before any analysis. The filter used is the discrete wavelet transform. For a better analysis, the choice of the mother wavelet is more important. Therefore, in this work, the most suitable analyzing wavelet for performing this filtering is: the 7th level Daubechies wavelet (db7). This latter is the most suitable for analyzing normal and pathological PCGs signals.

Bispectral analysis

A bispectral analysis is an advanced signal processing technique that quantifies quadratic nonlinearities among the components of a signal.¹⁷⁻¹⁹ It is defined as the Fourier transform of the third cumulant. Considering that the Fourier transform of the second-order cumulant (the auto-correlation function) is known by the power spectral density (PSD). The Hanning window length of 256 was used. The bi-spectral is defined by **Equation 1**.

$$B(f_1, f_2) = E[X(f_1)X(f_1)X^*(f_1 + f_2)] \quad \text{Eq. 1}$$

Where $X(f)$ is the discrete Fourier transform (DFT) of (nT) .

$X^*(nT)$ is the conjugate of $x(nT)$,

$E[\cdot]$: is the operator of mathematical expectation.

f_1+f_2 : is the frequency of the harmonic component

Since the correlation function is an even function, and its FT gives a symmetry spectrum (i.e. the spectrum repeats twice "mirror effect"), we find that the bi-spectrum which represents the FT of the tri-correlation function, repeats itself four times. It is therefore enough to calculate the spectrum for the frequencies that lie in the non-redundant region Ω as it is illustrated in **Figure 3**. For more details see²⁰.

Figure 3. The non-redundant region for the calculation of bispectral frequencies.¹¹

Synchronization degree

The synchronization degree is defined as the ratio between the number of harmonics and all the sinusoids number of the bispectrum. We must indicate here that the number of harmonic and the sinusoids must be calculating n times if it is generated n times.

$$Syn = \frac{\sum_{k=1}^{n-1} f_k}{\sum_{i=1}^n f_{ik}} \quad \text{Eq. 2}$$

$$f_k = f_i + f_j$$

$$i = 1, \dots, n$$

$$j = 1, \dots, n$$

Results and discussion

The bispectral algorithm has been implemented and applied on three sets of PCG signals: group A corresponding to normal cases without click or murmur, group B corresponding to PCG signals with a click, and group C corresponding to PCG signals with murmurs. Heart sounds are auscultated at four different sites on the chest wall which corresponding to the location of blood flow as it passes through the aortic, pulmonic, tricuspid, and mitral valves, respectively. The obtained results are illustrated in **Figures 4 to 12** and resumed in **Tables 2 and 3**.

Group A

The bispectra of the sound S1 and S2 of the record (coa.wav) in group A are illustrated in **Figures 4 and 5** respectively. The color represents the relative variation of the amplitude of the bispectrum. The red color indicates the strongest increase, and the blue line indicates the greatest decrease.

The analysis of the internal components of heart sounds (M1 and T1 for S1: A2 and P2 for S2) makes it possible, through the measurements obtained and the variation of the parameters studied, to know the operating state of the corresponding valves (mitral (M1), tricuspid (T1), aortic (A2) and pulmonary (P2) which can help the clinician in establishing the medical diagnosis or the surgeon in the case of valve transplantation.

The bispectra show a predominance of two peaks in each sound: (M1 and T1) in sound S1, and (A2 and P2) in sound S2.

The peak M1 (**Figure 4, Table 2**) represents only one frequency, it is around (179,43, 179.43) Hz, however T1 is around (179,43, 358.86) Hz. As we remark the frequency 353.86 Hz represents a quadratic interaction, it is the double of the M1 component frequency ($358.86 = 179.43 \times 2$). The components M1 and T1 of sound S1 are due to the closing of the mitral valve and the tricuspid valve respectively. According to this result, we can say that the frequency of the signal corresponding to the closing tricuspid valve is double the frequency of the signal corresponding to the closing mitral valve.

Figure 4. Bispectrum of S1 sound in normal case (Group A, record "n")

Figure 5. Bispectrum of S2 sound in normal case (Group A, record "n")

Similar results are obtained in the bispectrum of S2 (**Figure 5**). The peak A2 represents only one frequency, it is around (239.24, 239.24) Hz, however P2 is around (239.24, 478.48) Hz, it represents a quadratic interaction ($478.48 = 239.24 \times 2$). According to this result, we can say that the frequency of the component A2 is double that of the component P2. This second sound S2 signal represents the end of the systole and the beginning of the diastole. However, the components A2 and P2 of S2 represent the closing of the aortic and pulmonary valves respectively. i.e. the frequency of the signal corresponding to the closing pulmonary valve is double the frequency of the signal corresponding to the closing aortic valve.

Similar results are obtained in the record "IM" in group A; however, in the signal "n" which represents a normal case, we found that A2 equal to M1 and P2 equal to T1 (**Table 2**). According to this result, we can say that in the normal case the frequency of the signal corresponding to the closing of the mitral valve equal to the frequency of the signal corresponding to the closing of the aortic valve, and the frequency of the signal corresponding to the closing tricuspid valve equal to the frequency of the signal corresponding to the closing pulmonary valve. This result leads us to conclude that the bispectral analysis can distinguish between normal cases and pathologic cases even if it has a morphology similar to that of the normal PCG signal.

However, the synchronization degree and as is illustrated in **Table 2**, shows a zero value in all the cases of group A, because there is no harmonic component.

Group B

Similar results are also obtained in the bispectra of the sounds S1 and S2 (record EC), as it is illustrated in **Figures 6 and 7** respectively. It shows a predominance of two peaks in each sound: (M1 and T1) in the sound S1, (A2 and P2) in the sound S2.

The peak M1 and A2 represent only one frequency, it is around (273.36, 273.36) Hz, however T1 and P2 are around (273.36, 546.72) Hz. As we remark, S1 and S2 are identical, and the frequency of T1 is twice the frequency M1, and the frequency of P2 is twice the frequency of A2.

However, the bispectrum of click in this signal shows also two peaks (**Figure 8, Table 2**), the first mr1 is around (820.08, 820.08) Hz, and the second mr2 is around (820.08, 1640.16) Hz. According to this result, we can remark, that the frequency 1640.16 Hz is twice the frequency 820.8 Hz. On other hand, the frequency 820.08 Hz results from the nonlinear interaction between the frequencies 546.72 Hz and 273.36 Hz which are found in the S1 and S2 bispectra; because it equals to the sum of two frequencies; which leads us to conclude that there is a nonlinear relationship between the click heart and the sounds S1 and S2, and that might suggest that the three sounds S1, S2, and click have the same generator system. It might also suggest that one of the obtained frequencies causes the others.

The synchronization degree between the different frequencies show a low value ($1/4=25\%$) (**Table 2**); because we have only one harmonic frequency (820.08) between four frequencies (273.36, 546.72, 820.08, 1640.16) Hz. Similar results are obtained in the other signals of group B, where we found low values that vary between 25% and 42%.

Table 2. Summary table of the results obtained

Group	Record	Heart Sound (S1/S2)		Click	Murmur
		S1 (M1/T1)	S2 (A2/P2)	Cki	MRi
A	n	M1(197.632,172.92) T1 (197.632, 370.53)	A2(197.632,172.928) P2(197.632,370.53)	/	/
	coa	M1 (179.43, 179.43) T1 (179.43, 358.86)	A2(239.24, 239.24) P2(239.24, 478.48)	/	/
	IM	M1(486.975,486.97) T1(486.975,973.95)	A2(324.65, 324.65) P2(324.65, 649.3)	/	/
B	EC	M1(273.36, 273.36) T1(273.36, 546.72)	A2(273.36, 273.36) P2(273.36, 546.72)	Ck1(820.08, 820.08) Ck2(820.08,1640.16)	/
	AG	M1(264.39, 264.39) T1(264.39,528.78)	A2(264.39, 264.39) P2(264.39,528.78)	Ck1 (528.78, 528.78) Ck2 (528.78, 793.17)	/
	EC1	M1(285.535,285.535) T1(285.535,571.07)	A2(285.535,285.535) P2(285.535,571.07)	Ck1 (815.715,815.715) Ck2 (815.715,1631.43)	/
	MP	M1(271.95, 271.905) T1(271.905, 534.81)	A2(271.95, 271.905) P2 /	Ck1 (815.715,815.715) Ck2 (815,715,1631.43)	/
	LS	M1(285.12, 285.12) T1(285.12,570.24)	A2(285.12, 285.12) P2(285.12,570.24)	Ck1 (855.36, 855.36)	/
	Mr	M1(659.456,659.456) T1(659.456,1318.912)	A2(494.592,494.592) P2(494.592,989.184)	/	MR1 (1648.64,1648.64) MR2 (1648.64,3297.28)
C	ar	M1(1000.56,1000.56) T1(1000.56,2001.12)	A2(1000.56,2001.12) /	/	MR1 (1000.56,2001.12)
	tr	M1(879.795,1173.06) T1(1173.06,2052.855)	A2(1173.06,1173.06) P2(1173.0,2346.12)	/	MR1 (11773.06,4398.975) MR2 (879.795,4692.24) MR3 (879.795,5572.03) MR4 (1173.06,5572.03) MR5 (43.98.975,5572.035) MR6 (4692.24,5572.035)

Figure 6. Bispectrum of S1 sound in pathologic case (Group B, record "EC")

Figure 7. Bispectrum of S2 sound in pathologic case (Group B, record "EC")

Figure 8. Bispectrum of click sound in pathologic case (Group B, record "EC")

Figure 9. Bispectrum of S1 sound in pathologic case (Group C, record "mitral-regurgitation")

Figure 10. Bispectrum of S2 sound in pathologic case (Group C, record "mitral-regurgitation")

Figure 11. Bispectrum of murmur sound in pathologic case (Group C, record "mitral-regurgitation")

Group C

Generally, and as it is illustrated in **Table 2**, the frequency components in all the records in this group, show that the frequency of T1 is the double of M1, and P2 is the double of A2, except in record "tr" (tricuspid-regurgitation), where its bispectra are illustrated in **Figures 9 to 11**. It shows a predominance of four peaks in the sound S1: (M1, T1, mr1,

and mr2), two peaks in S2 (A2 and P2), and six peaks (MR1, MR2, MR3, MR4, MR5, and MR6) in murmur sound signal.

M1 is around (879.795, 1173.06) Hz, T1 around (1173.06, 2052.855) Hz, mr1 around (2932.65, 405.71) Hz, and mr2 around (1173.06, 4105.71) Hz, (**Figure 9**).

A2 is around (1173.06, 1173.06) Hz, P2 around (1173.0, 234612) Hz. (**Figure 10**).

Always and as we remark P2 is twice A2. i.e. regardless of the kind of signal: healthy or pathological cases, the frequency of signal corresponding to the closing pulmonic valve is double the frequency of the signal corresponding to the closing aortic valve. However, in this case, T1 is different from M1; because the bispectrum contains two others component (mr1 and mr2) corresponding to murmur sound; for the reason that the mitral valve does not close properly and blood surges back to the left atrium during systole, and the murmur start at S1.

As we remark, the frequencies 2052.855, 2932.65, and 4105.71 Hz represent a nonlinear relationship between the frequencies (879.795+1173.06), (2052.855+879.795), and (2052.855*2), which confirms that S1 is incorporated in murmur sound signal.

However, the frequencies of the murmur are (**Figure 11**): MR1 is around (879.795, 5572.35), MR4 is around (1173.06, 5572.035), MR5 is around (43.98.975, 5572.035), and MR6 is around (4692.24, 5572.035).

As we remark there is a nonlinear interaction between the different frequencies: the frequency 5572.035 Hz is the interaction between 4692.24 and 879.795 (4692.24 +879.795). The frequency 4398.975 is a nonlinear interaction between the frequency 2052.855 Hz which was obtained in the bispectrum of S1 and 2346.12 Hz which was obtained in the bispectrum of S2.

The frequency 4105.71 is the nonlinear interaction between 1173.6 and 2932.65.

On other hand, the frequencies 2932.65 and 2052.855 Hz represent also harmonic components obtained in S1 bispectrum. However, the frequency 4692.24 is double the frequency 2346.12 Hz which is obtained in B2 bispectrum.

So we can conclude that the synchronization degree is very high (5/6= 83.33%) (**Table 3**); because the number of harmonics is five (5572.035, 4398.975, 4105.71, 2932.65 and

2052.855 Hz), between six frequencies (879.795, 1173.06, 4692.24, 5572.035, 4398.975, and 4105.71 Hz). There is a perfect harmony between frequencies, and might also suggest that one of the obtained frequencies causes the others.

Similar results are obtained in the other records, where we found a high value of synchronization degree, which varies between 60% and 83.33% (**Table 3**).

Evaluation 1

In this section, we will present a short comparison between, STFT, CWT, and Bispectral analysis. The STFT, WCT analysis algorithms are implemented, and applied on the same used database, but in this paper, we show only the result of one signal as an example.

In the STFT algorithm, the Hanning window was used, with a length of 256, and an overlap of 50%. However, in the CWT algorithm the wavelet Daubechies 7 (db7) was used.

As it is illustrated in **Figure 12**, the STFT of the signal “n” shows only one component of each sound (**Figure 12b**). Each component spreads for large time and large frequency, and can't give us precise information about the number of components and their location in time of each sound.

The obtained results using CWT on the two sounds (S1 and S2), are shown in **Figure 13a** and **b**. There is high resolution in time and scale compared to STFT results. The CWT shows a predominance of two peaks of each sound (M1 and T1) for the sound S1 and (A2 and P2) for the sound S2.

It can so easily discriminate between the components of each sound and specifies the location of each of them; however, it remains limited, because it can't give us precise information about the frequencies, or the relationship between them.

Table 3. Synchronization degree

Group	Record	Frequencies of harmonic components	Number of harmonic components	Number of the total frequencies	Synchronization degree
A	n	/	/	/	0
	coa	/	/	/	0
	IM	/	/	/	0
B	EC	820.08	1	4	25%
	AG	793.17	1	3	1/3=33%
	EC1	856.605, 1142.14, 1713.21	3	7	3/7=42%
	MP	815.715	1	4	¼=25%
	LS	855.36	1	3	1/3=33%
C	Mr	1154.048, 1813.504, 2472.96	3	5	3/5=60%
	ar	1100616,3101.736,1801.008,2201.232, 1300.728	5	7	5/7=71.43%
	tr	5572.035, 4398.975, 4105.71, 2932.65, 2052.855	5	6	5/6=83.33%

Figure 12. a) Normal PCG signal (one cycle), b) STFT analysis of one cycle of normal PCG signal

Figure 13. a) CWT analysis of the sound S1, b) CWT analysis of the sound S2

Evaluation 2

In order to evaluate the proposed algorithm, a comparison between the synchronization degree and energetic ratio is illustrated in **Figure 14**.

The energetic ratio is an intrinsic characteristic related to the amount of the murmur in one cycle of PCG signal. One of the important indicators of severity is the increased energy of murmur in favor of B1 and B2 sounds.

For this, we use a new parameter, noted RE (energetic ratio), to estimate the degree of severity (**Equation 3**), which is calculated by the ratio between the energy of the murmur (E_2) and the total energy of the signal (one cycle).

The energetic ratio RE is given as a percentage, its maximum value is 100%. This latter will highlight the dominance of the murmur over the B1 and B2 noises. The heart murmurs can be classified according to three degrees of severity:²¹

light, $RE < 30\%$

Moderate, $30\% < REA < 70\%$

Severe, $RE > 70\%$

$$RE = \frac{E_2}{E_1 + E_2} \quad \text{Eq. 3}$$

With

E_1 : Sound energy (B1, B2)

E_2 : murmur energy

Figure 14. Synchronization and energy ration histogram of the three groups PCG signals

The ANOVA test is a statistical classifier; it is used to identify normal and pathological cases. The p-value is the measure used to identify significant statistical differences between different energetic ratio values. $p < .01$ are considered significant values, while values of $p < .001$ are considered very significant values.

According to **Figure 14**, the synchronization degree shows very significant values ($p < .001$) compared to the energetic ratio ($p < .01$), where we found zero values for group A, middle values in group B, and high values in group C.

Conclusions

In this paper, an attempt is made to study and analyze the impact of murmurs on cardiac sounds S1 and S2 and vice versa using bispectral analysis.

The bispectral analysis is found to be the most successful technique for the analysis of the relationship between sounds S1, S2, clicks, and murmurs on one hand, and between internal components of these sounds on the other hand. The proposed algorithm allows the best representation of this relationship between the different sounds and the internal components (M1, T1, A2, P2, and MRi).

This study shows that the frequencies of sounds S1, S2, clicks, and murmurs are not accidentally generated; but it is generated by the same generator system, and that whatever the pathological severity degree, the heart works in perfect harmony. Even though the STFT can provide correctly the

time, but it can't distinguish between the internal components, which are successfully determined by CWT, but it can't find the relationship between them.

We can conclude that the three algorithms (STFT, CWT, and bispectral analysis) are complementary to facilitate a good approach and to better understand the cardiac sounds.

The synchronization degree shows high values in group C, low values for group B, and zero in group A; indicating high severity degrees in signals with murmurs, low severity degrees in signals with clicks, and no danger in signals without clicks or murmurs.

The proposed algorithm, when compared to the energetic ratio showed good discrimination between the three cases according to the ANOVA test.

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