Use of the fast Fourier transform for frequency analysis of the first heart sound in normal man*

Ajit P. Yoganathan Ramesh Gupta Firdaus E. Udwadia†
J. Wayen Miller William H. Corcoran‡

Chemical Engineering Laboratory, California Institute of Technology, Pasadena, California 91125, USA

Radha Sarma John L. Johnson Richard J. Bing

Huntington Memorial Hospital, Pasadena, California 91105, USA

Abstract—*The first heart sound of 29 normal, young males, recorded at the apex of the heart, was analysed for the power content as a function of frequency using the technique of the fast Fourier transform. The frequency spectra were seen to contain peaks in the low-frequency range (10–50 Hz) and the medium-frequency range (50–140 Hz). The average spectrum of the entire study shows a peak at 30 Hz, and an average attenuation of the first heart sound at the apex, of 16 dB/octave. The peaks are probably related to the elastic properties of the heart muscles and the dynamic events causing the first sound. Therefore important diagnostic information might be obtained from frequency studies of heart sounds. Such studies should increase the clinical importance of phonocardiography.*

Introduction

AUSCULTATION is one of the sensitive tests of the functional integrity of the heart. In many cases, murmurs or alterations in the heart sounds are the only definite signs of organic heart disease, appearing long before the stress on the cardiovascular system is sufficient to produce other signs and symptoms (RUSHMER, 1970). Therefore, the recorded phonocardiogram contains very valuable information, which, if analysed quantitatively in a proper manner, could lead to important diagnostic results. Phonocardiography has over the last three decades become a widely used clinical procedure (MCKUSICK, 1958). It is one of the noninvasive techniques available to study and analyse the condition of the human heart. Cardiac auscultation and phonocardiography have significantly improved in recent years because of modern electronic instrumentation and new methods of data collection and analysis. Application of simple, inexpensive, and noninvasive diagnostic methods has long been overdue. Phonocardiography has much to offer towards this goal.

Studies on the various aspects of heart sounds have been carried out by many cardiologists. Of these, LUISADA (1959, 1971) and RUSHMER (1970) have done much of the pioneering work. Recently, ADOLPH *et al* (1970) and VAN VOLLENHOVEN *et al.* (1968) have suggested that significant information can be obtained from frequency analysis of heart sounds. Thus, if diagnostic information has to be extracted from the frequency spectrum of heart sounds, it is essential that accurate studies be done on the various heart sounds both for normal subjects and those with known cardiac diseases.

Until now, very few studies have been made on the frequency spectrum of heart sounds. Moreover, the methods used in these studies have been approximate. For example, frequency spectra have been obtained by sweeping the heart-sound signals with bandpass filters (ADOLPH *et al.*, 1970; SAKAI *et al.*, 1971),

In this study, we have used the fast Fourier transform (f.f.t.) to analyse the first heart sound in 29 normal, healthy, young males. This method of analysis has a high degree of accuracy and was used previously in the analysis of the Korotkoff sounds (GUPTA *et al.*, 1974). The frequency spectra obtained by this method contain peaks, which in turn may be related to the elasticity of the heart muscles and the various dynamic events leading to the production of the first heart sound. These spectra should be of value in the design of filters for heart-sound analysis, as well as in the diagnosis of cardiac disease.

Clinical methods and instrumentation

Healthy, young, 'normal' males from 18 to 38 years of age were used for this study. The absence of heart disease was established on the basis of no known heart ailments and a normal reading for the first six leads of a standard electrocardiogram. All sound recordings were performed in a quiet room, with the subject in a supine position and the microphone placed on the apex area of the precordium.

The equipment used in data collection and analysis is shown in Fig. 1. A contact-type microphone (Hewlett Packard 21050A) was used to obtain the heart-sound signals. A retaining rubber belt ensured that the microphone was maintained at the correct location on the subject's chest. The signal picked up

* *First received 16th December 1974 and in final form 1st January 1975*

† *Department of Civil Engineering, University of Southern California Los Angeles, California 90033*

‡ *To whom all correspondence should be sent*

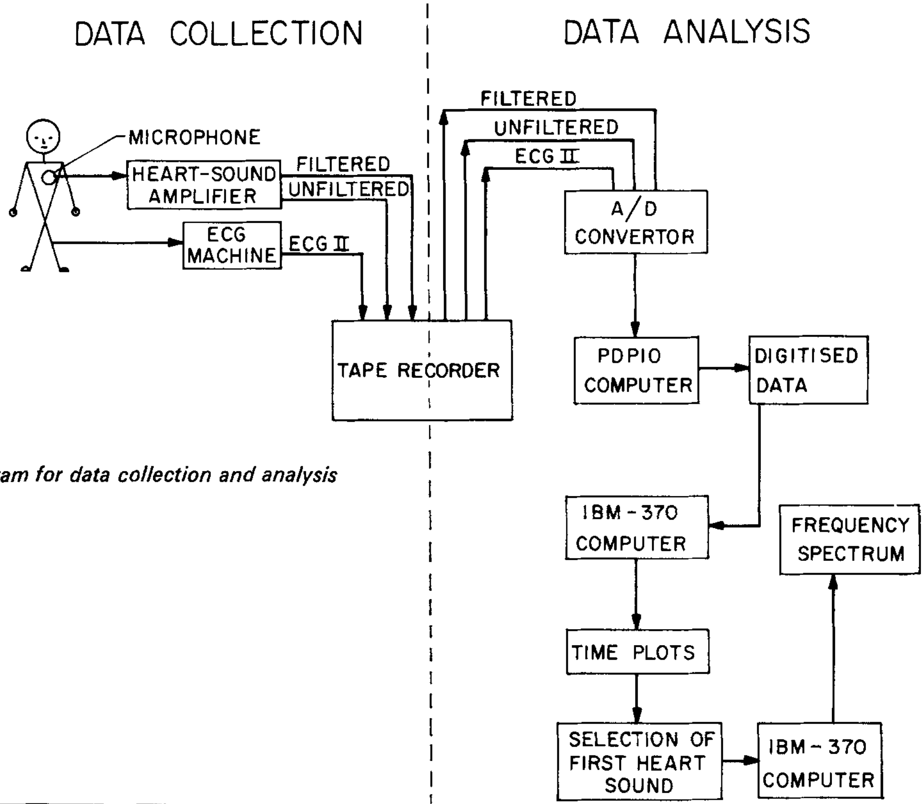

Fig. 1 Flow diagram for data collection and analysis

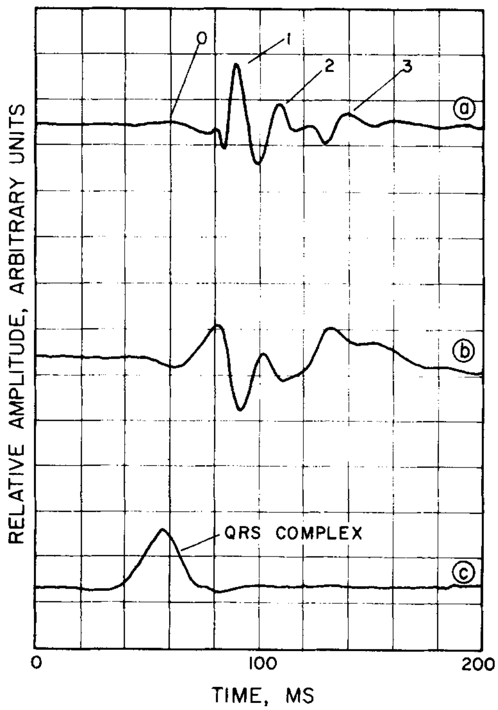

Fig. 2 Typical amplitude/time plot
(a) Filtered first heart sound
(b) Unfiltered first heart sound
(c) e.c.g. lead II

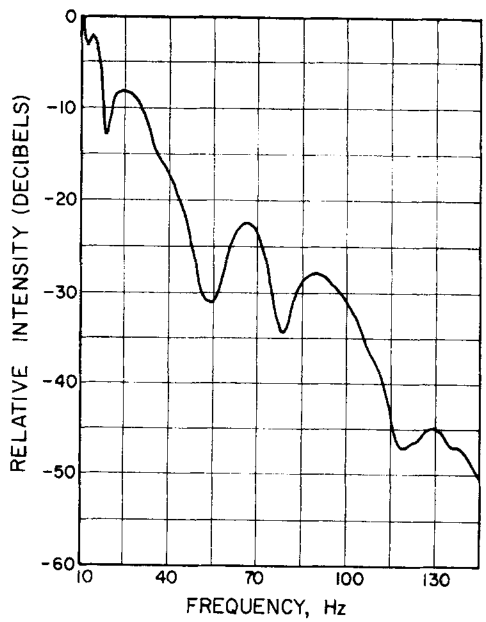

Fig. 3 Frequency spectrum of the first heart sound of subject S 16

by the microphone was amplified by a high-pass amplifier (Hewlett Packard 8813A) and then recorded on an f.m. tape recorder (Hewlett Packard 3960). To ensure that the low-frequency signals would not dominate the high-frequency signals and to improve the signal-to-noise ratio at the higher frequencies, a 12 dB/octave filter with a cutoff frequency of 200 Hz was used on the amplifier. In addition to the filtered heart sound, the unfiltered heart sound and lead II of the e.c.g. were recorded simultaneously on the tape recorder. The lead II of the e.c.g. was used as a time base for the heart sounds. The first sound was identified by its time separation from the QRS complex of the e.c.g. signal.

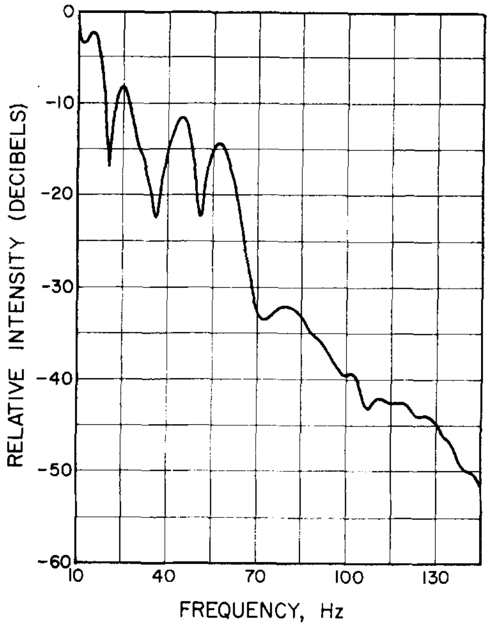

Fig. 4 Frequency spectrum of the first heart sound of subject S 19

Data analysis

The recorded signals were played back from the tape recorder to an analogue-to-digital convertor at the Caltech computing centre, and 30-second epochs of date were digitised for each experiment (digitisation rate of 1000 points per second). The digitised data were stored on a magnetic tape. This tape was then used to generate the time plots on the Calcomp plotter. Fig. 2 shows a portion of a typical plot of the digitised data.

A 250 ms time segment, or window, containing the first heart sound, was selected from each cardiac cycle of the plotted data. A frequency spectrum of each of these 250 ms time segments was obtained using the fast-Fourier-transform algorithm of Cooley and Tukey (1965). Finally, a mean-frequency spectrum for each subject was obtained by averaging the spectra of 15 first-heart sounds. This average spectrum was corrected for the 12 db/octave filtering, and the resulting spectrum with a frequency least count of 1 Hz was plotted in graphical form. Typical spectra are shown in Figs. 3 and 4.

The frequency spectra of the 29 subjects were averaged. This average spectrum is shown in Fig. 5. The average frequency spectrum assumes that the 29 spectra have a value of 0 dB at 10 Hz.

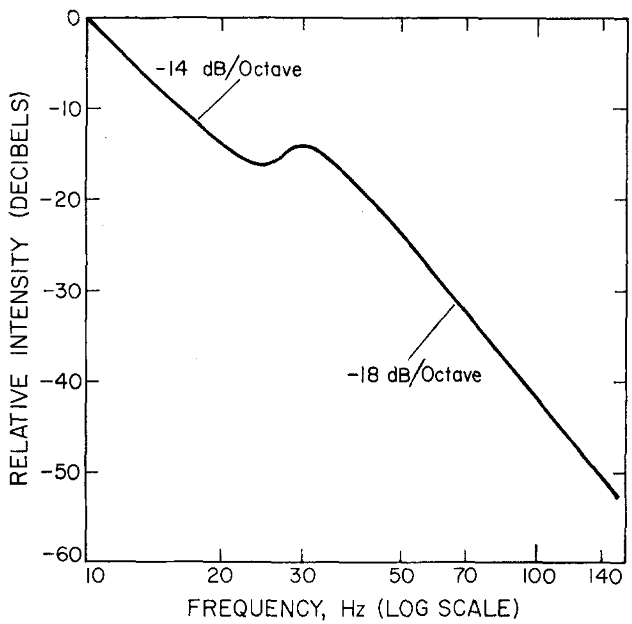

Fig. 5 Average frequency spectrum of 29 subjects

Results

The frequency spectra of the first heart sound of 29 normal healthy males were analysed. It was observed that the first heart sound contains peaks in its frequency spectrum. The observed peaks, which are greater than 2·5 dB in height, are tabulated in Table 1. For the present study, the analysis was conducted on the heart sounds recorded at the apex. The recordings at the apex are the least attenuated, because the heart is in direct contact with the thorax and should therefore give a good indication of the frequency content of the first heart sound. The reproducibility of the resonant peaks was verified by recording the heart sounds of three of the volunteers twice within a period of four weeks and carrying out the frequency analysis.

Table 1. Frequency peaks in the frequency spectra of the first heart sound of 29 normal males

Subject	Age	Frequency peaks
	years	Hz
S 1	37	30, 46, 70, 97, 124
S 2	24	38, 53, 67, 91
S 3	26	36, 45, 68
S 4	22	27, 40, 67
S 5	28	33, 60
S 6	27	38
S 7	32	21, 44, 76, 97
S 8	23	28, 46
S 9	25	43, 97
S 10	23	33
S 11	23	22, 33, 67
S 12	25	25, 39, 99
S 13	22	22, 33, 48, 130
S 14	24	33, 60, 107
S 15	21	16, 25, 42, 100
S 16	35	25, 66, 89, 128
S 17	26	21, 36, 66, 103
S 18	23	28, 52, 81
S 19	19	25, 45, 58
S 20	27	34, 64, 133
S 21	22	21, 37, 51, 94
S 22	28	29. 76
S 23	25	25, 112
S 24	32	30, 58, 135
S 25	22	16, 28, 41, 115
S 26	21	16, 25, 42, 63, 93
S 27	24	20, 30, 49, 67, 106
S 28	23	33, 50, 87
S 29	24	30, 58, 72, 122

A majority of the subjects had at least three peaks in the frequency spectrum of the first heart sound. The peaks were divided into two frequency ranges. Peaks in the range 10–50 Hz were called low-frequency peaks, and those in the range 50–140 Hz were classified as medium-frequency peaks.

In the low-frequency range, 28 out of 29 subjects were found to have a peak between 25–38 Hz. Moreover, all of these 28 subjects were found to have only a single peak in the frequency interval 25–38 Hz. In the medium-frequency range, 26 of the 29 subjects were found to have peaks. However, unlike the peaks in the low-frequency range, the peaks in the medium-frequency range were not confined to a narrow frequency band but were widely scattered.

These observations are also manifested by the frequency-spectrum curve averaged over the 29 subjects and shown in Fig. 5. The average spectrum exhibits a peak at about 30 Hz. In the medium-frequency range, however, peaking is much less obvious because of the individual variation from subject to subject. The average spectrum has an attenuation of 14 dB/octave between 10 and 25 Hz and 18 dB/octave between 40 and 150 Hz.

There have been very few studies on the frequency analysis of the heart sounds reported in the literature. ADOLPH *et al.* (1970) carried out a frequency analysis of the first heart sound during the isovolumic contraction period, and observed a peak in the power spectrum. This frequency peak was related to the ventricular elasticity. SAKAI *et al.* (1971) have also observed peaks in the power spectrum of the first heart sound. In all of these studies, power spectra were obtained by sweeping the signal with a band-pass filter having a band width of 20 Hz. This procedure gives only an approximate result because the technique has very poor frequency resolution. Also, very narrow bandpass filters must be used if narrow and small peaks are to be detected. The data-analysis technique used in the present study has a higher degree of accuracy and is capable of detecting small peaks in the frequency spectrum of the heart sounds.

Studies by MAAS and WEBER (1952) and HOLLDACK (1952) indicated that in general the attenuation of the first heart sound was about 12 dB/octave. Recently, SAKAI *et al.* (1971) reported that this attenuation is less than 12 dB/octave. In the present study, however, an attenuation of 14 to 18 dB/octave has been observed for the first heart sound at the apex. The difference can, perhaps, be attributed to the different clinical methods and instrumentation used. A knowledge of the true attenuation will help in the design of electronic equipment used to study heart sounds.

An understanding of the peaks observed in the frequency spectra of the first heart sound should give valuable information about the anatomical structure of the heart and may provide important diagnostic information for certain cardiovascular diseases. Generally speaking, these peaks are probably related to the various dynamic events associated with the production of the first heart sound. Thus if each of these peaks can be associated with a different dynamic event or element in the heart, then an important investigative tool will be available to check the functional integrity of the heart.

It is generally accepted that the zeroth and the third components of the first heart sound (Fig. 2) are composed of the low frequencies, and the first and second components are composed of the medium frequencies. Thus, the peaks in the low-frequency range should correspond to the events associated with the zeroth and the third components. Similarly, peaks in the medium-frequency range should correspond to the first and second components of the first heart sound.

Work is under way to develop a more complete model to explain the observed results. It involves the use of intracardiac phonocatheterisation measurements to associate the peaks with the various dynamic events that give rise to the first heart sound. Also, external and intracardiac phonocardiographic data will be collected from patients with known cardiovascular diseases.

Acknowledgment—We wish to express our appreciation to Hilton Buggs for experimental help. Financial support from the Donald E. Baxter and Ahmanson Foundations is gratefully acknowledged.

References

ADOLPH, R. J., STEPHENS, J. F. and TANAKA, K. (1970) The clinical value of frequency analysis of the first heart sound in myocardial infarction. *Circulation* **41,** 1003.

COOLEY, J. W, and TUKEY, J. W. (1965) An algorithm for the machine calculation of complex Fourier series. *Math. Comput.* **19,** 297.

GUPTA, R., MILLER, J. W., YOGANATHAN, A. P., KIM, B. M., UDWADIA, F. E. and CORCORAN, W. H. (1974) Spectral analysis of arterial sounds: a noninvasive method of studying arterial disease. Submitted to the *J, Med & Biol. Eng.*

HOLLDACK, K. (1952) Ergebrise der inneran Medizin und Kunderheilkunde **3,** 407.

LUISADA, A. A. (Ed.) (1959) Symposium on phonocardiography. *Am. J. Cardiol.* **4,** 1.

LUISADA, A. A. (Ed.) (1971) Symposium on cardiovascular sound. *Ibid.* **28,** 127.

MAAS, H. and WEBBER, A. (1952) *Cardiologia* **21,** 773.

MCKUSICK, V. A. (1958) *Cardiovascular sounds in health and disease.* Williams and Wilkins Co., Baltimore.

RUSHMER, R. F. (1970) *Cardiovascular dynamics* 3rd edn. W. B. Saunder Co., Philadelphia.

SAFONOV, Yu D. (1969) The biohydraulic mechanisms producing heart sounds. *Cor Vasa* **10,** 295.

SAKAI, A., FEIGEN, L. P. and LUISADA, A. A. (1971) Frequency distribution of the heart sounds in normal man. *Cardiovas. Res.* **5,** 358.

VAN VOLLENHOVEN, E.. VAN ROTTERDAM, A., DURENBOS, T. and SCHLESINGER, F. G. (1968) Frequency analysis of heart murmurs. *Med. & Biol. Eng.* **7,** 227.

Usage de la transformation rapide de Fourier pour l'analyse de la fréquence du premier son cardiaque chez l'homme

Sommaire—On an analysé le premier son cardiaque enregistré au sommet cardiaque chez 29 jeunes hommes normaux, pour déterminer sa composition en fonction de la fréquence à l'aide de la technique de transformation rapide de Fourier. On remarqua que la spectre des fréquences contenait des pointes dans la zone des basses fréquences (10–50 Hz) et dans la zone des moyennes fréquences (50–140 Hz). La moyenne du spectre complet de l'étude présente une pointe a 30 Hz et une atténuation moyenne de 16 dB/octave au sommet du premier son cardiaque. Les pointes sont probablement apparentées aux propriétés élastiques de muscle cardiaque et les phénoménes occasionnant le premier son. Des informations diagnostiques importantes peuvent donc être dérivées de l'étude des fréquences des sons cardiaques. De telles études pourraient augmenter l'importance clinique de la phonocardiographie.

Verwendung der schnellen Fourier-Transformierten zur Frequenzanalyse des ersten Herztones beim normalen Menschen

Zusammenfassung—Der erste Herzton von 29 normalen jungen Männern an der Herzspitze wurde auf seinen Energiegehalt als Frequenzfunktion überprüft, wobei das Verfahren der schnellen Fourier-Transformierten verwendet wurde. Es wurde festgestellt, daß die Frequenzspektren Spitzen im niedrigen Frequenzbereich (10–50 Hz) und im mittleren Frequenzbereich (50–140 Hz) enthielten. Das mittlere Spekrtum der gesamten Untersuchung zeigt eine Spitze bei 30 Hz und eine durchschnittliche Dämpfung des ersten Herztons an der Herzspitze von 16 dB/Oktave. Die Spitzen beziehen sich wahrscheinlich auf die elastischen Eigenschaften des Herzmuskels und die dynamischen Vorgänge, die den ersten Ton verursachen. Aus Frequenzuntersuchungen der ersten Herztöne könnte man daher wichtige diagnostische Angaben erhalten. Solche Untersuchungen dürften die klinische Bedeutung der Phonokardiografie erhöhen.