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An Effiecient Modeling Technique for Heart Sounds and Murmurs

Kiran Kumari Patil*, Dr.B.S Nagabhushan, Dr. Vijaya Kumar B.P
*(*Research Scholar Dr. MGR University, Chennai)*

Abstract— Cardiac auscultation is highly subjective and a cognitive process and the amount information that can be obtained by listening heart sounds largely depends on the expertise, experience and acuity of the ear of the physician. In general, the classification and interpretation of heart sounds and murmurs is based on a adjective 0-6/6 grade scale and described by using “faint”, “soft”, “loud”, “ high pitch”, “clear”, “thrill”, “tremor”, “musical” and others terms. These terms are not well-defined and suitable mathematical models are not available. Apart from that, the adjective scales vary among the doctors and difficult to derive a standard model for heart sound quality and correct clinical interpretation.

In this research paper, we propose a novel framework based on psychoacoustic principles and derive psychoacoustic models for the heart sounds and murmurs. We discuss the theoretical foundations, psychoacoustic principles and derive the mathematical models for the psychoacoustic features such as loudness, sharpness, intensity, strength, roughness, tonality etc. for a set of heart sounds and murmurs. The proposed framework helps in deriving heart sound quality and also used for the comparison and correlation with normal and pathologic murmurs and enhances clinical decisions.
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Index Terms— psychoacoutic principles, psychoacoutic models, heart sounds, auscultation, phonocardiography

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1 Introduction

Heart sounds and murmurs are acoustic phenomenon caused by the mechnical events of cardiac system. Auscultation or hearing of heart sounds using conventional stethscope or electronic stehoscope is not purely a mechnical phenomenon of sound wave propagation, but also auditory, sensory, cognative and perceptual event. Digital cardiac auscultation is an art and science of interpreating hearts sounds and murmurs used for clinical diagnostics. Congnitive process that paly significant role heart sound perception and clinical interpreatation. The phonocardiography (PCG) — the art and science of recording and interpreting of heart sounds using latest digital technology has significantly helped to understand and interpret the complex heart sounds (normal, abnormal sounds including murmurs). The PCG is a display of the heart sound signal with respect time (time domain) and frequency components or spectral properties (frequency domain) and plotting the heart sounds and murmurs can provide useful information to the physician by complementing cardiac auscultation Phonocardiography techniques are used for the effective clinical investigations and corrective diagnostic heart related diseases and in particular valvular heart diseases. When a heart valve is stenotic or damaged, the abnormal blood flow patterns produce a series of audible vibratory sounds known as murmurs [3]. Doctors and physicians detect these disorders by listening to heart sounds at different locations across the torso. Murmurs heared during routine physical exminations offer important clues to the presence of undetected and asymptomatic cardiac disease. The process of interpreating heart sounds is called cardiac auscultation. It is a simple, non-invasive tec niques helps in early detection of cardiac disorders. Different cardiac ailments produce a potentially overwhelming set of acoustic pathological events and correctly identfying a disorder requires discrimination of subtle variations in the timing characteristics and spectral properties of heart sounds. The analysis and interpretation is complicated by the natural variations in heart sounds introduced by factors such as the gender, age, habitus and dynamic state of the patients. Even in adults, anixiety, stress, fever, anemia etc. may also cause benign murmurs. Typically, these cases are distinguished by examining the intensity of sounds, in addition to their timing and frequency content. Sounds that are interesting from the perspective of auscultation are often short lived (less than 20 millseconds) and seperated from one another by less than 30 milliseconds. Pathological signals indicative of cardiac diseases are also often much quieter than other heart sounds and their audibility varies across sucessive heart beats. Even with extensive experience, physicians may often disagree about sounds, in particular with brief heart sounds. These inaccuracies are attributed

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to human auditory limitations which include insensitivity to frequencies, slow response to rapidly occurring changes in acoustic signals and an inability to unmask soft sounds in the promixity of loud ones. Murmurs are extra heart sounds that are produced as a result of turbulent blood flow which is sufficient to produce audible noise. Murmurs may be present in normal hearts without any heart diseases are called innocent murmurs. The murmurs due to valvular heart diseases are called pathologic murmurs and needs to evaluate by the cardiologists. In general, the murmurs [3, 4] can be classified by seven different physical characteristics: timing, shape, location, radiation, intensity, pitch and quality. It may also include psychoacuostic characteristics such as loudness, heart sound intensity, heart sound pressure, sharpness and fluctuations. Timing refers to whether the murmur is a systolic or diastolic murmur depending on the S1 and S2 sounds of a standard heart sound cycle and plays vital role in clinical decisions.

Shape refers to the intensity of the heart sounds over time. We can derive the intensity contours and can be described in musical note such as “cresccendo”, “decrescendo”, or “crescendodecrescendo”.

Radiation refers to where the sound of the heart sounds and murmurs radiates and normally radiates in the direction of the blood flow. The radiated sound can be captured and displayed as radiation patterns and helps in specific characterizations of murmurs.

Intensity refers to the loudness of the murmur, and is graded on a scale from 0-6/6 adjective scale as shown in the following Table I. The terms such as “soft”, “faint”, “loud” ,”blowing”, “harsh”, “rumbling”and others have a subjective meaning and needs to be modeled precisely

Pitch of a murmur is low, medium or high and is determined by whether it can be auscultated best with the bell or diaphragm of a stetchscope. Pitch mainly refers to the fundmental frequency of the heart sounds and murmurs.

From the above discussios, it clear that the physical characteristics such as timing, shape, pitch, loudness, radiation, sound intensity, sound pressure and other parameters are clinically important and and described using a adjective scales as shown in table 1.

Table 1: Gradings on a scale from 0-6/6

Grade	Description
Grade 1	Very faint
Grade 2	Soft
Grade 3	Heared clearly on pericardium.
Grade 4	Loud with palpable thrill sound. May also be vibratory or tremor on palpatation.
Grade 5	Loud, clear with thrill.
Grade 6	Very loud with thrill

In order to address the above challenges, we derive psychoacoustics principlaes for the hearts sounds and murmurs in a novel way and specfic contributions of the research work. We propose and derive psychoacoutsic models based on the psychoacoustics principles for heart sounds and murmurs.We derive psychoacoutsic models and map them to the psychoacustic features such as loundness, pitch, sound intensity, sharpness, etc. with mathematical equations.We also discuss the classifciation of murmurs and adjective scales and also try to relate them into the psychoacoustic features. For example, the grade 4 murmur which is loud and thrill and derive the loundness contour and characterize the thrill by observing the contour of loudness pattern.We highlight the usage of psychoacuostic model for the heart sound qualities.

2. PSYCHOACOUSTIC PRINCIPLES AND MODLES

Psychoacoustics is the study of the subjective human perception of sounds [1]. Alternatively it can be described as the study of psychological correlates of the physical parameters of acoustics [1]. The field of psychoacoustic aims to model parameters of auditory sensation in terms of physical signal parameters and provide a framework and modeling capabilities for the acoustic sounds. The psychoacoustic models of sound perception exploiting the imperceptable sounds are used in the audio compression such as MP3 standards; non-linear response of the ear is exploited in the noise reduction systems and communication networks. The human ear can nominally hear sounds in the range 20 HZ to 20,000 Hz (20 kHz). Frequency reso

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lution of the ear is 0.36 Hz within the octave of 1,000–2,000 Hz. That is, changes in pitch larger than 0.36 Hz can be perceived in a clinical setting. Other scales have been derived directly from experiments on human hearing perception, such as the Mel scale and Bark scale and these are approximately logarithmic in frequency at the high-frequency end, but nearly linear at the low-frequency end. Ear drums are sensitive only to variations in the sound pressure, but can detect pressure changes as small as 2×10–10 ATM and as great or greater than 1 ATM. The sound pressue level (SPL) is also measured logarithimically, with all pressures referenced to 1.97385×10–10 ATM. The lower limit of audibility is therefore defined as 0 dB, but the upper limit is not as clearly defined. By measuring this minimum intensity for testing tones of various frequencies, a frequency dependent absolute threshold of hearing (ATH) curve may be derived. Typically, ear shows a peak of sensitivity (i.e., its lowest ATH) between 1 kHz and 5 kHz, though the threshold changes with age, with older ears showing decreased sensitivity above 2 kHz. Equal-loudness contours indicate the sound pressure level (dB), over the range of audible frequencies, which are perceived as being of equal loudness and may be ploted. We use classical reference [5] which represents a set of algorithms for calculating auditory sensations including loudness, sharpness, roughness, softness, sound strength and intensity, and fluctuation strength and extend it for the heart sounds and murmurs. The classification of murmurs is characterized by using the psychoacoustic features and derives mathematical equations.

3. PROPOSED MODELS

3.1 Loudness of heart sound and murmurs

The loudness is modeled by the following equation, where N is loudness, N' is the loudness of a given critical band or also know as specific loudness, and dz is the increment in the critical band scale.

$$N = \int_{0}^{24} N'dz \qquad (1)$$

The unit of loudness, the sone, is a ratio scale referenced against the sensation produced by a 1 kHz sine tone with a sound pressure level of 40 dB. The models draw on data gained from subjective testing and from a physiological understanding of the auditory periphery. The “loudness” property of heart sounds and murmurs helps in characterization, classification and discrimination of various murmurs in clinical investigations. We can plot the loudness contour using above equations and derive deep insight in the heart sound analysis and interpretations. The complexity of the loudness of complex heart sound needs to be investigated in multistages and becomes complicated for time varying sounds, dynamical effects like forward masking and temporal loudness integration [2, 6, 5] have to be considered When the physician hears the heart sounds and murmurs, the loudness is a clinically significant feature and can be measured in sone and be mapped to the vertical axis of the Figure 1 in terms of the adjective scales of murmur classifications.

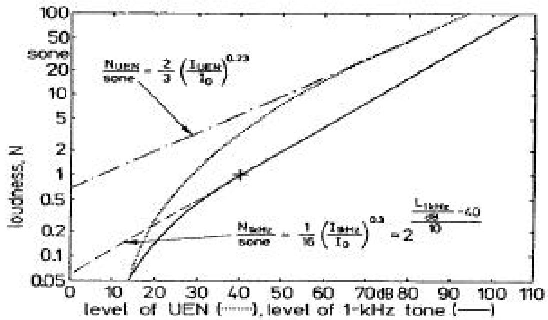

Figure 1. Loudness function of a 1- kHz tone (solid) and of Uniform Exciting Noise (dotted), broken and dashed-dotted lines with corresponding equations (adopted from [5])

3.2 Sharpness of heat sound and murmurs

Sharpness or brightness is one of the most prominent features of timbre. Timbre is more complicated, being determined by the harmonic content of the signal. The hearing is based on the amplitude of the frequencies and is very insensitive to their phases. The shape of hearts sounds and murmurs in time domain waveform is only indirectly related to hearing and poses serious challenges in correct interpretation of heart sounds. The models are based on the centroid (signal spectrum or loudness pattern) of the heart sounds and murmurs. The sharpness is modeled as a weighted centroid of the specific loudness pattern. The unit is acum, referenced to a band of noise 1 critical band wide, centered on 1 kHz at 60 dB. It is also referred to the perception that the sound is “sharp”, “harsh” or “soft” when used in the context of heart sound perception and clinical interpretations. It is related to the proportion of high frequency energy present in the sound, weighted towards energy in the region above 3 kHz. For harmonic tones, sharpness can be controlled through distribution of the harmonic spectral envelope. The model used [5, 9, 7] for the calculating the sharpness of tones is summarized by the Equation 2.

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$$s = 0.11 \frac{\int_0^{24Bark} N'g(z)zdz}{\int_0^{24} N'dz} \qquad (2)$$

where the S is sharpness, N' is specific loudness, z is the bark scale of auditory filters and g(z) is a weighting function that emphasis z for the critical band rates. It was found that the sharpness of narrow band noises increases proportionally with the critical band rate for center frequencies below about 3 kHz. At higher frequencies, however, sharpness increases more strongly, an effect that has to be taken into account when the sharpness S is calculated using a formula that gives the weighted first momentum of the specific loudness pattern: In equation (2), the denominator gives the total loudness, while the upper integral is the weighted momentum mentioned. The psychoacoustic feature - sharpness can be used for the following murmurs.

Early systolic ejection click murmur is a high frequency, early systolic sound occurring 0.03- 0.07 second after S1 [4]. The sound is generated either by the sudden upward doming of an abnormal semilunar valve (aortic or plutonic) and sharp click sounds.

Opening Snap murmur is a high frequency, early diastolic sound that is associated with MS [3]. It occurs 0.04-0.12 second after S2 and may or may not be associated with a late peaking or rumbling diastolic murmur of varying sharpness with peaking at specific temporal patterns.

3.3 Pitch of heart and murmurs

A psycho acoustical pitch ratio scale is a difficult concept due to the complexity of pitch perception and cognition. Reference [6, 10] describes some of the complexity of pitch structures for harmonic tones (such as pitch height, octave equivalence and cycle of fifths) through multidimensional geometric figures. In addition to complex structures of pitch height, pitch has the dimension of pitch strength, also known as "tonalness". The harmonic series is of great importance in pitch perception, and mainly pitched sounds in everyday experience exhibit harmonic spectra. In general, it is usually determined by the fundamental frequency as a pitch percept. A model of pitch perception is analyzed using template matching or autocorrelation techniques. Pitch is used to describe the tonal quality of the murmur be it high pitched or low pitched. For those of us not musically inclined, a simple way to distinguish pitch is to determine whether the sound is heard best with the diaphragm of the stethoscope, i.e., high pitched, or with the bell, i.e., low pitched. Murmurs of mitral or tricuspid stenosis are best heard with the bell. Some of other hearts sounds that can characterize the pitch are: *S3 sound* is a low frequency, mid diastolic sound occurring 0.14-0.22 second after S2. The frequency components of low frequency heart sounds are difficult to hear and can be modeled and uniquely find pitch features of the heart sounds and murmurs [3]. *S4 sound* is also a low frequency, late diastolic sound occurring 0.08-0.20 second prior to S1. It is generated during presystolic ventricular filling due to atrial contraction, hypertension and diastolic dysfunction. The sequencing and ordering with respect to the S1 and S2 in a standard cardiac cycle and obtain pitch pattern and frequency components using spectral techniques will assist the doctor for the better clinical decisions [3].

3.4 Roughness of heart sounds and murmurs

Roughness is a sensation caused by quite rapid amplitude modulation within auditory filters. This modulation can be caused by beats between two pure tone components, or by a signal with amplitude or frequency modulation. Beating within an auditory filter channel has been used to explain the acoustic component of tonal dissonance and represent roughness of the heart sounds [5]. The unit of roughness is the asper, which is referenced to a 1 kHz tone at 60 dB with 100% amplitude modulation at 70 Hz. The model presented in [5,8] by for calculating the roughness of modulated tones having a single modulation frequency is given in Equation 5, where R is roughness, fmod is the modulation frequency, and L_E is the excitation level within an auditory filter. This uses the time-varying excitation pattern of the ear (similar to the specific loudness pattern, except that the magnitude is in decibels rather than sones/bark), with the difference between maximum and minimum excitation levels integrated across auditory filters used to determine roughness.

$$R = 0.3 \frac{f_{\text{mod}}}{kHz} \int_0^{24Bark} \frac{\Delta L_E(z)dz}{dB/Bark} asper \qquad (3)$$

The roughness of the heart sound can be used for the modeling aortic insufficiency (AI) may be congenital rheumatic, and collagen vascular disease. The murmur is a high frequency (blowing) decrescendo murmur beginning in early cardiac cycle and uniquely radiates to the top of the head. The roughness of the murmurs can be uniquely characterized using the above equation and needs further investigations. Mitral regurgitation (MR) is associated with endocarditis, and ischemic heart diseases [4]. The murmur is typically a high frequency, holosystolic, plateau murmur that is best heard at the apex. The murmur often radiates to the left axilla and back. There is no appreciable change in murmur intensity with cycle length (as with AS). MR may be associated with S3 in more severe cases. Here we have to use intensity, high frequency and radiation patterns in a consistent way and need further investigation and clinical validations.

4. CONCLUSIONS

The cardiac auscultation is an effective diagnostic technique used in the early detection of cardiac diseases in particular the valvular diseases, including the murmurs. It is argued that the most of the doctors and physicians depend on their experience and make subjective interpretations of heart diseases. In this paper, we proposed psychoacoustic models based on a psychoacoustic principles and mathematical foundations and discussed the psychoacoustic features (pitch, intensity, timbre, loudness, power, intensity and other clinically important psychoacoustic features) that can be modeled, analyzed and provide effective aid of clinical decisions related to heart diseases, and in particular murmurs. These models offer a reasoning framework for the subjective reasoning of heart sounds and derived psychoacoustical models. It is also used to model the quality of heart sounds for many standardization efforts and can be used as an effective teaching aid for the cardiac auscultations. Our preliminary investigations and experimental results on our psychoacoustic models are quite encouraging and provide a deeper insight into the perception and interpretation of cardiac auscultations. The visualization tools for the psychoacoustic models are in progress and will help in clinical decisions. Further investigations and validation of the proposed psychoacoustic models are planned for the future work.

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