Comparison of Binomial, ZAM and Minimum Cross-Entropy Time-Frequency Distributions of Intracardiac Heart Sounds.

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Abstract

One reason why automated heart sound analysis remains unfeasible may be the inadequacy of conventional spectral techniques in representing the nonstationary, multicomponent characteristics of phonocardiograms. This study compares several generalized time-frequency distributions (GTFDs) applied to intracardiac phonocardiograms (ICP) obtained at rest in six patients using catheter- mounted transducers. ICPs were bandpass filtered (50-500 Hz) and digitized at 4 KHz. The TFDs employed in this study were the binomial transform (BT), Zhao-Atlas-Marks (ZAM) distribution, minimum cross-entropy (MCE) distributions and the spectrogram. The BT and MCE representations in particular show improved concentration of ICP energy in time-frequency vs. the spectrogram. These findings suggest that several GTFDs may prove useful in the design of automated auscultation systems.

1. Introduction

Surely no other medical instrument combines the attributes of widespread availability, low cost and diagnostic potential to the same degree as does the humble stethoscope, the virtual icon of the medical profession.

The art of listening to heart sounds (auscultation) has long been an important component of the physical examination providing the physician with valuable diagnostic and prognostic information. [1] Unfortunately, auscultation has remained somewhat of an art and clinical information provided by the stethoscope and the trained physician's ear has advanced little over the past 50 years.

Efforts to automate or at least better quantify heart sounds have met with very limited success because of the complex nature of heart sounds. Heart sounds reflect mechano-acoustic events which originate from multiple sites within the four chambers of the heart, valves and the great vessels. In general, the vibrations result from the rapid acceleration and deceleration of the blood/chamber systems [2].

Despite recent correlation of heart sounds with physiological events, the exact cause of many components of the sounds remain unknown [3,4]. Heart sound research is further complicated because the transmission of the acoustic signals through structures which surround the heart distort the signal on its pathway to the surface of the chest where transducers record the faint vibrations [5]. Many factors including sensor placement and body habitus make consistent recordings of heart sounds problematic.

The objective of this study is to determine whether newly reported time-frequency techniques can be used in conjunction with intracardiac heart sound recording systems to elucidate subtle acoustic events during the cardiac cycle in patients with and without heart disease.

2.0 Methods

Intracardiac phonocardiograms (ICPs) were obtained using a custom-made multisensor, phono-catheter (Millar Instruments, Inc., Houston, TX). The catheter had one pair of piezoelectric, micromanometric transducers located at the distal tip and a second transducer pair located 5 cm from the tip. This transducer behaves as a first-order RC circuit, effectively providing a tunable high-pass filter whose frequency response is -3 dB at approximately 90 Hz [6].

Following the retrograde placement of the catheter under fluoroscopic guidance, phonocardiograms and high-fidelity pressure recordings were simultaneously obtained, along with an EKG. Phonocardiograms were recorded from both the left ventricle and ascending aorta with six patients in a supine, resting state; see Fig 1.

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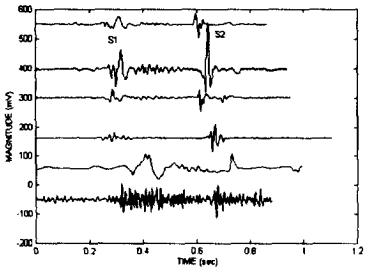

Fig. 1. Intracardiac phonocardiograms (ICPs) from six patients, representing one full cardiac cycle.

Phonocardiograms were band-pass filtered at 50-500 Hz (-12 dB/octave) and recorded on a wideband FM recorder. The ICPs were post-processed by filtering signals at 500 Hz (-20 dB/octave) using linear-phase anti-aliasing filters prior to analog-to-digital conversion.

A sampling rate of 2000 samples per second was chosen at a rate of 4 times the Nyquist frequency. Previous investigators have shown the maximal frequency content of ICPs has been found to be < 500 Hz [9]. Segments of the data containing complete cardiac cycles were extracted from raw data using custom-designed software and exported via Internet to a Sun SPARCstation at Hughes Aircraft (Fullerton CA) for subsequent time-frequency analysis and graphing (MATLAB software, MathWorks Inc., Natick MA).

In addition, a synthesized crossing-chirp test signal was generated and used as a standard input to each of the TFD techniques used in this study. The input signal (Fig. 2-a), is the sum of rising and falling chirp signals in the range between 0 - 500 Hz. Note the low amplitude region near the center of the signal.

3. Results

The two-chirp signal (Fig. 2-a) was synthesized to assess the ability of TFDs to discriminate time-varying elements. The lower resolution of the spectrogram and its lack of finite time support are evident from Fig.2-b. The GTFDs of the chirp signal via the three newer methods are shown in Figs. 2 c-e.

One cardiac cycle from the first patient's data (top signal in Fig.1) was selected to illustrate the four GTFD methods. This phonocardiogram (Fig. 3) was obtained from a patient without heart disease. The TFDs of this ICP are shown in Figs. 4 a-d below.

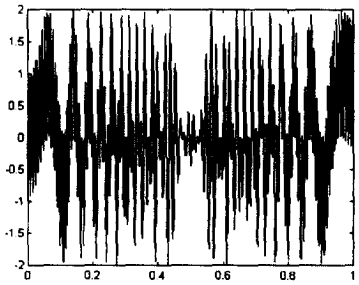

Fig 2-a. Test signal: sum of two chirps.

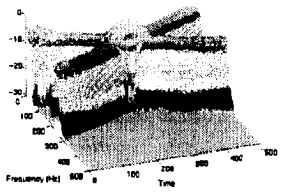

Fig.2-b. Spectrogram of chirps

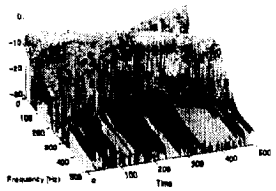

Fig 2-c. ZAM-TFD of chirps

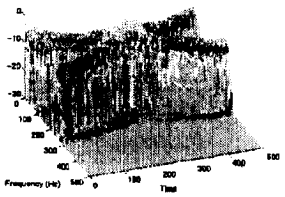

Fig. 2-d. BT-TFD of chirps

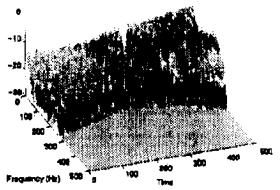

Fig. 3-e. MCE-TFD of chirps

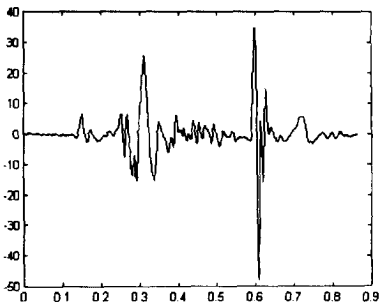

Fig.3. A normal ICP used in GTFD methods

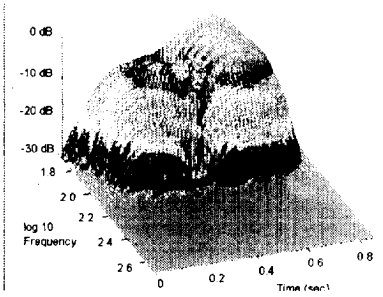

Fig 3-a. Spectrogram of ICP#1

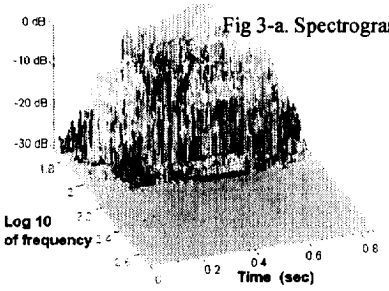

Fig. 3-b. ZAM-TFD of ICP#1.

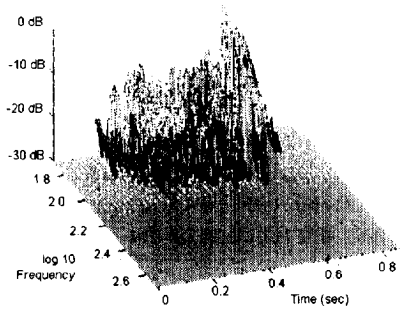

Fig. 3-c. BT-TFD of ICP#1

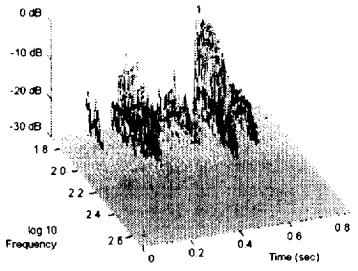

Fig. 3-d. MCE-TFD of ICP#1.

4. Discussion

Historically, investigators have applied frequency domain techniques to the entire cardiac period, multiple periods or segments of the cardiac cycle in order to quantify acoustic information in heart sound recordings [4,6,7]. Limited insight was provided into physiologic and pathologic processes with these techniques, however, because heart sounds reflect multicomponent, nonstationary, impulsive, and chaotic events during the cardiac cycle.

The need for analysis methods combining temporal and spectral information lead naturally to the implementation of the spectrogram (the squared magnitude of the short-time Fourier transform) [8,9]. However, the inability of this method to provide adequate simultaneous resolution in both time and frequency again limited advances in heart sound research. More sophisticated approaches to heart sound analysis were generally overlooked until Wood et. al . suggested that general-class time frequency transforms could be useful in investigation of heart sounds during the isovolumic contraction period [10]. These investigators employed an open-chest animal model with an array of surface mounted accelerometers to study acoustic phenomena. Their results suggested that there is a rising frequency component in the first heart sound which reflected changes in properties of the myocardium during early systole. This seminal study stimulated our interest in using TFD to characterize the time-frequency distributions in man.

In this study, we employed a multisensor catheter mounted piezoelectric to localize heart sound recording to specific regions within the heart , obtaining well-localized signals with a good signal-to-noise ratio. These ICPs were analyzed using three members of the class of GTFDs and results compared with those from the spectrogram.

4.1 General Time Frequency Distributions

Investigators, motivated by Wigner's pioneering work in the 1930s have attempted to improve upon the spectrogram as a tool for joint time-frequency representation. Cohen [11] incorporated this body of work into a single class of functions, now known as Cohen-class or generalized time-frequency distributions (GTFD).

The mathematical basis for the GTFD class is the so-called *instantaneous autocorrelation* of the signal *s(t):*

$$R_s(t,\tau) = s(t + \frac{\tau}{2})\, s^*(t - \frac{\tau}{2})$$

This "self-windowing" function gives the GTFD a "bi-linear" nature (i.e., the signal appears twice in the calculation). This removes the requirement for an imposed window function which severely limits the spectrogram in terms of joint time-frequency resolution. However, there is an undesirable "side effect" inherent in $R(t,\tau)$: whenever the signal consists of multiple components, the bilinear calculation produces "cross-terms" which have no physical interpretation.

The "parent distribution" of the GTFD class, the Wigner

distribution (WD), is obtained by taking the Fourier transform (FT) of $R(t,\tau)$ with respect to τ. Cohen has described the many desirable properties of the WD (e.g., greater theoretical resolution, satisfaction of the time and frequency "marginals", conservation of temporal and spectral energy) as well as undesirable characteristics: the cross-terms and the existence of non-positive (spurious) energy values.

A description of how one may reduce these cross terms is given by Jeong and Williams in the language of traditional linear, time-invariant system theory. The *inverse-FT* of $R(t,\tau)$ has been termed the *ambiguity function,* $A(\theta,\tau)$; a function of lag variables both in frequency and time. Cross-terms may be reduced if a suitable *kernel* function $\phi(\theta,\tau)$ is found to convolve in two dimensions with $A(\theta,\tau)$. A class of "reduced interference distributions" has been designed [12] according to the effect of this kernel function upon $R(t,\tau)$ in the ambiguity domain. The GTFD class can then be expressed as:

$$P(t,f) = \iiint \phi(\theta,\tau)\ A(\theta,\tau)\ e^{-j(\theta t+\tau\omega)} d\theta d\tau$$

The importance of this formula is that the behavior of the entire TFD can be readily understood once the operation of the kernel function $\phi(\theta,\tau)$ in the ambiguity plane is characterized. Since the location of the cross-terms in this domain is signal-dependent, no single kernel will work well for all types of signals [12,13]. Therefore, caution is advised in applying GTFDs to physiologic phenomena whose characteristics are not fully understood.

4.2 Binomial kernel

Choi and Williams developed the first of the "modern" GTFD kernels based on an exponential function in ambiguity space. One reduced-interference implementation based on the Choi-Williams kernel is the Binomial Transform (BT), whose discrete form is given in terms of (m,n) lag indices by [12]:

$$\Psi(n,m) = \frac{1}{2^{|m|}} \sum_{k=0}^{|m|} \binom{m}{k} \delta(n+|m|/2-k)$$

The BT-TFD has been applied by Wood [10] and others to several types of biological signals. Due to the properties of its Gaussian-shaped kernel (in the θ,τ plane), this may be the most general-purpose of the GTFDs.

4.3 ZAM kernel

Another interesting TFD with cross-term suppressing features was proposed by Zhao, Atlas and Marks, hence known as the ZAM-TFD. Cone-shaped in the (t,τ) domain, its kernel is a sinc-like function in the ambiguity plane:

$$\phi_{ZAM}(\theta,\tau) = |\tau| \frac{\sin(2\pi\theta|\tau|/2)}{\pi\theta}$$

The ZAM-TFD has been shown to be effective in tracking frequency-hopping signals and representing signals in the presence of white noise [14].

4.4 Minimum cross-entropy (MCE)

The MCE , in contrast to the bilinear GTFDs, is one of class (Cohen-Posch) of kernels which are strictly positive-valued [15]. This desirable property is achieved because the MCE-TFD kernel is a function of the signal itself; it is not simply bilinear.

Loughlin et. al. [16] show how such a proper, positive TFD can be constructed by guessing a prior estimate of an unknown distribution, and then minimizing the cross entropy:

$$\Delta H(Q,\hat{P}) = \int_{-\infty}^{\infty}\int_{-\infty}^{\infty} Q(t,f) \log\frac{Q(t,f)}{\hat{P}(t,f)}\, dtdf$$

Since the spectrogram in non-negative and intuitively understood, it is typically used as a blurred, prior estimate (or estimates) of the desired TFD, which is arrived at via an iterative method optionally constrained by conditional moment constraints. The mathematical complexity of the MCE-TFD may be justified by the desireable properties of a positive TFD; in our study, the MCE gave the sharpest concentrations of temporal-spectral energies of the GTFDs tested.

According to [17], a distinction should be drawn between *concentration* of TFD energy vs. the related property of *resolution*, in describing the distribution of our non-analytic

signal. This implementation of the MCE kernel used only the constraint of the first moment of the marginals, and was comparable with the other GTFDs in execution time.

5. Conclusion

The results of our study suggest that Cohen's general class of time-frequency distributions may prove useful in characterizing in a meaningful way the nature of heart sounds. However, the choice of a GTFD is a decision which should be rigorously validated, particularly when the signal of interest is poorly understood.

6. Acknowledgements

The authors are indebted to Dai Tran, of Hughes Aircraft Corp. and Srivat Krishnamachari (formerly of University of Michigan EECS Department) for their patient assistance in understanding and using the TFD techniques, and Glen Gueller (Brooke Army Medical Center's EMIC/IMD) for his help in preparing these graphics.

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